Application of Hydrodynamic Cavitation in Environmental Engineering

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About the author

Janusz Ozonek, a graduate of Silesian Technical University in Gliwice was specializing in the scope of chemical engineering in the fields close to the problems of environmental protection. After the studies he worked in the following research institutes: Inorganic Chemistry Research Institute in Gliwice and Organic Industry Institute in Warsaw. For the next 8 years he worked in the industry in the Company of Chemical Reagents in Lublin.

He has been connected with Lublin University of Technology since 1980. In this University he started an intensive research on the ozone synthesis process and improvement of the phenomenological description for this process in the plasma-chemical reactor. The research constituted the basis for the doctoral dissertation, defended at the Chemical Department of the Silesian Technical University in Gliwice. The development of the model of temperature distribution in the ozonizer depending on the hydrodynamic parameters and power supply was also an important achievement resulting from the conducted research.

Most of the works of Janusz Ozonek are interdisciplinary. The chemical ozone synthesis process itself, along with running the processes in the environment of low-temperature plasma require an approach from the side of physical elementary processes and is purposeful for the environmental engineering.

Janusz Ozonek is an author or co-author of 5 books, over 40 papers published in technical magazines and over 80 papers presented on the scientific and technical symposiums and conferences both national and international. The subject of the papers is focusing on environmental protection and is mainly connected with the issue of reducing the energy consumption in the process of ozone synthesis and its usage in eco-technologies.

He is a member of the International Ozone Association, a member of the Committee of Low-Temperature Plasma Chemistry of the Lublin department of the Polish Academy of Sciences, a member-correspondent of Lublin Science Society and a member of Polish Chemical Society.

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List of symbols

A	m^2	area
c_p	$J \cdot kg^{-1} \cdot K^{-1}$	specific heat
d	m	diameter
f	Hz	frequency
g	$m \cdot s^{-2}$	acceleration due to gravity
K	–	cavitation number
L	m	characteristic dimension
$\dot{m}$	$kg \cdot s^{-1}$	mass flow
M	$kg \cdot mol^{-1}$	molar mass
p	$N \cdot m^2$	pressure
P	W	power
p_g	$N \cdot m^{-2}$	static pressure of gas in the bubble
p_n	$N \cdot m^{-2}$	vapour pressure of the liquid
R	m	radius of cavitation bubble
R_0	m	initial cavitation bubble radius
S	$J \cdot K^{-1}$	entropy
t	°C	temperature
t	s	time
T	K	temperature
U	W	internal energy
$\dot{V}$	$m^3 \cdot s^{-1}$	liquid flow rate
w	$m \cdot s^{-1}$	fluid velocity
x	–	distance coordinate
z	–	polytrophic exponent

GREEK CHARACTERS

α	m^{-1}	ratio of the perimeter of a hole to the hole area
β	–	dimensionless number, ratio of the sum of the hole area(s) of the orifice plate to the pipe area
μ	$kg \cdot m^{-1} \cdot s^{-1}$	dynamic viscosity
ρ	$kg \cdot m^{-3}$	liquid density
ω	$m \cdot s^{-1}$	ultrasonic wave velocity
α	m^{-1}	ratio of the perimeter of a hole to the hole area
ν	$m^2 \cdot s^{-1}$	kinematic viscosity
η	$Pa \cdot s$	dynamic viscosity

SUBSCRIPTS

o	– initial
w	– water
k	– final
l	– liquid
max	– maximum value
min	– minimum value
g	– gas
el	– electric
AOPs	Advanced Oxidation Processes
EDCs	Endocrine Disrupting Compounds
EPA	Environmental Protection Agency
GC-MS	Gas Chromatography Mass Spectrometry
HC	Hydrodynamic Cavitation
m/z	Mass/charge (electron) ratio
MS	Mass Spectrometry
PAH	Polycyclic Aromatic Hydrocarbons
US	Ultrasound

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Introduction

With the development of civilization and industry an increasing number of new and complex chemical compounds are being produced which, together with sewage, municipal and industrial wastes find their way into the natural environment. These substances do not remain inert to living organisms, including humans, and unfortunately in most cases leave permanent traces in nature.

Cavitation is a phenomenon, widespread in many areas of technology. This phenomenon accompanies liquid flow through channels with variable geometries. In the environmental protection technologies the effects of cavitation have become very useful in assisting chemical processes, especially in technologies related to the degradation of substances particularly harmful to humans and his immediate surroundings.

Traditional treatment methods do not always produce the expected results. There exists a certain group of organic non-biodegradable pollutants, having toxic, mutagenic, or carcinogenic properties. An important requirement is that the flow containing the hazardous compounds be treated in the cheapest possible but safe manner. Therefore, there is also the need to use modern treatment techniques, which undoubtedly include Advanced Oxidation Processes (AOP), based on reactions involving hydroxyl ($^{\bullet}OH$) radicals. These methods are currently being intensively investigated with the aim of applying them to the removal of certain compounds from wastewater. The removal of these compounds using conventional oxidation methods increases the cost of the process, due to increased oxidant consumption. However, using advanced oxidation processes, it is possible to obtain a greater degree of pollutant degradation.

Research results from the past few years, into the application of advanced oxidation processes in environmental engineering technologies, show that cavitation is a promising technique in this field, due to the accompanying sonochemical processes.

It should be noted that the processes involving hydrodynamic cavitation may complement other methods such as ozonation, oxidation using hydrogen peroxide (H_2O_2), or techniques based on UV radiation or ultrasound, which in total leads to a greater effectiveness in pollution reduction, whilst at the same time reducing costs and energy consumption.

In the subject literature there are many studies related to acoustic cavitation and the use of associated processes in water and effluent treatment technologies. Despite knowing about hydrodynamic cavitation for many years, its use to eliminate pollutants in contaminated water and effluent, particularly industrial, has not been fully researched.

Until recently, attention has been focused mainly on the negative effects of cavitation and its influence on the durability of equipment (e.g. cavitational erosion). However, as research carried out in recent years has shown, physical and chemical processes accompanying cavitation can be used in new technologies to treat water, sewage and to decompose low biodegradable compounds.

Contemporary research into cavitation is concentrated mainly into three areas. The first concerns the development of a model describing the phenomenon, which reflects the imploding bubble dynamics, both in terms of a single bubble as well as the entire population. Existing classical models initiated by Rayleigh in 1917 require a number of simplifications and omit many factors which significantly impact the physicochemical processes that occur during cavitation. The second research area focuses on the negative impact of hydrodynamic cavitation in liquids and depends on reducing its negative effects on a vessel's propulsion system, or on pump rotors. The third area of research is the search for the utilisation of cavitation's positive effects, in as wide an area as possible. Examples include the speeding up of the sonochemical reactions inside the cavitation bubbles, sonoluminescence, coagulation and dispersion, and many others. It is this group of problems which is being analysed in this book.

The use of hydrodynamic cavitation allows, among other things, to increase the amount of effluent saturation (solutions) with oxidising gases such as ozone or oxygen, and it also allows to intensify the oxidation processes occurring on the phase boundary surfaces by significantly increasing the surface area. During the processes which accompany the disappearance of cavitation (implosion), there is an intensive exchange of substances in the cavitation regions (bubbles, caverns) which support the chemical processes, including oxidation.

The problem of utilising hydrodynamic cavitation in technical solutions, to increase the decomposition effectiveness of low biodegradable chemical compounds, is not only valid, but constitutes an increasing call for man to work on the protection of his natural environment. It is also the author's area of academic interest, and this book presents a theoretical analysis, along with experimental work in this field, developed on the basis of literature, research reports and personal experience.

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Table of contents

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CHAPTER 1

Characteristics of the cavitation phenomenon

1.1 THE ESSENCE OF CAVITATION

The name cavitation as used in physics and technology originates from the Latin word *cavitas* (a hollow space or cavity). The first correct analysis of this phenomenon was presented by Reynolds in 1894. Cavitation describes a particular phenomenon which occurs inside a liquid when subjected to changes in the pressure field over time and distance. These changes depend on the liquid rarefying to a sufficiently low critical pressure, causing the formation of voids, filled with vapour from the liquid, as well as dissolved gases in the liquid. Then upon violent compression these voids, filled with vapour and gas, implode.

Cavitation is not observed in gases, which is due to the lack of surface tension, as well as other characteristics of the gaseous state. Liquids, however, even under an isothermal fall in pressure to saturated vapour pressure, turn into the gaseous state, in which the phenomenon is discrete within the liquid and the vapour is released in the form of spherical bubbles throughout the volume of the liquid.

Thus, bubbles (also termed cavitation cavities) form in the cavitation liquid, filled with the liquid's vapour as well as any dissolved gases in the liquid. In the region of higher pressure, above a critical value, the bubbles implode violently which causes in the imploding microregion of the collapse, a dramatic increase in pressure. Hence, cavitation affects the condition of the material over its surface since regions are formed, not only filled with the liquid but also with vapour and gases dissolved in the liquid. If the pressure of the liquid is less than the saturated vapour pressure, the bubbles increase in volume, which causes larger regions of cavitation liquid formation.

There are many different causes of cavitation (Figure 1.1). However, they most commonly appear in the following processes when applied to liquids, namely:

1. In hydrodynamic processes—cavitation occurs in a flowing liquid during a fall in the static pressure, caused by flow conditions or external influences. It is commonly produced in constricted or curved channels and also as a result of motion of bodies in a liquid such as a ship's propeller. Thus, this type of cavitation appears as a result of a local constriction to the flow path of the liquid or the detachment of the stream from the surface of streamlined bodies.
2. In processes involving ultrasound, cavitation in such cases is induced by the pulsations within the liquid due the dispersion of acoustic waves created by impact, vibrations of the surfaces enclosing the liquid or the vibration of submerged objects within the liquid. The separation of the liquid molecules and the formation of the cavitation bubbles occur during the rarefaction

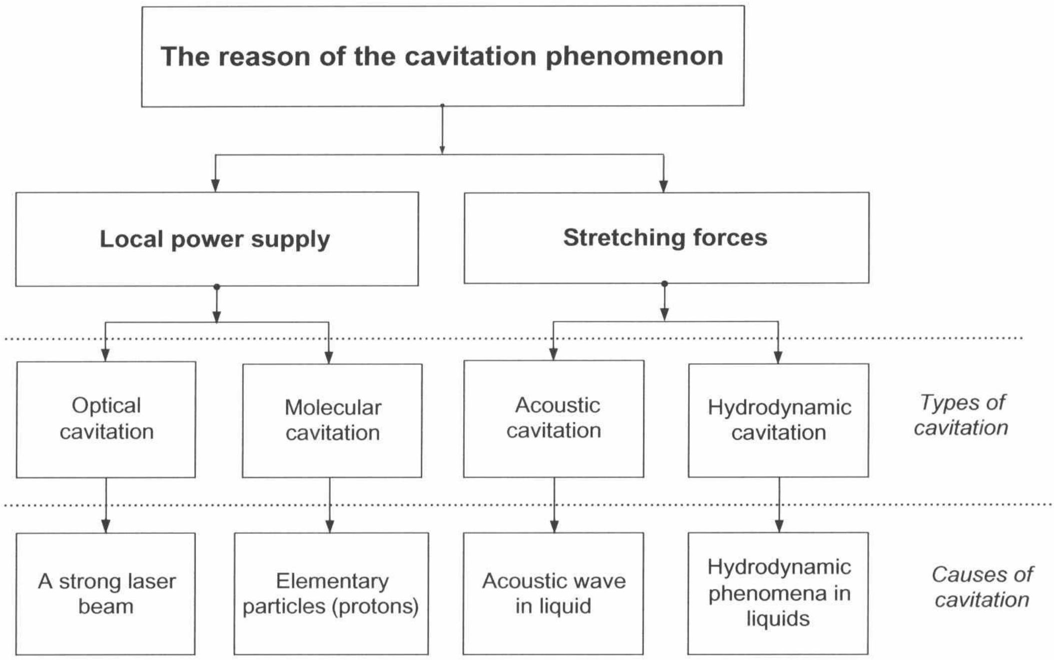

Figure 1.1. The main causes of cavitation in liquids.

half-cycle, and their disappearance during the compression half-cycle of the cavitation medium.

3. In processes which supply significant energy to small volumes within the liquid e.g. by a laser beam or a stream of heavy elementary particles such as protons. Both methods cause a local increase in the internal energy of the liquid, up to a point, at which the liquid undergoes a phase change into the gaseous state thereby releasing the dissolved gases. The effect is to create bubbles of vapour and gases similar to the ones produced in hydrodynamic cavitation.

In the case of hydrodynamic and acoustic cavitation, cavitation bubbles appear inside the liquid as a result of the local pulling apart of the medium under the influence of great expansive forces, which are produced as a result of a sudden drop in local pressure, which can occur in hydrodynamic processes, as well as in high intensity ultrasonic fields (20 kHz to 1 MHz).

Optical and molecular cavitation is a consequence of local dissipation of energy, whose source can be for example a strong laser beam causing electrostriction of the environment and the creation of local pressures (Śliwiński, 2001, Elpiner, 1968). This method of cavitation generation enables precisely controlling the cavitation parameters such as the size of the bubbles and their location within the liquid. Due to the high operating costs, both optical cavitation, as well as molecular cavitation have not found wide scale practical applications, and are only the subject of laboratory research (Margulis, 2004, Piotrowska, 1968, Hoffman, 1996).

In this book the author has concentrated mainly on the phenomenon of hydrodynamic cavitation produced in a liquid flowing through geometric volumes favourable to the appearance of this phenomenon. Hence, the rest of this book relates mainly to this subject.

1.2 TYPES OF CAVITATION—FORMS OF CAVITATION CLOUDS

We can identify the various types of cavitation depending on where the cavitation cloud occurs and the initial conditions. With reference to scientific literature in Poland and worldwide, it is possible to identify several characteristic forms of cavitation. The difficulty in developing a single method of classification is caused by a diversity of conditions when performing the analysis. Franc and Michel (2004) identify eight characteristic types namely:

1. Travelling Bubble Cavitation appears as bubbles moving along a solid body which become visible in the vicinity of a low pressure point.
2. Cavitation bubbles in the shear layer develop when a submerged liquid jet is introduced into a container containing water and on a sharp edge of a boundary layer separation.
3. Sheet cavitation also described as attached bubble cavitation. For axisymmetric bodies the term 'ring cavitation' is used. The bubbles are formed on the surface of the solid body and subsequently are then detached by the flow.
4. Sheet cavitation is also known as laminar cavitation in its advanced stage. This type of cavitation appears as a cavity filled with a homogenous mixture of vapour and gas with a glossy surface.
5. Localised attached cavitation, also described as localised sheet cavitation is associated with the local roughness of the surface and appears as attached cavities.
6. Localised bubble cavitation occurs as a continuous stream of bubbles forming in specific places on the surface of a solid body. This form is also associated with the pitted nature of the surface.
7. Hub vortex cavitation occurs in the cores of vortices spiralling away from the flow around the obstacle.
8. Tip vortex cavitation, appears in the core of vortices flowing from the load bearing surface.

In turn Arzumanov differentiates only two basic forms of cavitation depending on the shape of the cavitation cloud (Bagieński, 1998):

1. Surface cavitation – develops on the surface of streamlined bodies and remains attached to their surfaces
2. Detached cavitation – carried along with the liquid flow.

Surface cavitation occurs on well streamlined surface elements forming points of resistance. It is created e.g. from cavitation nuclei present on boundary surfaces restricting flow and develops on the element's surface. It can be found in pipelines, Venturi restrictions etc. This cavitation which can take on many different forms is dependent on the geometry of the conduit and the flow parameters. It can be in the form of bubbles, sheet (laminar) or attached sheet cavitation.

Detached vortex cavitation appears along the axis of the steam, in vortices behind the "weak" streamlined elements forming places of resistance. It also develops from nucleation (cavitation nuclei) found in crevices, on boundary surfaces restricting flow, and also in the wake itself. It also appears in the wake flowing with significant speed from orifices or zone linking streams from various directions. Detached vortex cavitation, in places of resistance, appears in the form of a vortex. In places of different types of resistance both forms of cavitation may appear.

According to the Polish Standard (PN-86/H-04426) the following forms of cavitation are differentiated:

1. Vaporous Cavitation – cavitation dependent on the sudden evaporation of the liquid from the bubbles' surface following a fall in pressure to that below the critical value, frequently close to the liquid's vapour pressure at a given temperature. It is characterised by the fact that the bubbles are vapour-filled and grow very quickly.
2. Gaseous cavitation – cavitation induced in a supersaturated liquid with the diffusion of dissolved gases. It is dependent on the diffusion of the gas into the gas- and vapour-filled bubbles already present in the liquid. It is characterised by the fact that the bubbles grow and collapse more slowly than during vaporous cavitation and are filled primarily with gases, diffusing from the liquid.
3. Flow cavitation (hydrodynamic) – cavitation formed in the flowing liquid during a fall in the static pressure caused by flow conditions or external factors. It is frequently found in constricted flow channels, in places of kinematic path curvature and deviations from the plane of the streamlined body.
4. Vibratory cavitation (acoustic) – cavitation induced by pressure pulsations within the liquid, caused most frequently by the dispersion of acoustic waves created by impact, vibrations of the surfaces enclosing the liquid or the vibration of bodies submerged within the liquid. The separation of the liquid molecules

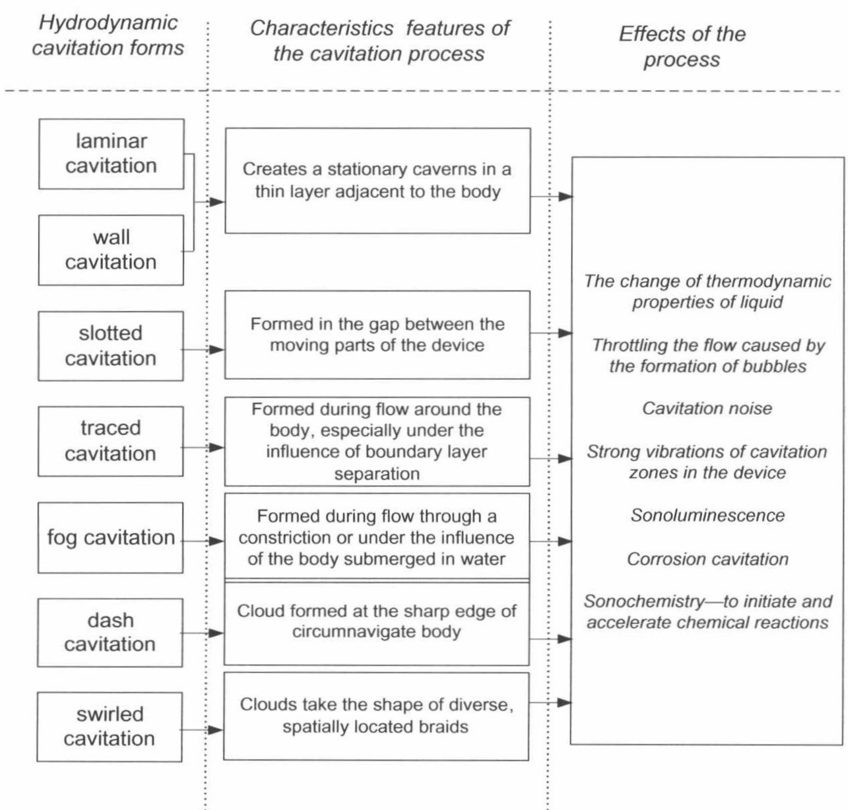

Figure 1.2. Classification of the main forms of cavitation according to their characteristics or behaviour of the cavitation medium and their interactions on the container walls.

and the formation of the cavitation bubbles occur during the rarefaction half-cycle whilst their collapse occurs during the compression half-cycle.

Due to characteristic features of the cavitation zone such as location and physical conditions, it possible to classify the types of cavitation depicted in Figure 1.2.

1.3 FACTORS FAVOURING THE FORMATION OF CAVITATION

Cavitation is caused by a number of factors which encompass not only the physical properties of the liquid, described by the appropriate physical properties (Brennen, 1995, Wójs, 2004, Cai et al., 2009), the thermal state of the liquid, but also the gaseous impurities dissolved in the liquid or other liquid impurities (Gogate, 2008, Margulis, 1995) and also impurities in the form of submerged bodies.

The cavitation nuclei, appearing in the form of gaseous, vapour microbubbles or particulates are essential to the formation of cavitation, the result of a reduction in the capability of the liquid to transfer tensile stress.

In pure liquids, deprived of any impurities, the liquid-gas phase transition as a result of liquid expansion is almost impossible, since large tensile stresses (negative pressures) in the order of hundreds of megapascals are necessary (Wójs, 2004). However, in reality, in nature and technology we have liquids containing large numbers of cavitation nuclei.

Possible potential cavitation nuclei can be found in large numbers in the liquid in the form of primary additives and pollutants. The division of additives and pollutants in natural waters is shown in Figure 1.3.

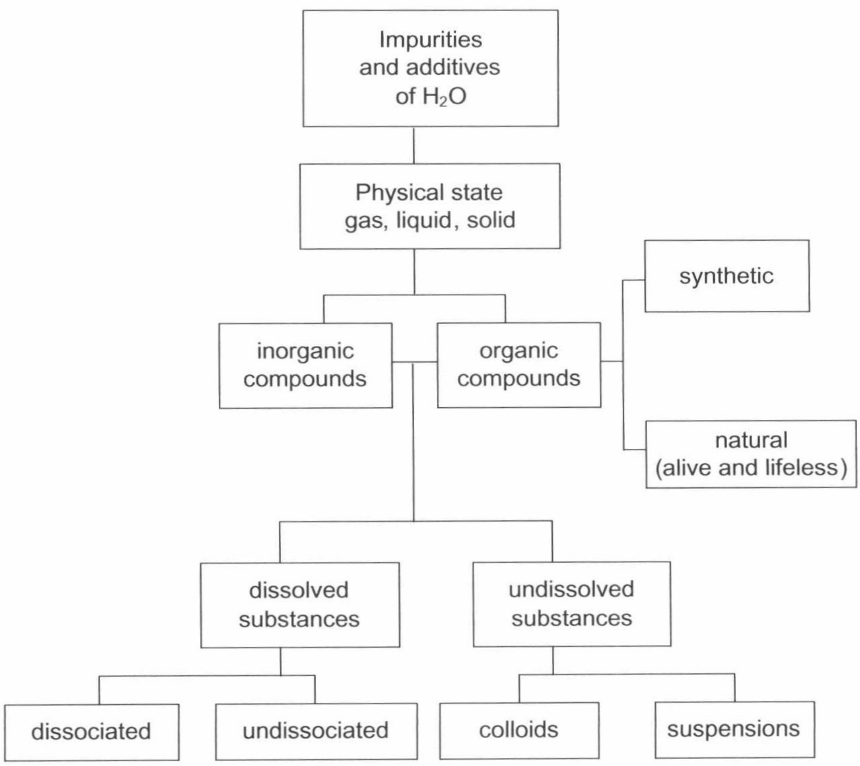

Figure 1.3. Division of pollutants and additives in natural waters.