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An Application of Orifice Hydrodynamic Cavitation Reactor for Tertiary Treatment of Wastewater Treatment Plant Effluents

Aleksandra Szaja[1*], Agnieszka Montusiewicz[1], Magdalena Lebiocka[1], Jan Skrzypiec[1]

[1] Faculty of Environmental Engineering, Lublin University of Technology, 20-618 Lublin, Nadbystrzycka 40 B, Poland

* Corresponding author's e-mail: a.szaja@pollub.pl

ABSTRACT

In this paper, a multi-orifice hydrodynamic cavitator (HC) has been applied as an effective device for water reclamation. Municipal wastewater after mechanical and biological treatment has been applied as a medium. The effectiveness of using this device has been evaluated on the basis on the microbiological indicators. Moreover, optimization of operating parameters was evaluated. Two experiments with different inlet pressure of 0.4 and 0.6 MPa were performed. The samples for analyses were taken at the following time intervals: 0, 15, 30, 60 and 90 min. The application of HC reactor provided the effective destruction of microorganisms, thus allowing for subsequent use of reclaimed water. With regard to *Escherichia coli* and Coliform bacteria destruction, the longest time of 90 min and higher pressure of 0.6 MPa might be considered as the most advantageous conditions to perform cavitation. In both cases, the microbes were deactivated in over 50%. In the case of *Enterococci*, *Pseudomonas aeruginosa* and colony count, more beneficial results were found at lower pressure of 0.4 MPa and 90 min. Therein, the high level of microorganisms destruction was achieved varied between 81 and 92%. The applied HC allowed for selecting optimal operating parameters and process control through the application of gauge system.

Keywords: cavitation, cavitation number, municipal wastewater, optimization of cavitational parameters, water reuse.

INTRODUCTION

Progressive climate changes that have been observed in recent years influenced water availability [1]. The threat of drought and related water deficit has been observed in the regions that have not experienced this problem. Additionally, the growing population and hence progressive economic development will cause increasing demands for good quality water [2]. Importantly, lack of water results in many negative consequences e.g. biodiversity degradation, economic losses related with limitation of agricultural and livestock areas, spreading diseases and finally human migrations as well as conflicts [3]. Therefore, new technologies and new solutions to save and recover water have been constantly sought.

Generally, wastewater treatment plants (WWTPs) apply only two basic steps: primary and secondary. However, given the water deficit, it seems necessary to recover and manage the WWTP effluents. The implementation of tertiary treatments might improve the wastewater quality, making it reusable for different purposes [4]. Nevertheless, many WWTPs have still not employed this stage, mainly due to significant investment and operating outlays. Thus far, available technologies have involved multi-stage treatment, including advances processes, such as coagulation, flocculation, sedimentation filtration, ultrafiltration and disinfection/oxidation [5, 6]. Moreover, the application of fluidized bed bioreactor and its modifications has been also observed [7-9]. Other solutions have employed microalgae [4, 10] or epuvalisation technique for effluent depuration [11]. However, the accurate technology depends on the subsequent application of reclaimed water. It might be used for an irrigation in agriculture and urban agglomeration (gardens, golf courses) [12, 13], technological processes (washing and cooling purposes) [14, 15] or to flush toilets [16]. Importantly, each application of reclaimed water brings the potential risk of contamination; therefore, maintaining its control is required [17].

Currently, an advanced oxidation process (AOP) is regarded as one of most emerging technology in wastewater treatment. It indicated a high efficiency and flexibility to remove contaminants that cannot be treated in different way. AOPs applied reactive hydroxyl radicals with high oxidation potential to oxidize harmful and toxic substances. The studies conducted so far, both on a laboratory and industrial scale, have shown that those techniques fill the gap in between conventional physicochemical and biological processes [18-20]. Among various AOPs, hydrodynamic cavitation (HC) combines low operating costs, great energy efficiency and significant treatment efficacy [21, 22]. HC is willingly applied on a technical scale because of the simple construction of the reactor and related simple operation. Moreover, such devices might be readily combined with other treatment methods [22-24]. Cavitation is a well-recognized phenomenon of an inception, growth and instantaneous implosion of cavitation bubbles or cavities appeared in a short period of time in many locations in the reactor [18, 25]. HC results in an extremely high local temperature (5000–6000 K) and pressure (405.3–506.6 MPa) initiating both physical and chemical effects, besides the mechanical ones [24, 26, 27]. It is commonly known that HC effects might be detrimental on solid surfaces and can cause material erosion [28, 29]. However, HC has been successfully applied for the treatment of various types of industrial wastewater [30], removing emerging pollutants [18, 31], polymer degradation [32], cell disruption [33] as well as for water disinfection [34]. It is worth investigating, if it will be useful in minimization of bacteriological contamination in treated municipal wastewater which discharged WWTPs. Using this technique, pollutants are degraded through the impact of many factors, e.g. oxidation of free radicals, thermal decomposition, impact of shock waves and shear forces [35]. Moreover, cavitation also have a beneficial effect on the materials, similarly to cavitation shoot peening, mainly due to the occurring mechanical effects [36]. This technique also has demonstrated the cleaning abilities [37].

In the present study, the effectiveness of applying the orifice HC reactor for tertiary treatment of WWTP effluents was evaluated. For this purpose, the quality of biological indicators within the experiments was assessed. The basic novelty in this study is related with the application of a specially designed HC reactor and orifice plate. Moreover, the studies evaluating the impact of cavitation in relation to the analysed indicators have not been conducted so far. Importantly, the influence of inlet pressure and time on the efficacy of the treatment was also discussed, thus allowing for choosing the most advantageous operational parameters.

MATERIAL AND METHODS

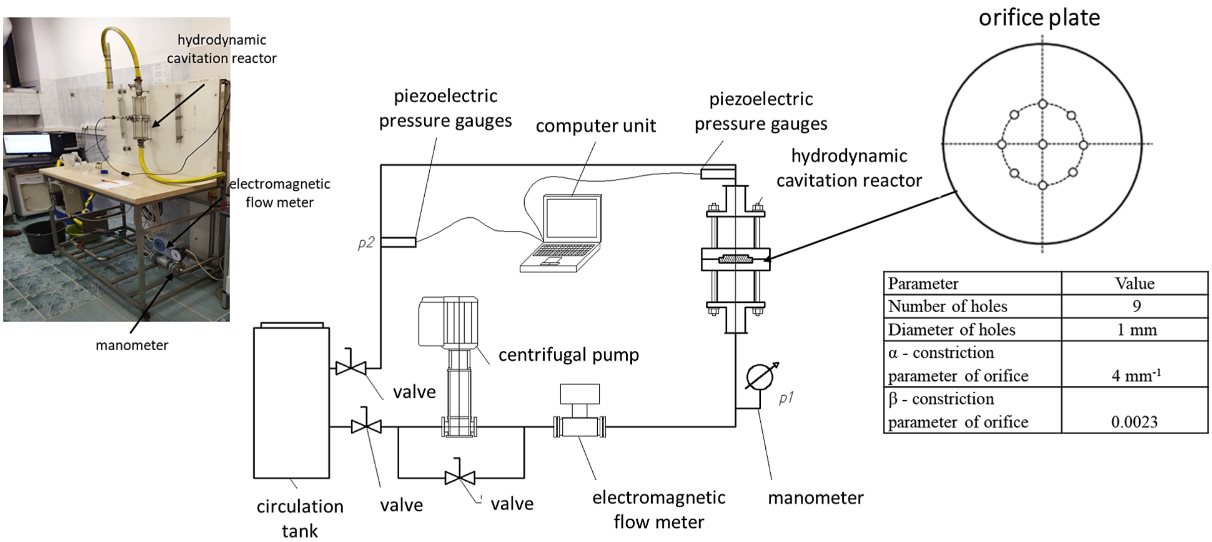
Materials and study area

For HC experiments, the wastewater from municipal Hajdów WWTP located in Lublin city (Poland) was applied. This facility collects both domestic and industrial wastewater from an agglomeration including the following settlements: Lublin, Świdnik, Konopnica, Wólka, Niemce and Głusk (Poland). The construction of Hajdów WWTP was completed in 1992. Since then, this facility has been modernized many times to improve treatment technology and energy balance. The WWTP involves mechanical and biological treatments with simultaneous enhanced removal of nitrogen and phosphorus. It has a high treatment efficiency estimated at 97.4% (in relation to basic pollution indicators). Although designed for average daily flow of 120 000 m^3/d, in 2022 it has been operated at the decreased daily flow of 74 000 m^3/d.

The wastewater used in the present study was taken in the amount of 35 L (for each experiment) from outlet collector that discharged the treated wastewater into the Bystrzyca river (Poland). After collection, the sample was immediately transported to laboratory and kept refrigerated at temperature of 5 °C for no longer than 24 hours.

HC experiments

To evaluate the effectiveness of application the HC reactor for water reclamation two experiments differing in terms of operational conditions were conducted. In the first one, the inlet pressure was maintained at 0.4 MPa; in turn, the second one at 0.6 MPa, respectively. Each experiment lasted 90 min. The samples for analyses were taken at the following time intervals: 0, 15, 30, 60 and 90 min. Both pressure and time intervals were selected



Parameter	Value
Number of holes	9
Diameter of holes	1 mm
α - constriction parameter of orifice	4 mm^{-1}
β - constriction parameter of orifice	0.0023

Fig. 1. The scheme of laboratory installation with characteristics of applied plate

based on the authors' previous experiences in the field of application HC in wastewater treatment, as well as taking into account the energy aspect [38]. The HC experiments were repeated twice, for each one a new fresh portion of wastewater was taken. The HC device with detailed description is shown in Figure 1. Its main parts includes: the feed tank with 30 L of capacity, a centrifugal pump, HC reactor, flow meter as well as piezoelectric pressure gauges and flex pipes. An orifice plate with 9 holes, each with diameter of 1 mm, was employed as HC inductor (Figure 1).

In this device, the wastewater circulated in a closing loop passing through the cavitation inductor multiple times, wherein there was no cooling in the system, thus the temperature of medium gradually increased. The characteristic of applied operational parameters are listed in Table 1.

Analytical methods

The microbiological quality of reclaimed water was evaluated on the basis of *Escherichia coli*, Coliform bacteria, *Enterococci, Pseudomonas aeruginosa*, colony count at temperature of 22 and 37 °C, respectively. Those indicators are considered as main microbiological parameters for drinking water, regulated by European and Polish legislation [39, 40]. These microbiological parameters were established according to the following standards:

- EN ISO 9308-1– *Escherichia coli*,
- EN ISO 9308-2 – Coliform bacteria,
- PN-EN ISO 7899-2:2004 – *Enterococci*,
- PN-EN 12780:2009 – *Pseudomonas aeruginosa*,
- PN-EN ISO 6222:2004 – colony count at 22 °C and 37 °C.

The effectiveness of microorganism disruption (E_{biol}) was evaluated based on the equation 1.

$$E_{biol} = \frac{CFU_o - CFU_{time}}{CFU_o} 100, \% \quad (1)$$

where: CFU_O – the initial colony-forming unit with regard to particular microbiological indicator (sample 0), CFU/1 mL;
CFU_{time} – the colony-forming unit with regard to particular microbiological indicator in the time interval of 15, 30, 60 or 90 min, CFU/1mL.

Moreover, in the collected samples, among physicochemical parameters pH, temperature, DOC (dissolved organic carbon) and SCOD (soluble chemical oxygen demand) were also monitored. To establish the two first parameters, a CPC-501 pH meter (Elmetron) was applied. In turn, to evaluate SOCD and DOC, the samples were firstly filtered through a membrane with a pore size of 0.45 µm. DOC parameter was established by the means of TOC-L analyser with

Table 1. The operational parameters applied in both HC experiments

Parameter	Unit	0.4 MPa	0.6 MPa
Orifice velocity	m/s	83.4	95.1
Flow rate	L/s	0.59	0.67
p_v	MPa	0.396	0.588
C_v	-	0.163	0.085

the measurement range of 4 µg/L - 30 000 mg/L (Shimadzu). The SCOD value was analysed using a Hach Lange DR 3900 VIS spectrophotometer involving cuvette tests (LCI 400, ISO 15705 approved) with the measurement range of 0-1000 mg/L. All analyses were performed immediately after collection to avoid the possibility of secondary contamination; the presented data are the average of three replicates.

Cavitation number (C_V) were evaluated according the following formula:

$$C_V = \frac{p - p_v}{0.5\varrho v_o^2} \tag{1}$$

where: p – the fully recovered downstream pressure measured by pressure gauges, Pa;
p_V – the vapor pressure of wastewater, Pa;
ϱ – wastewater density, kg/m³;
v_0 – velocity of wastewater, m/s.

Both pressures (p and p_V) and temperature fluctuations were monitored using Keller PR-33X pressure gauges with resolution of 0.0001 MPa. The monitored data was collected and displayed by software ControlCenter Series 30 (CCS30) communicates with KELLER devices.

RESULTS AND DISCUSSION

The results in terms of microbiological parameters were presented in Figure 2. *Escherichia coli* and Coliform bacteria there are considered as reliable indicators of fecal contamination in environment. Their presence in drinking water and food might lead to serious diseases that require long-term treatment. Due to their significant resistance and rapid multiplication, their presence in water in particular is dangerous [41, 42].

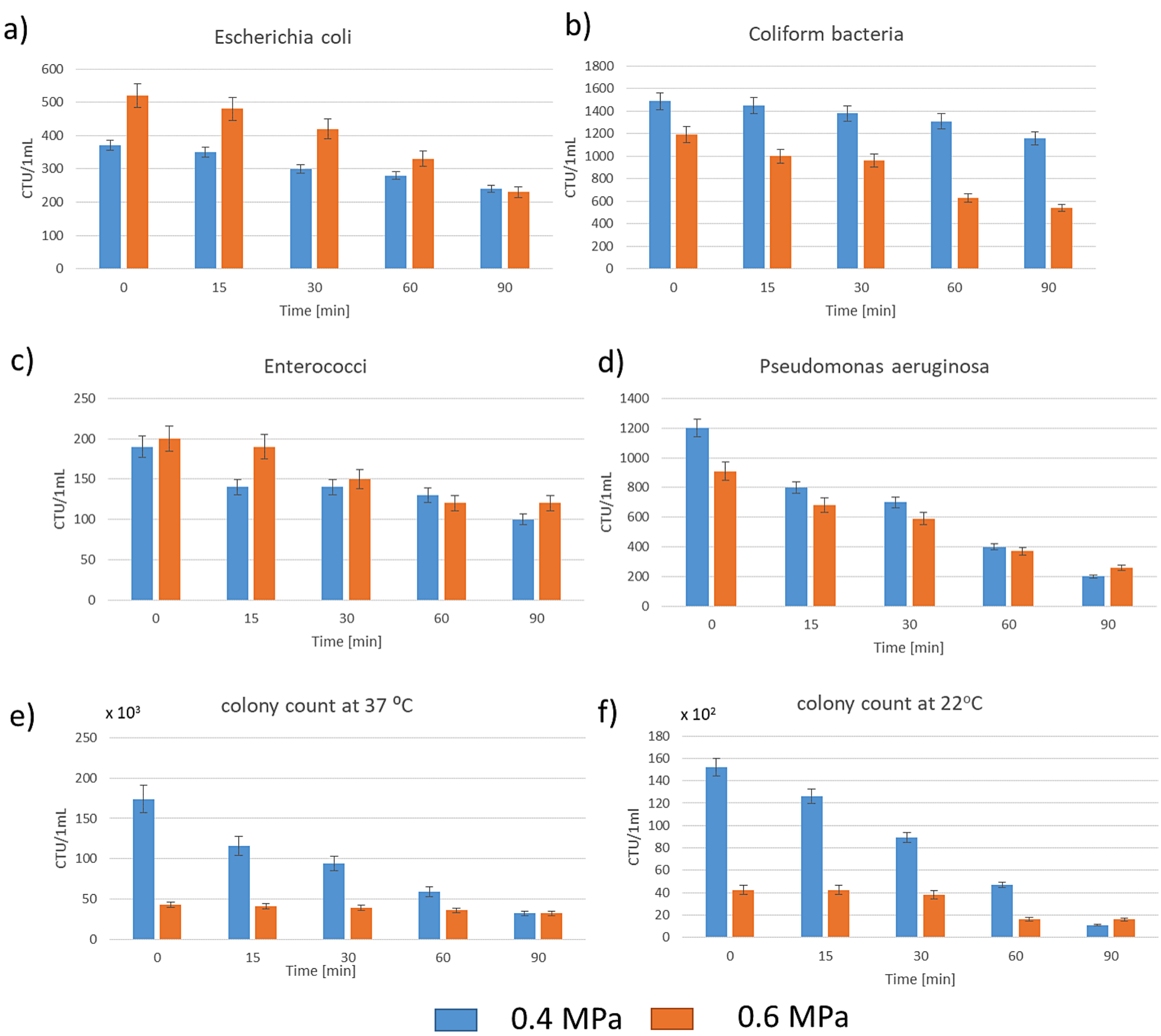


Fig. 2. The results of bacteriological wastewater analysis in time intervals (CFU - colony-forming unit, average data with standard deviation are shown)

Moreover, their presence in water might also indicate the potential contamination with other pathogenic microorganisms e.g. *Salmonella* spp., *Vibrio cholerae* and *Shigella* spp. [43].

Regarding both *Escherichia coli* and Coliform bacteria, major E_{biol} exceeding more than 55% was obtained at a higher pressure of 0.6 MPa for 90 min. However, at the same pressure, shortening the time to 60 min resulted in a slight deterioration of this index value, in particular in relation to Coliform bacteria. Therein, E_{biol} reached still high level of 47%. At lower pressure, the count of *Escherichia coli* and Coliform bacteria were reduced to a lesser extent. As previously, major E_{biol} was noticed at 90 min, reaching the value of 35% and 22% for *Escherichia coli* and Coliform bacteria, respectively. Nevertheless, at this pressure, extending the time did not contribute to a significant reduction in the count of the microorganisms mentioned.

The obtained results are consistent with those presented by other researchers. Sun et al.[44] indicated that multiple-orifice plate and high pressure resulted in the highest reduction of microbial cells in milk [45]. Other studies indicated even 100% efficacy in E. coli removal in water. However, therein an advanced rotational HC reactor was applied that involving both sonochemical and hydrodynamical effects for a cell description [46]. Mezule et al. [47] also used the rotor HC cavitator for *E.coli* deactivation. Therein, the division of 75% of *E. coli* cells has been stopped after 3 min of process and energy input of 490 W/L. Similar high efficiency of *E.coli* destruction was achieved by Dalfré Filho et al. [48]. In this study, naturally contaminated water was treated by HC involving orifice reactor, 90% inactivation of *E. coli* were observed after 900 s of experiment and high pressure of 10 MPa.

Enterococci are recognized as another indicator of fecal contamination. They are gram-positive cocci that occur in a human and animal digestive tract. They also may lead to several serious infections that are difficult to treat because of the resistance to antimicrobial agents [49]. In this study, at both 0.4 and 0.6 MPa and comparable time intervals, a similar degrees of microorganism destruction were observed. However, the higher efficacy of 47% was noted for the lower pressure of 0.4 MPa and time of 90 min.

Pseudomonas aeruginosa is another bacterium that presents frequently in water systems that threatens the human health because of its resistance to available antibiotics. It is particular burdensome, because it can easily colonize pipeline surfaces making a biofilm that is problematic to remove [50]. The applied HC reactor at both pressures of 0.4 and 0.6 MPa allowed for an effective cell destruction of *Pseudomonas aeruginosa*. Interestingly, the major effectiveness was obtained at lower pressure, therein in 90 min E_{biol} reached the value of 83%. In turn, for 0.6 MPa at the same time interval, this value was 71%. It should be noticed that considerable E_{biol} above 40% was achieved already after 30 minutes of cavitation at both pressures. The formerly conducted studies also confirmed the high efficiency of *Pseudomonas aeruginosa* deactivation using HC. In a study performed by Loraine et al. [51], the application of eight-orifice STRATOJET reactor at a p pressure of 16.5 MPa led to 3-log decrease in *P. aeruginosa* concentration after 90 min of cavitation.

Colony counts at 22 °C (psychrophilic) and 37 °C (mesophilic) describe the general hygienic status of the water. Presence in large numbers might indicate a possible organic pollution. However, growth of microorganisms under psychrophilic conditions is harmless to humans and might even support the water treatment, including ammonium nitrogen removal as well as manganese and iron oxidation. In turn, mesophilic conditions might confirm fecal contamination. In the case of both indicators, the most favourable results were obtained at lower pressure of 0.4 MPa. E_{biol} in 90 min was established at a significant level of 92 and 81% for 22 °C and 37 °C, respectively. In turn, for 0.6 MPa and the same time interval, those indicators reached the level of 63 and 26% for 22 °C and 37 °C, respectively. Moreover, the lower pressure allowed for obtaining E_{biol} exceeding 40% in a shorter period of time, which seems particularly profitable considering the energy consumption. In the case of higher pressure of 0.6 MPa, relatively high colony count at 37 °C was obtained. This fact might probably be related with re-contamination of the sample.

Considering all analysed microbiological indicators at both pressures of 0.4 and 0.6 MPa with the prolongation of time, the effectiveness of microorganisms disruption increases. Importantly, the highest level of microorganisms deactivation at both pressures was achieved at the longest time of 90 min. This fact is related with the number of passes through the cavitation zone. Longer time resulted in a more passages through the cavitation zone that led to higher disinfection effectiveness.

Moreover, with prolongation of time, an increase in temperature was noted, which also promoted the destruction of microorganisms.

The dominant mechanism that affects the reduction of microorganisms within HC is cell disruption [33]. HC generates shock waves, microjets, and shear stresses that might lead to microbial inactivation. They are included in the mechanical effects of HC [34, 44, 46]. Other contributing factors that might enhance the efficiency of microorganism deactivation are oxidation potential of free radicals [52, 53]. In the case of present study, the oxidation effects should be included as the orifice construction favours the radical generation. Also thermal effects may influence the results, especially that the applied device was not equipped by cooling system. Therefore, within both HC experiments the visible temperature increment might be observed (Fig. 3). It is commonly known that this parameter might influence fluid properties, including viscosity, vapour pressure, surface tension, and concentration of dissolved gases [54]. The enhanced temperature might accelerate the rate of microorganisms destruction due to the changes in thermodynamic characteristics of the treated medium.

The transformation observed with regard to microbiological indicators affected the physicochemical indicators. As it is presented in Figure 3, at both pressures the prolongation of time leads to increments in SCOD and DOC concentrations.

This observation resulted from decomposition of organic matter that occurred within microorganism cell destruction and release of easily biodegradable organic matter to treated wastewater. The major solubilisation was observed at time interval of 60 and 90 min at both pressures. Under these conditions, the deactivation of microbes occurred with the greatest intensity. The enhanced solubilisation observed within HC might be found in previous studies [18, 55, 56]. Another effect that might be observed in this study is related with growth in pH value progressing with the extension of time correlated with formation of different radicals [44, 57].

There are many aspects that might also impact the HC performance. A major one is cavitation number; to initiate cavitation phenomenon this parameter should not exceed the limit value of 1 [56, 57]. The former study demonstrated that lower C_v resulted in enhancement of cavity generation and collapsing per unit time [58].

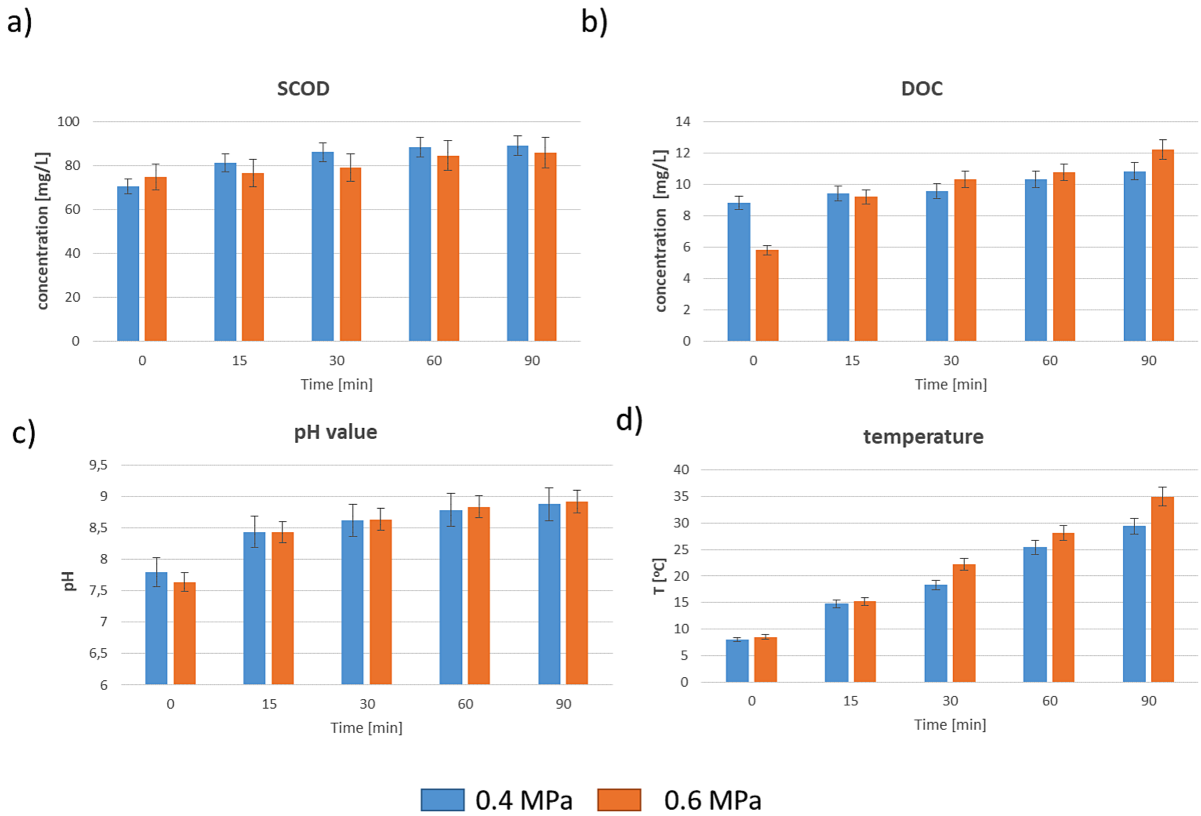


Fig. 3. The physicochemical characteristics of wastewater samples (SCOD – soluble chemical oxygen demand, DOC – dissolved organic carbon, average results with standard deviation are presented)

That might accelerate the chemical and physical effects occurring within HC [34]. Generally, C_v decreases with the increase of inlet pressure. In this study this effect was observed, with a higher pressure a lower value of the cavitation number was obtained (Table 1). However, in this research, there is no clear tendency. The application of higher pressure resulted in more efficient *Escherichia coli* and Coliform bacteria removal. In turn, the lower pressure favoured *Enterococci*, *Pseudomonas aeruginosa* and total bacteria count deactivation. Such differences are mainly related with various structures of the cell walls. Moreover, those microbes indicate varying resistance to environmental factors e.g. temperature, pH, or pressure. It is known that *E.coli* is characterised by long-term survival in water, even at increased temperature and high pressure [59, 60]. Therefore, in this study those microbes are deactivated at higher pressure of 0.6 MPa. Major removal efficiency in the case of lower pressure with respect to *Enterococci*, *Pseudomonas aeruginosa* and total bacteria count deactivation is mainly due to structure of their cell wall. Another aspect that influenced the effectiveness of their deactivation is related with initial content of microbes, and parameters of treated medium e.g. pH or temperature. Such mechanisms have been reported in literature [18].

Moreover, the efficacy of microorganism deactivation is closely related to the type of HC reactor. Thus far, in a laboratory and industrial scale, the following HC reactors have been examined: orifice, venturi, rotating and Vortex based types. The orifice ones are characterised by simple construction and relatively low-lost maintenance. However, better disinfection effect might be found using multiple-hole reactor with smaller diameter [18]. This type of reactor was used in this work. In turn, rotating and Vortex types present a greater cavitational activity as compared to orifice or venture ones. However, they are characterised by significant energy demand and related major operational outlays. Moreover, their cavitational intensity is more difficult to control, as compared to the venturi and orifice HC reactors.

Considering all the analysed cases, the pressure of 0.6 MPa and time of 90 min were selected as the most advantageous for *E. coli* and coliform deactivation. In relation to remain microbiological indicators as optimal conditions, the pressure of 0.4 MPa and time of 90 min were assumed. According to UE and Polish legislation the obtained results do not meet the requirements of water for human consumption [39, 40]. However, it should be mentioned that these are the most stringent regulations. In turn, the applied technology used allows meeting the quality requirements for bathing water quality [61]. Regarding its further use, the reclaimed water precludes its use in the food industry. Though, it can be successfully applied for irrigation purposes [62]. It worth mentioning that HC has a confirmed efficacy in terms of persistent organic pollutants removal e.g. antibiotics, pesticides, endocrine disruptors etc. [63, 64]. Currently, these substances are not removed in conventional two-stage WWTPs are returned to the environment pose a threat to human health [58]. Moreover, HC in combination with conventional disinfection method e.g. chlorination, it can be used for industrial purposes, e.g. for washing, contributing to reduction of the dosed oxidant amount while improving water quality. As compared to the traditionally applied methods in a tertiary treatment stage e.g. coagulation, flocculation, microfiltration, nanofiltration or reverse osmosis, the HC presents several benefits. The above-mentioned methods are known as energy-intensive technologies, often involving necessity of dosing reagents, contributing in this way to a significant increase in operating costs of WWTPs. The investment cost of these technologies is also substantial. Therefore, HC seems be a profitable solution for many WWTPs that want applied reclaimed water for various purposes.

CONCLUSIONS

The application of orifice hydrodynamic cavitation reactor provided the effective destruction of microorganisms, thus allowing for further use of reclaimed water e.g. in irrigation. Taking into account the effectiveness of *Escherichia coli* and Coliform bacteria destruction, the longest time of 90 min and higher pressure of 0.6 MPa might be considered as the most advantageous condition to perform HC. In turn, regarding other microbiological parameters e.g. *Enterococci*, *Pseudomonas aeruginosa* and colony count at 22 °C and 37 °C more beneficial results were found at lower pressure of 0.4 MPa. The observed deactivation mechanisms are probably related mainly with mechanical effects of HC e.g. influence of the pressure gradient, increased temperature, impact of shockwaves, shear forces as well as microjet velocities. The applied HC reactor was characterised by a simple construction and associated easy operation. Additionally, it allows for selection an optimal operating parameters and process control through the application of gauge system. The presented research results are preliminary, the further studies will be related to the use of different plates and application of various operational parameters e.g. time, pressures, cavitation number will be carried out.

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