National Conference with International Participation
ENGINEERING MECHANICS 2007
Svratka, Czech Republic, May 14 – 17, 2007

CAVITATION AND BUBBLE NUCLEATION IN WATER WITH ADMIXTURES

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Summary: *The paper summarizes the results of experimental investigation of bubble nucleation in a cavitation nozzle. The extension of the experimental water cavitation setup based on cavitation nozzle principle is described. The extension allows performing measurements with tap as well as purified water contaminated with various gases and liquid substances of known concentration. Some conclusions based on the measurements using the cavitation nozzle principle for determining the size of critical bubble radii are presented.*

1. Introduction

Hydrodynamic cavitation (i.e. cavitation where the pressure decrease required to form bubbles is ensured by liquid motion) presents a tough challenge for pump designers. Cavitation reduces pump efficiency and blade erosion caused by collapsing bubbles decreases machine reliability and generates flow unsteadiness. The complex 3-dimensional unsteady nature of cavitating flows is well documented (Franc, 2004). It involves complex phenomena such as highly non-linear dynamic behavior of bubbles, bubble nucleation, bubble fission and/or coalescence, relative motion between the bubble and the liquid, non-uniform distribution of bubbles in the flow, non-uniform distribution of bubble sizes, bubble-bubble interactions, heat and mass transfer across the bubble boundary, non-sphericity of the bubble, interaction of bubbles with the walls, liquid compressibility, turbulence, and others. Many effects have been modeled as separate problems with respectable success, however, some aspects of the cavitating flows are not yet fully understood. One of the fundamental questions is the origination of bubbles under hydrodynamic conditions, which has been studied extensively in the Laboratory of Phase Kinetics of the Institute of Thermomechanics, AS CR. The overview of the experimental setup and some experimental conclusions are presented in this article.

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2. The importance of bubble nuclei

Ordinary water is an organic substance containing a number of chemical and mechanical impurities including air, which is present either in the dissolved state or inside microscopic nuclei. The existence and the persistence of these nuclei in conditions under which they should be dissolved according to theoretical assumptions is most likely caused by concentration of chemical impurities near the bubble boundary which tend to immobilize it against molecular diffusion. These nuclei then assume the role of nucleation initiators and are responsible for the failure of homogenous nucleation theories for water at normal conditions.

The pump designer has to design the geometry and the operation regime of the pump with regard to cavitation. The design criteria can be based on efficiency (reduced due to lowered density of the bubbly flow), blade erosion (caused by violent collapses of cavitation bubbles near the blade surface), or machine stability (non-linear dynamic behavior of bubbles causes flow-induced vibrations). Regardless of the chosen criteria the designer needs to know the size and the number of microscopic nuclei. Although the classical theory of homogeneous nucleation describes the nucleation of droplets in vapor with good accuracy, it is due to the reasons mentioned earlier that it cannot be used for bubble nucleation under hydrodynamic conditions without a substantial modification. As a result, the size and number of nuclei are typically determined empirically or from experimental measurements for each specific water sample. This is a major drawback for numerical models of cavitating flows.

3. Extension of the experimental setup for estimation of nuclei size

The generalized theory of nucleation for liquid mixtures (Maršík, 2003) aims to estimate the size of the critical nucleus with respect to the physical properties and chemical composition of the liquid mixture. The experimental setup in the Laboratory of Phase Kinetics of the Institute of Thermomechanics of AS CR allows estimating the critical size of a bubble nucleus in flowing water using the cavitation nozzle principle (Zima, 2003) and the generalized theory. Water can be saturated with a given amount of gas (such as air, O_2 or CO_2). The device has been extended to allow the use of purified water (up to 95-98% chemical impurities removed) and the addition of liquid contaminants (such as surfactants) using a mixture preparation tank. The scheme of the experimental setup is shown in Fig. 1.

4. Measurement of nucleation work correction coefficient

The generalized theory of nucleation explains the discrepancy between the classical theory and experimental observations by taking into account the effect of the non-equilibrium (dissipative) processes on the work of creation of bubble nucleus. This effect is expressed using a substance dependent correction coefficient α, which must be determined experimentally. The nucleation work W is split into the equilibrium portion W_{eq} and the non-equilibrium portion F_{noneq}:

$$W = W_{eq} + F_{noneq} = W_{eq}(1-2\alpha),\ 0 \le \alpha \le 0.5 \quad (1)$$

The equilibrium work is expressed as follows:

$$W_{eq} = \sigma R \left[\left(\frac{4\pi}{3kT} \right)^2 v^{-1} \left(\frac{\partial p}{\partial v} \right)_T^{-1} \right]^{1/3} \qquad (2)$$

where σ is the surface tension of water, R is the critical bubble radius, k is Boltzmann constant, T is temperature, v is specific volume and p is pressure.

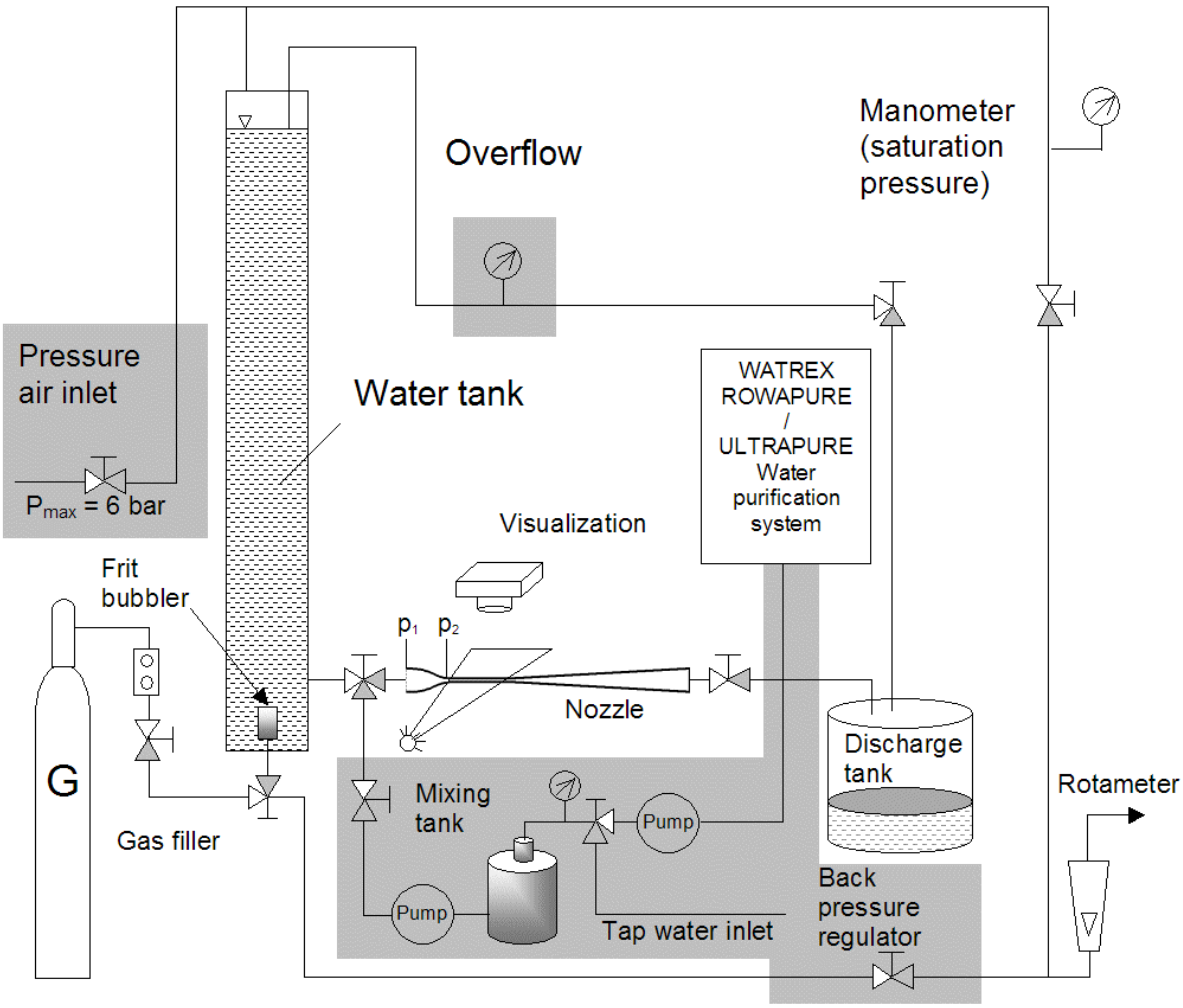

Fig. 1: Simplified scheme of experimental setup with cavitation nozzle. The gray background designates the updated parts.

By measuring the critical (choking) pressure and flow rate and numerical calculation of bubbly flow in a hydrodynamically choked nozzle it is possible to estimate the critical bubble size. By comparing the equilibrium and the total nucleation work for an expected nucleation rate the coefficient α in Eq. 1 can be estimated. The resulting value of α is near 0.5 and the typical critical bubble size is of the order of 10^{-7} m. The results can then be used in numerical simulation (Zima, 2004 and Zima, 2006).

5. Results and conclusions

The following effects have been studied experimentally: (i) *Pressurization.* It was found that the preparation of tap water by pressurization before the measurement (for example by 3 bars for several hours) will decrease the critical pressure in the nozzle throat by as much as 5%. This points at the presence of residual bubbles that can be removed by pressurization. (ii) *Water purity*. By comparing the measurement of tap water with water purified using the WATREX purification system it was found that the difference of the critical pressure in the nozzle throat is within the error of the measurement. This leads to conclusion that the mechanism of bubble creation is independent of the typical impurities removed during the purification. (iii) *Effect of surfactants and temperature.* The effect of surfactant and temperature was investigated briefly and could not be continued due to technical difficulties associated with the effect of elevated temperature and residual surfactant on the device operation. (iv) *Dissolved gas*. The measurements of different concentrations of air in water (besides CO_2) in tap and purified water were performed. It was found that the critical pressure in the nozzle throat increases slightly with gas content.

6. Acknowledgements

This work has been supported by grants no. 101/04/P108 and 101/07/1612 of the Grant Agency of the Czech Republic.

7. References

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