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The issue of cavitation number value in studies of water treatment by hydrodynamic cavitation

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ABSTRACT

Within the last years there has been a substantial increase in reports of utilization of hydrodynamic cavitation in various applications. It has came to our attention that many times the results are poorly repeatable with the main reason being that the researchers put significant emphasis on the value of the cavitation number when describing the conditions at which their device operates.

In the present paper we firstly point to the fact that the cavitation number cannot be used as a single parameter that gives the cavitation condition and that large inconsistencies in the reports exist. Then we show experiments where the influences of the geometry, the flow velocity, the medium temperature and quality on the size, dynamics and aggressiveness of cavitation were assessed. Finally we show that there are significant inconsistencies in the definition of the cavitation number itself.

In conclusions we propose a number of parameters, which should accompany any report on the utilization of hydrodynamic cavitation, to make it repeatable and to enable faster progress of science and technology development.

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1. Introduction

The use of acoustic cavitation for water and wastewater treatment is a well known procedure [1]. Yet, the use of hydrodynamic cavitation as a sole technique or in combination with other techniques such as ultrasound has only recently been suggested and employed. As the field of utilization of hydrodynamic cavitation is growing, it came to our (we are mechanical engineers who deal primarily with fluid dynamics problems) attention that researchers put significant emphasis on the value of the cavitation number (also known as cavitation parameter, σ value or Thoma number – Th) when describing their techniques, devices and procedures for water treatment.

Already a brief literature survey reveals the following examples. Saharan et al. [2] report on an optimal cavitation number of 0.13–0.18 at which decolorisation rate is maximum. Raut-Jadhav et al. [3] recommend (besides other conditions) a value of $\sigma = 0.067$. Sivakumar & Pandit [4] conclude that lower values of cavitation number mean higher extent of degradation of pharmaceuticals. Badve et al. [5] report maximal reduction in COD at $\sigma = 0.4$. Bagal & Gogate [6] claim that the greatest benefits of cavitation are obtained at $\sigma = 0.1–1$. Gogate [7] writes that cavitation generally appears at $\sigma = 1$ and that significant cavitational effects appear at σ values of less than 1. Capocelli et al. [8] found an optimal and cavitation number of 0.25 in terms of removal rate and energy efficiency. Wang & Zang [9] report on the dependency of degradation rate of alachlor on the value of cavitation number. Gore et al. [10] write that the degradation of reactive orange 4 depends on cavitation number and other parameters. Senthil Kumar et al. [11] show the influence of cavitation number on chemical effects. Sawant et al. [12] state that cavitation number predicts the relative intensity of cavitation taking place in various cavitation devices and can be used as preliminary tool to compare the relative performance of a cavitational system. Wu et al. [13] compare cavitation numbers for different geometries and claim that for effects to occur σ values should much smaller than 1. Cavitation number of 0.14 was used for bacterial inactivation by Filho et al. [14]. And finally Aroyo et al. [15] and Mezule et al. [16], show almost no details on the operating conditions of their devices.

In this paper we would like to point out the issues of the definition of the cavitation number and call out to all the research community to properly describe their experiments, which are, due to the lack of data on the operating conditions poorly repeatable or even unrepeatable at all. In other words: describing the cavitation conditions solely by the value of the cavitation number is inappropriate and misleading.

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2. Cavitation number

In the simplest reasoning one can assume that vapor bubbles appear as the pressure in the liquid drops below the vapor pressure of the liquid at the given temperature. This condition can be formulated as:

$$p_{\min} = p_v, \tag{1}$$

where p_{min} is the minimum static pressure (in time or space reference) and p_v is the vapor pressure at a given temperature of the liquid. Many times researchers tend to use non-dimensionalised values – in the present case this is the pressure coefficient C_p (also known as the Euler number) defined as:

$$c_p(\vec{r}, t) = \frac{p(\vec{r}, t) - p_0}{\frac{\rho v^2}{2}}, \tag{2}$$

where p_0 and v_0 are reference pressure and velocity (again at a reference time and space). Combining Eqs. (1) and (2) reveals the pressure coefficient for the moment when cavitation first occurs:

$$c_{p,\min} = \frac{p_{\min} - p_0}{\frac{\rho v^2}{2}}. \tag{3}$$

$c_{p,\ min}$ is a negative number, which is a function of geometry and the velocity. If one could obtain the value of $c_{p,\ min}$ then the reference pressure $p_{0,cav}$ at which cavitation would first appear could be determined:

$$p_{o,cav} = p_v + \frac{1}{2}\rho v^2(-c_{p,\min}), \tag{4}$$

which is now dependent on the geometry, fluid, fluid temperature and the velocity of the flow.

What Diether Thoma derived in 1920' is a form of the Euler number (Eq. (2)). The most fundamental non-dimensional parameter, which is since then utilized for evaluating the potential for cavitation – the cavitation number σ is written as:

$$\sigma = \frac{p_0 - p_v}{\frac{\rho v^2}{2}}. \tag{5}$$

Every flow, cavitating or not, can be attributed by a cavitation number, its value again depends on the geometry, fluid, fluid temperature and the velocity of the flow. The conditions at which cavitation first appears can also be written as:

$$\sigma_i = -c_{p,\min} \tag{6}$$

where index i stands for "incipient" and σ_i for incipient cavitation number. Lowering the value of cavitation number results in the appearance of cavitation or the increase of extent of already present cavitation.

Cavitation number was primarily applied to open flow problems, such as hydrofoils. Later it was also used for orifices or Venturies where (partial) choking of the flow can occur – form this point on its usefulness can become an issue.

3. Experiment

Tests were performed in a cavitation tunnel at the Laboratory for Water and Turbine Machines, University of Ljubljana.

The experiments (and results) can be divided into 5 general parts:

- *Investigation of the geometry influence:* Here we make measurements at a constant pressure, constant flow velocity, constant temperature and consequently constant cavitation number, but we slightly change the geometry of the Venturi section.
- *Investigation of the influence of flow velocity:* Here we make measurements at a constant cavitation number, constant temperature and the same geometry, but we vary the flow velocity and consequently the pressure (we vary the later in order to achieve the same cavitation number).
- *Investigation of the influence of fluid temperature:* Here we make measurements at a constant cavitation number, constant flow velocity and the same geometry, but we vary the fluid temperature and consequently the pressure (we vary the later in order to achieve the same cavitation number).
- *Investigation of the influence of fluid quality:* Here we make measurements at a constant cavitation number, constant flow velocity, constant temperature and the same geometry, but we vary the gas content (cavitation nuclei population) of water.
- *Investigation of the influence of the cavitation number definition:* Here we make measurements at a constant pressure, constant flow velocity, constant temperature and the same geometry. Later we calculate the cavitation number σ, based on different definitions found in literature.

3.1. Test-rig

The cavitation tunnel (Fig. 1) has a closed circuit and the following important features:

- compressor and a vacuum pump, which enable the variation of the system pressure,
- a frequency controlled pump operation by which we can set a desired flow rate,
- heating and cooling systems for the fluid by which the operating temperature can be set.

The listed features enable setting of all influential parameters in the cavitation number definition (Eq. (5)).

A 4.5 kW pump (1) enables the variation of the rotation frequency in order to set the flow rate. Downstream of the pump, a partially filled tank (2) is installed for water heating and for damping the periodical flow rate and pressure fluctuations. Cavitation and its effects are observed in a test section (3). The tank further downstream (4) is used for cooling of the circulation water – a secondary cooling water loop is installed in it. The valves (5) and (6) enable easy and fast disconnection of the test section from the main loop. The flow rate is measured by an electromagnetic flow meter (7) ABB ProcessMaster 300 (DN 40) with a 0.4% uncertainty on measurements. Fluid temperature is obtained with a type Pt100 (8) with an ±0.15% uncertainty. The pressure in the test rig is adjusted in the partially filled tank (2) connected to a compressor (10) and a vacuum pump (11).

The pressure is measured at 5 different positions – 9a (in the tank (2)), 9b,c,d,e (shown in more detail in Fig. 2) by ABB 266AST pressure transducers. The uncertainty of the measurements ±0.04%.

The quality of water can significantly influence the aggressiveness of cavitation – lower gas content results in more aggressive cavitation [17]. In order to assure repeatable measurements the quantity of the dissolved gases was measured by the Van-Slyke method [18] according to [19,20] the increase of the dissolved gases is proportional to the increase of the cavitation nuclei content.

3.2. Test-section

Four Venturi-type sections were used in the present study (Fig. 2). They all have a constant width of 10 mm and the cross-section at the throat is 10 × 10 mm^2 for all of them. Three have the same general geometry with a convergent angles of 18° and

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