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Review

Wastewater treatment by means of advanced oxidation processes based on cavitation – A review

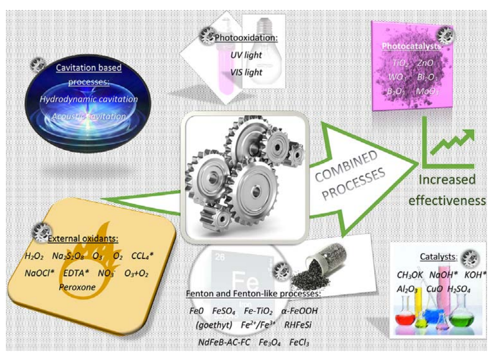
Michał Gągol[a], Andrzej Przyjazny[b], Grzegorz Boczkaj[a,*]

[a] Gdańsk University of Technology, Faculty of Chemistry, Department of Chemical and Process Engineering, Gdansk, Poland
[b] Kettering University, 1700 University Avenue, Department of Chemistry & Biochemistry, Flint, MI 48504, USA

HIGHLIGHTS

- Application of hydrodynamic and acoustic cavitation to oxidation of organic pollutants.
- Design of cavitation devices for effluent treatment.
- Comparison of efficiency of oxidation of organic pollutants in the cavitation processes.

GRAPHICAL ABSTRACT



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ABSTRACT

Hydrodynamic and acoustic cavitation combined with advanced oxidation processes (AOPs), including, among others, the Fenton process, is a promising alternative to the technologies of wastewater treatment technologies in use today. The present review discusses processes based on cavitation combined with AOPs and evaluates their effectiveness in oxidation of organic contaminants. Complete degradation of, among others, *p*-nitrotoluene, *p*-aminophenol, 1,4-dioxane, alachlor, chloroform, trichloroethylene, sodium pentachlorophenate and carbon tetrachloride was achieved by using hydrodynamic cavitation or acoustic cavitation alone. Cavitation is also an effective method of disinfection of water. Complete oxidation of hardly degradable organic contaminants, including pharmaceuticals, organic dyes, insecticides, phenol and its derivatives was observed when using hybrid processes: hydrodynamic or acoustic cavitation combined with the Fenton process, ozonation, hydrogen peroxide, UV irradiation, catalysts and persulfates. The review also discusses the cavitational reactors used in the wastewater treatment and the effect of process parameters (including pH, temperature, concentration and kind of contaminants) on the effectiveness of oxidation. The oxidation effectiveness for individual treatment methods is compared and their advantages and limitations discussed. The analysis of economics of the treatment processes performed to evaluate the possibility of scaling up reveals that the only economical processes should be based on hydrodynamic cavitation (mainly due to low cost of reactors and low consumption of electrical energy compared with ultrasonic reactors).

* Corresponding author at: Gdansk University of Technology, Faculty of Chemistry, Department of Chemical and Process Engineering, 80-233 Gdansk, G. Narutowicza St. 11/12, Poland.
E-mail address: grzegorz.boczkaj@pg.edu.pl (G. Boczkaj).

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1. Introduction

Treatment of industrial effluents has long been a challenge for modern technologies combining high effectiveness of degradation of pollutants with low costs of the process. At the same time, new technological developments should incorporate the concept of green chemistry [1]. It is thus an interesting area of research dealing with the development of effective technologies for degradation of specific chemical compounds or selected groups of pollutants. The developed procedures are validated by using real effluents for which they are intended.

Advanced oxidation processes (AOP) have been of substantial interest for many years [2–4]. They combine high effectiveness of pollutant removal through oxidation reactions with highly efficient generation of hydroxyl radicals, often aided by catalytic and photocatalytic processes.

A recent trend in treatment of industrial effluents involves the use of advanced oxidation processes combined with cavitation (Fig. 1). This paper attempts to summarize and evaluate these processes in relation to existing AOPs and to indicate trends in research on the application of cavitation to treatment of industrial effluents.

2. Cavitation phenomenon and types of cavitation

Cavitation is the rapid transition from the liquid to the gaseous state as a result of lowering the pressure which is accompanied by the formation in the liquid of so-called cavitation bubbles having a tremendous force of implosion (the formation of cavitation bubbles in a stream of flowing liquid is shown in Fig. 2). The main parameters affecting their formation are: temperature, static pressure of a fluid and dynamic pressure associated with the linear velocity of a fluid. A decrease in a local static pressure in a stream of flowing liquid results in a drop of its boiling point which causes increased evaporation and the appearance of gas bubbles. During a subsequent increase in pressure the bubbles implode generating an intense shock wave with a great destructive force. A nanosecond long implosion the temperature inside the collapsing bubble can reach as much as 4726.8 °C, and the pressure around 9869 atm [5–7]. This effect is often employed in effluent treatment technologies because it enhances the process of removal of pollutants. It enables decomposition of water molecules into a variety of species with a high oxidation potential, including HO€·, HO2$^{-\cdot}$ and H_2O_2, which react with the majority of organic pollutants [8].

Cavitation is presently used in a number of technologies, such as [9]:

- production of emulsions,
- cleaning various surfaces,
- highly efficient heating devices,
- pumps for viscous fluids,
- cosmetic treatments, acoustic toothbrushes,
- or in processes aiding effluent treatment.

Cavitation is classified with respect to conditions of formation and development of cavitation bubbles into [9]:

- hydrodynamic cavitation,
- vaporous cavitation,
- gaseous cavitation,
- and vibrational cavitation, so-called acoustic cavitation.

Treatment of effluents makes use mostly of hydrodynamic and acoustic cavitation. In hydrodynamic cavitation, gas bubbles are generated by special design of reactors or flow systems forcing a liquid to flow under reduced pressure. This involves the creation of a local drop in static pressure of a liquid below the critical value by a local increase in flow rate or change in external conditions, such as flow line curvature, detachment of liquid stream from the side of the container or channel constrictions. Acoustic cavitation uses an acoustic wave which appears in a liquid as a result of its vibrations or vibrations of the surroundings. The vibrations are generated by ultrasounds which break apart the liquid or cause vibrations of the solid bodies immersed in it.

3. Hydrodynamic cavitation in degradation processes of organic contaminants in aqueous phase

Hydrodynamic cavitation has found a widespread use in treatment of the aqueous phase, for example to aid biological and physico-chemical removal of organic pollutants [10]. Cavitation enables more efficient generation of hydroxyl radicals responsible for oxidation of the majority of contaminants. It also creates in the medium being treated local hot spots in which imploding gas bubbles causes sudden spikes in pressure and temperature. This allows further dissociation of contaminants by pyrolysis [11]. In addition, volatile organic pollutants can penetrate into the cavities being formed which, imploding with a high energy will aid the oxidation process even more effectively [12].

The collapse energy of cavitation bubbles is often used to destroy the structures of microorganisms and bacteria present in effluents. The destruction of structures of microorganisms allows, among others, more effective drying of biomass and production of biogas [3], which improves the operation of wastewater treatment plants.

In a physical-photochemical approach, cavitation initiates the process of oxidation of contaminants on the surface of photochemical catalysts, improving the electron transfer process by creating electron hole pairs [13]. Cavitation also enhances chemical generation of highly reactive hydroxyl radicals, thus enabling oxidation of a variety of organic pollutants, such as carboxylic acids [14,15], pesticides [16,17],

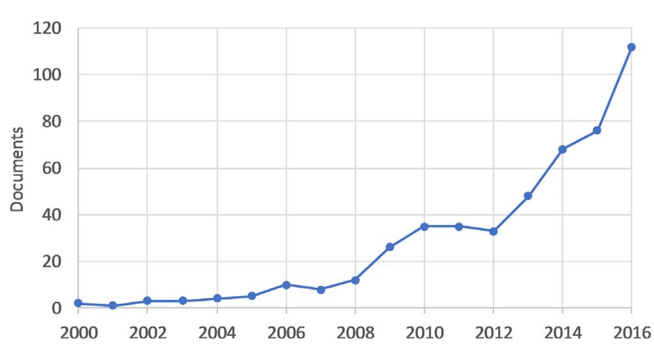

Fig. 1. Documents about cavitation combined with AOPs in wastewater treatment from 2000 to 2016 (based on *Scopus.com* base files available on 04.09.2017).

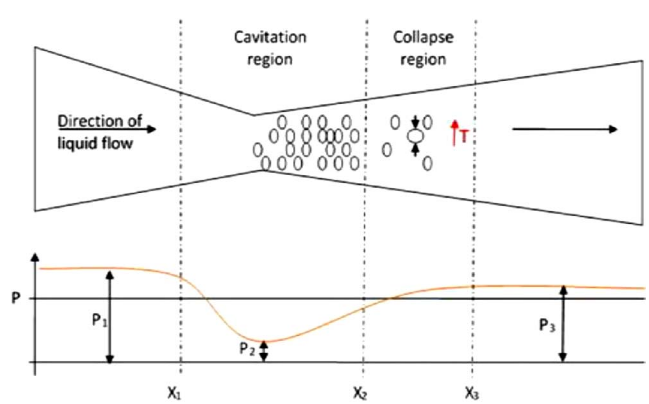

Fig. 2. Scheme of formation of gas bubbles in Venturi tube by hydrodynamic cavitation. P_1/P_3 static pressure before/after throat, P_2 – static pressure in throat, P – vapor pressure of liquid.