Archives of Materials Science and Engineering

Volume 52
Issue 2
December 2011
Pages 112-117

International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

Effect of different design features of the reactor on hydrodynamic cavitation process

J. Ozonek [a], K. Lenik [b,*]
[a] Institute of Environmental Protection Engineering, Lublin University of Technology, ul. Nadbysztrzycka 38D, 20-618 Lublin, Poland
[b] Department of Fundamental Technics, Lublin University of Technology, ul. Nadbysztrzycka 38D, 20-618 Lublin, Poland
* Corresponding author: E-mail address: wz.kpt@pollub.pl

Received 02.09.2011; published in revised form 01.12.2011

ABSTRACT

Purpose: The determination of the effect of the change of inducers' shape and surface on the cavitation process.

Design/methodology/approach: Experimental studies of the effect of pressure changes in the function of the construction change of cavitation inducer on the hydrodynamic cavitation process.

Findings: Selected effects of the cavitation process were discussed with variable pressures obtained by changing the geometry of cavitation inducer.

Research limitations/implications: Analysis of the cavitation process in the function of geometric features of the cavitation inducer.

Practical implications: The possibility of controlling the hydrodynamic cavitation process.

Originality/value: The assessment of the effect of the cavitation reactor selection on the process or/and the selection of the solution for the specific conditions of the course of the cavitation process.

Keywords: Cavitation phenomena; Hydrodynamic cavitation; Cavitation number; Hydrodynamic reactor

Reference to this paper should be given in the following way:

J. Ozonek, K. Lenik, Effect of different design features of the reactor on hydrodynamic cavitation process, Archives of Materials Science and Engineering 52/2 (2011) 112-117.

MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

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 pressure field changes 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 to pressures at which these voids, filled with vapour and gas, implode [1-4].

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.

Cavitation is a common phenomenon presented in numerous branches of technology. This phenomenon accompanies the flows of liquids through the canals of characteristic variables and is useful in aiding chemical processes, especially in the technologies connected with the degradation of substances particularly harmful for human beings and their environment [5-7].

Contemporary researches on cavitation phenomenon focus on three fields of study [1,8-11]. The first one refers to the elaboration of the model of the phenomenon itself reflecting the dynamics of imploding bubbles both with reference to a single bubble and the whole population. The existing classic models initiated by Rayleigh in 1917 require a number of simplifications and ignore many factors having a considerable influence on the physical and chemical processes accompanying the phenomenon. The second field on study mainly refers to the negative influence of the hydrodynamic cavitation in liquids and consists in limiting its negative effects in ship propulsion system or in pump propellers. The third field of conducted studies constitutes the search for application, to a larger and larger extend, the positive effects of the cavitation phenomenon. The examples can be: the acceleration of sonochemical reaction occurring inside cavitation bubbles, sonoluminescence phenomenon, coagulation and dispersion processes as well as many others. These are the issues that are analyzed in the paper.

The use of hydrodynamic cavitation process makes it possible to increase the saturation level of wastewaters (solutions) with gaseous oxidants such as ozone or oxygen and also allows to intensify the oxidation processes occurring on the surfaces of the boundary phases by considerable increase in the size of these surfaces. During the processes accompanying the disappearance of cavitation (implosion) an extensive exchange of substances takes place in the cavitation regions (bubbles, cavities) which enhances the course of chemical processes including oxidation.

The main factors which determine the formation of the hydrodynamic cavitation field and the effectiveness of the cavitation process can be divided into three groups (Fig. 1).

The first group consists of parameters which determine the structural characteristics of the reactor; the size and shape of the cavitation inducer and the flow chamber. The second group includes parameters characterising the properties of the liquid medium, in the main: viscosity, density, surface tension and the dissolved gas contents. The third group includes parameters that are associated with the characteristics of the technological process; the "processing" time (the number of times the medium passes through the cavitation region), the interdependence between the process's temperature and pressure.

The technological efficiency of the cavitation process depends on the cumulative effect of the above mentioned parameters.

The range of parameters which describe the cavitation process, in particular the number of cavitation bubbles generated and their implosion conditions (pressure and temperature during bubble collapse), is thus quite extensive.

The appearance of cavitation in the liquid can be written in the following form [12, 13]:

$$f\left(\frac{l_1}{l},...,\frac{l_n}{l},K,Re,We\right)=0 \tag{1}$$

where: l, l_1, l_2,...l_n - Linear values defining the size, shape, location of the body, and in addition its surface condition, microbubble dimensions and solid particles constituting the cavitation nucleus,

K, Re, We - Numbers (Cavitation, Reynolds and Weber) characteristic for cavitation

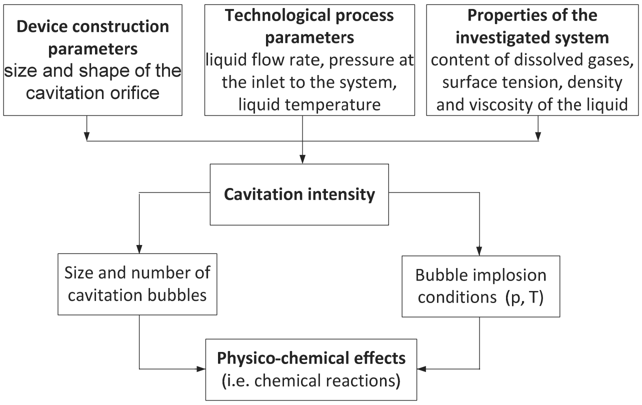

Fig. 1. Basic factors influencing the intensity of the cavitation process

Increasing the Reynolds number (*Re*) is usually accompanied by an increase in the Cavitation number (*K*). This may be the result of an increase in the flow rate or a decrease in the coefficient of kinematic viscosity, which also leads to local increases in velocity by reducing the thickness of the boundary layer.

Increasing the Weber number (*We*) is usually accompanied by an increase in the Cavitation number. Like the Reynolds number, it is the result of an increase in the velocity or a decrease in the coefficient of surface tension. Surface tension forces tend towards minimising the bubble being formed in water, and in particular make it difficult for the cavitation nuclei to pass through bubbles of finite dimensions.

The cavitation phenomenon can be considered as the sum of individual interactions of the bubbles or as a cavitation cloud. The other method gives the true reflection of the process particularly for the greater density of the cavitation bubbles. The number of the bubbles (cavitation occurrences), the size and temperature during an impulse can be estimated experimentally (sonoluminescence), on the basis of the effect of the chemical reaction or theoretically (computer simulation) [14-16].

In analysing the cavitation phenomenon a parameter or a criterion number should be specified, allowing for a quantitative flow assessment in two aspects:

- a parameter, which assumes a unique value for each set of dynamically similar cavitation conditions
- a parameter describing the flow conditions without cavitation and also conditions for the creation, collapse or at the various stages of cavitation development.

As a dimensionless parameter characterizing the cavitation conditions in hydraulic systems the cavitation number K has been adopted [1,5,12]. It is defined in the following form:

$$K=\frac{(p_1-p_n)}{\frac{\rho\cdot w_1^2}{2}} \tag{2}$$

where: p_1 - static pressure in an undisturbed flow [Pa], p_n - vapour pressure [Pa], ρ - liquid density [kg/m^3], w - liquid velocity in an undisturbed flow in cavitation inducer [m/s].

A physical meaning to the cavitation number can be assigned as follows: in equation 2, pressure appears in the numerator which determines when cavitation will disappear whilst dynamic pressure appears in the denominator. A pressure change at a boundary or on the surface of a body, around which the liquid flows, is in the main part dependent on the change in the flow rate. Therefore, the dynamic pressure can be regarded as defining the size of the pressure drop, resulting in cavities forming and growing.

The issues of the cavitation processes application, in particular hydrodynamic cavitation, is linked with the need to solve a number of technical problems. The main problems include the specification of rational parameters determining the induction of the cavitation phenomenon. This means that, considering the variable character of such parameters as inlet pressure and cavitation controller position with respect to the hole of the orifice plate, the current task to be done is to determine the different design features of the reactor and their influence on the hydrodynamic cavitation.

2. Experimental procedure

The basic arrangement for the creation of cavitation, both in the laboratory and in the target technology is the cavitation unit. The cavitation reactor is a physicochemical reactor of a relatively simple build, but the properties of its individual components have a significant impact on the processing of the cavitation liquid. The basic condition for the creation of a diverse cavitation bubble field is the attainment of collapsing cavitation bubbles, of different shapes and sizes, over a period of time. This condition is realised through equipment design [17-20].

Studies were conducted to determine the effect of significant parameters including geometric and hydrodynamic, and to determine the effect of process conditions on the intensity of cavitation. These included research into:

- determine the effect of pressure and flow rate of the liquid on the cavitation intensity,
- the effect of the cavitation inducer shape on the cavitation process,
- determine the hydrodynamic characteristics of the cavitation reactor.

Figure 2 is a schematic diagram showing the facilities used to study hydrodynamic cavitation in the laboratory. The cavitation reactor (1) is connected via pipes to the circulation tank 50 dm^3 (3) and a Wilo centrifugal pump (2).

The regulation of the pressure in cavitation system takes place as a result of the change in rotation of the electric engine driving Wilo MVIE 208-2G/PNIG pump by means of thyristor controller, thus changing the pump performance. The pump performance is measured with M1500AA electromagnetic flow meter produced by Badger Meter Inc. The measurements of the pressure and temperature changes during cavitation process were taken with the use of PR-35X piezoelectric pressure gauges made by Keller.

Figure 3 show the design schematic and implementation of the experimental reactor during research.

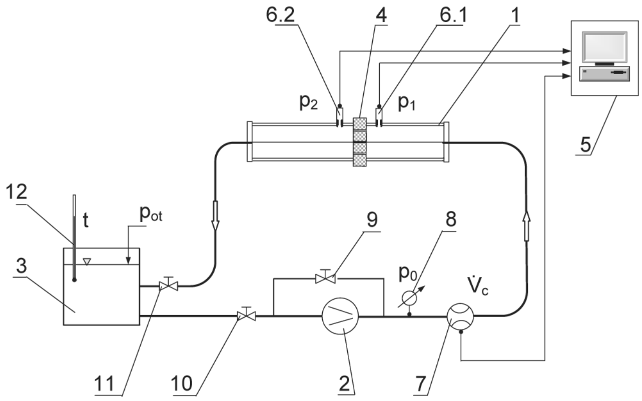

Fig. 2. The experimental set-up for the generation of hydrodynamic cavitation: 1 - hydrodynamic reactor, 2 - centrifugal pump, 3 - circulation tank, 4 - interchangeable orifice plates with holes (cavitation inducers), 5 - measurement and acquisition system, 6.1 and 6.2 - Keller piezoelectric pressure gauges, 7 - electromagnetic flow meter, 8 - pressure gauge, 9 - control valve, 10, 11 - valves, 12 - thermocouple

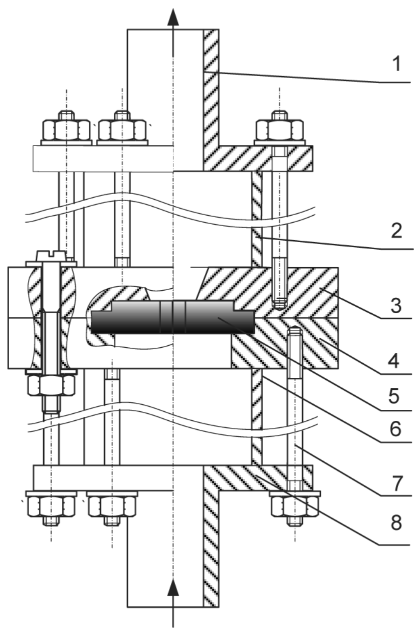

Fig. 3. Schematic diagram of a cavitation reactor: 1, 8 - tappings, 2, 6 - acrylic glass tube, 3, 4 - steel discs connecting the casings, 5 - cavitation inducer, 7 - bolts connecting the cavitation reactor components, 8 - flashings

The hydrodynamic cavitation reactor consists of a cavitation inducer (5) and a casing. The casing consists of two steel discs (3, 4), bolted together (7) which house the cavitation inducer, tubes of poly(methyl methacrylate) (PMMA) (2, 6) enclose the cavitation region and two tappings (1,8) enable connection to the system.

In the expansion part of the reactor, the tappings were connected to a measuring device (a Keller pressure sensor) for recording pressure and temperature changes in the cavitation region. Cavitation inducers used in the studies were in the form of a steel disc (orifice plate), of 64 mm external diameter with holes, mounted in the body of the cavitation reactor. The cavitation reactor design allows for the quick replacement of cavitation inducers. The cavitation reactor walls are made of organic glass. This allows for continuous observations of the cavitation process. The reactor elements are made of stainless steel, characterised by high chemical resistance and high resistance to erosion and abrasion.

Cavitation inducers used in experiments are in the form of multi-hole plates which differ from one another with the quantity, distribution and shape of cavitation holes of which geometric characteristics are given in Figure 4 and Table 1.

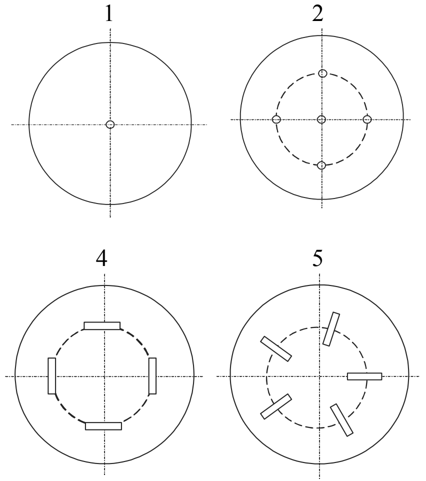

Fig. 4. Details of the orifice plates (cavitation inducers) used in the study

Table 1.
Flow geometry of the orifice plate

Plate No	Characteristic dimentions of the hole, mm	Flow area, mm^2	α, mm^{-1}	β	Total perimeters of holes, mm
1	ϕ 1	0.78	4.0	0.00026	3.14
2	5×ϕ 1	3.93	4.0	0.0013	15.7
3	9×ϕ 1	7.06	4.0	0.0023	28.26
4	4×1.5×5	30.00	1.73	0.0099	52.00
5	5×1×5	25.00	2.4	0.0083	60.00

The determination of the intensity of the hydrodynamic cavitation phenomenon plays a crucial role in designing and operation of the facilities used in technological applications.

The intensity of the generated cavitation significantly depends on the geometry of the component causing the cavitation. The geometry can be described by the geometric numbers characteristic of the hydrodynamic flow conditions. These are parameterised as follows [10,11,20]:

$$\alpha = \frac{total\ sum\ \ of\ all\ the\ hole\ circumferences}{sum\ of\ hole\ area(s)\ on\ the\ orifice\ \ plate} \quad [mm^{-1}] \tag{3}$$

$$\beta = \frac{sum\ of\ the\ hole\ area(s)\ on\ the\ orifice\ plate}{the\ cross\ sectional\ area\ of\ the\ pipe} \tag{4}$$

The geometric parameter α is defined as a ratio of the total circumference of the holes in the orifice plate to the section area of the pipeline feeding the hydrocavitation reactor and has an influence on the shape of the stream developing behind the inducer.

The value β is often referred to as the flow number, its magnitude significantly affects the cavitation number and thus determines the intensity of the resulting cavitation.

3. Results and discussion

The important parameters for the hydrodynamic cavitation process are: the pressure (p_1) powering the cavitation reactor, the pressure developed on the expansion side, the saturated vapour pressure of the liquid as well as its density, and the velocity of the liquid flow through the cavitation holes. For smaller cavitation numbers (K), the number of bubbles produced per unit time increases as well as the intensity of the cavitation process.

Figure 5 shows the influence of pressure on changes in the liquid flow rate depending on the shape of the cavitation inducer. At a constant liquid pressure at the cavitation reactor inlet, the flow rate depends significantly on the shape of the cavitation inducer, and increases with a rise in the flow number, β characterising the degree of throttling of the outflow liquid surface area from the orifice plate.

In the case of plates characterized by a small circumference of cavitation holes, the cavitation number (K) is smaller and the cavitation process is more intensive.

Figure 6 shows the effect of the inlet pressure to the hydrodynamic reactor on the value of the cavitation number (K), depending on the shape of the cavitation inducer.

Figures 7 and 8 present the influence of the parameters α and β on the cavitation number with the constant pressure p_0 = 7 bars at the inlet of the cavitation system. For the inducers analyzed in the studies the values of α parameter are included in the range 1.74-4.0, and of β in the range 0.00026-0.0099. A decrease in the cavitation number was observed with an increase of the throttling degree of the liquid flowing through the inducer (smaller values of β parameter). For the inducers of similar active area of the flow but of a different geometry (inducer 4 and 5) the cavitation number changes in a small range. The character of the stream developing behind the cavitation inducer resulting from the geometric shape of the cavitation hole has also got an influence on the intensity of the cavitation phenomenon (Figure 7). A decrease in the cavitation number takes place with an increase in α parameter. For the inducers of the identical values of α parameter (inducer 1, 2 and 3) the process occurs more intensively with the higher throttling degree of the flowing liquid (smaller number of holes in the inducer).

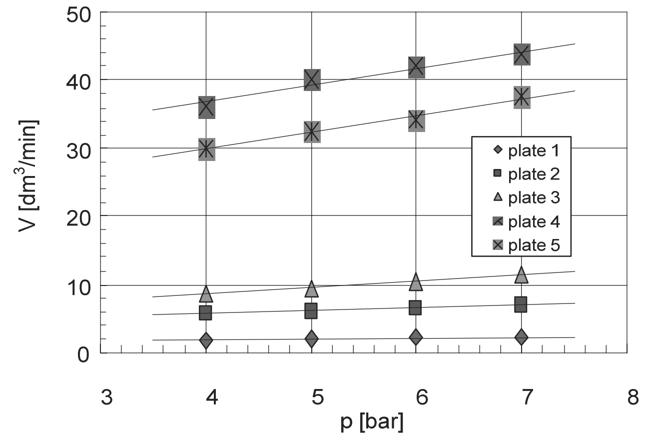

Fig. 5. Hydraulic characteristics of the orifice plates: the effect of the inlet pressure on the flow rate depending on the shape of the cavitation inducer

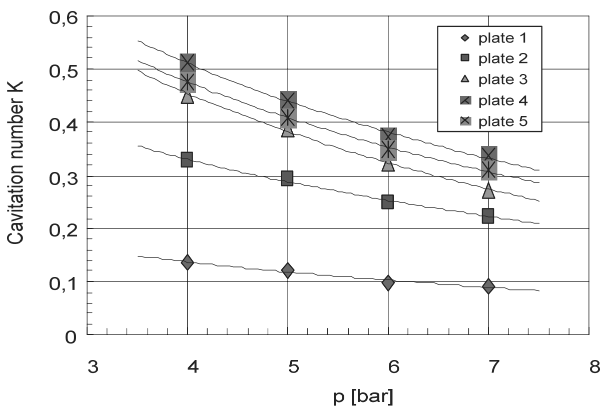

Fig. 6. The effect of the inlet pressure to the hydrodynamic reactor on the cavitation number depending on the shape of the cavitation inducer

What results from the experimental data obtained it that the geometry of the inducer has got a significant influence on the cavitation number (K). The cavitation number changes within the range of 0.1-0.4 and depends on the geometric shape of the cavitation inducer (Fig. 6) and on the pressure feeding the hydrocavitation reactor. During the experimental study of the cavitation process the changes in pressure on the expansion side of the reactor were recorded.

Figure 9 shows changes in temperature and pressure on the expansion side of the cavitation reactor as a function of the supply pressure at a distance of 400 mm beyond the orifice plate for various supply pressures to the cavitation reactor.

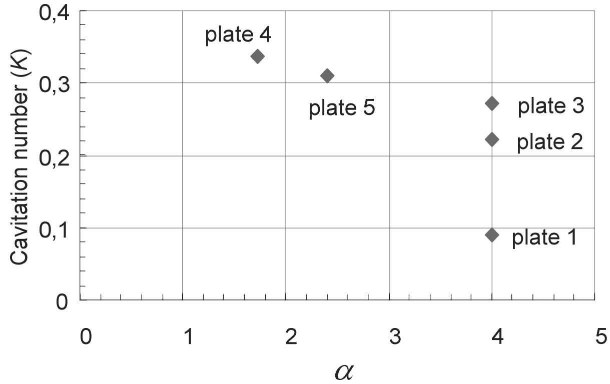

Fig. 7. The effect of the flow number α on the cavitation number, p = 7 bar, t = 20°C

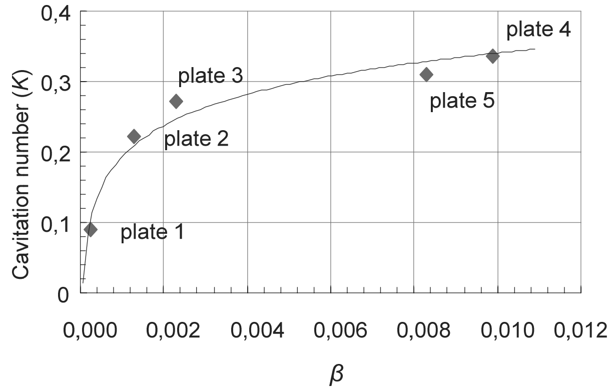

Fig. 8. The effect of the flow number β on the cavitation number, p = 7 bar, t = 20°C

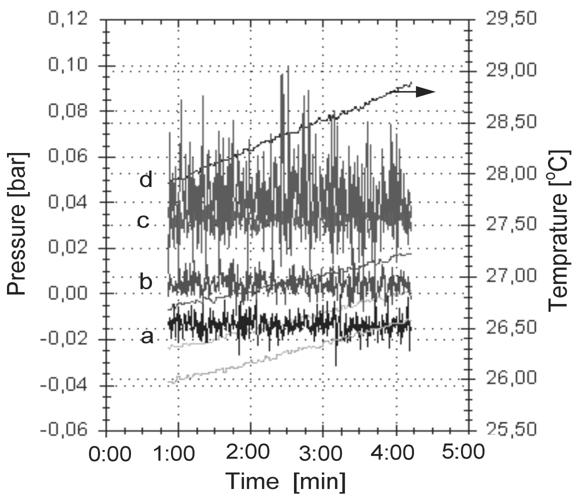

Fig. 9. Changes to the pressure in the cavitation region and temperature in the cavitating liquid at different supply pressures: a) 6 bar, b) 7 bar, c) 8 bar, d) 9 bar using orifice plate number 3

4. Conclusions

The results of the conducted studies have confirmed that the construction features of the element generating cavitation influence the induction, the course and the intensity of the cavitation process. The shape and sizes of the holes in a plate have an impact on the structure of the cavitation field. Due to their geometric diversity and the distribution on a plate it is possible to influence the conditions of the generation of the cavitation regions of different structures and of various bubble sizes.

The experiments and the analysis conducted refer particularly to such geometric features of the cavitation inducer as:

- the size of the hole area with respect to the pipeline area (β coefficient),
- the size of the hole in the inducer,
- the number of the holes and their position on the section of the cavitation inducer,
- the shape of the cavitation holes.

The analysis of the obtained results of the experiments has allowed to confirm the parameters assumed on the basis of the theoretical considerations that influence the cavitation process as well as to evaluate its intensity.

The intensity of the cavitation process greatly depends on the geometry of the element generating the cavitation phenomenon and can be characterized by the cavitation number and by geometric coefficients α and β referring to the sizes and the shape of the element constituting the cavitation inducer. For cavitation inducers of the identical total area of the holes lower values of the cavitation number were observed in the case of inducers characterized by a greater value of the throttling coefficient α.

Acknowledgements

The presented work was supported by the Polish Ministry of Science and Higher Education under research Project No 7514/B/T02/2011/40.

References

[1] J.P. Franc, J.M. Michel, Fundamentals of cavitation, Kluwer Academic Publishers, Dordrecht, 2004.

[2] C.E. Brennen, Cavitation and bubble dynamics, Oxford University Press, New York, 1995.

[3] Litwinienko, A. Nekroz, K. Łukasik, Technological application of hydrodynamic cavitation - experiences and perspectives, Lublin Scientific Society, Lublin, 2005.

[4] F. Capin, E. Herbert, Cavitation in water: a review, Comptes Rendus Physique 7 (2006) 1000-1017.

[5] K. Wójs, Cavitation in liquids with different rheological properties, Publishing House of Wroclaw University of Technology, Wrocław, 2004.

[6] K.S. Suslick, M.M. Mdleeni, J.Y. Rejs, Chemistry induced by hydrodynamic cavitation, American Chemistry Society, 119 (1997) 9303-9306.

[7] P.R. Gogate, A.B. Pandit, Engineering design methods for cavitation reactors II: Hydrodynamic cavitation, American Institute of Chemical Engineering Journal 46/8 (2000) 1641-1649.

[8] P.R. Gogate, Cavitational reactors for process intensification of chemical processing applications: A critical review, Chemical Engineering and Processing 47 (2008) 515-527.

[9] P.R. Gogate, Hydrodynamic cavitation for food and water processing, Food Bioprocess Technology 4 (2011) 996-1011.

[10] K. Jyoti, A. Pandit, Effect of cavitation on chemical disinfection efficiency, Water Research 38 (2004) 2249-2258.

[11] M. Sivakumar, A. Pandit, Wastewater treatment: a novel energy efficient hydrodynamic cavitation technique, Ultrasonic Sonochemistry 9 (2002) 123-131.

[12] J. Bagieński, Cavitation in water supply and heating devices, Publishing House of Poznan University of Technology, Poznań, 1998.

[13] J. Cai, X. Huai, X. Li, Dynamic behaviors of cavitation buble for the steady cavitating flow, Journal of Thermal Science 18 (2009) 338-344.

[14] N.P. Vichare, P.R. Gogate, A.B. Pandit, Optimization of hydrodynamic cavitation using a model reaction, Chemical Engineering Technology 23 (2000) 683-690.

[15] P.S. Kumar, V.S. Moholkar, Conceptual design of a novel hydrodynamic cavitation reactor, Chemical Engineering Science 62 (2007) 2698-2711.

[16] S. Arrojo, Y. Benito, A theoretical study of hydrodynamic cavitation, Ultrasonics Sonochemistry 15 (2008) 203-211.

[17] J. Ozonek, A. Odrzywolski, M. Depta, J. Kujawska, Degradation of PAHs in water solution in the conditions of hydrodynamic cavitation, Monographs of Environmental Engineering Committee of Polish Academy of Sciences 58 (2009) 167-175.

[18] K. Lenik, J. Ozonek, The evaluation of the cavitation number in hydrodynamic cavitation including the influence of the orifice plate geometry, Proceedings of the XIV National and V International Conference of the Science and Technology, Metrology in Manufacturing Techniques, Pułtusk, 2011, 187-193.

[19] J. Szulżyk-Cieplak, S. Fijałkowski, J. Ozonek, Application of the hydrodynamic cavitation in water and wastewater treatment, Proceedings of the II Congress of Environmental Engineering, Monographs of the Environmental Engineering Committee Polish Academy of Sciences 33(2005) 279-282.

[20] P. Braeutigam, M. Franke, Z.L. Wu, B. Ondruschka, Role of different parameters in the optimization of hydrodynamic cavitation, Chemical Engineering Technology 33 (2010) 932-940.