Influence of temperature and phase transitions on cavitation in liquids

R N Golykh, V N Khmelev and R V Barsukov

Biysk Technological Institute (branch) of Altai State Technical University named after I.I. Polzunov, 27, street named after Hero of Soviet Union Trofimov, Biysk, Altai region, 659305, Russian Federation

E-mail: romangl90@gmail.com

Abstract. The paper presents model of formation of cavitation in liquids taking into account influence of temperature and phase transitions. Analysis of the proposed model allowed us to establish that the evaporation and condensation processes of cryogenic liquid at the boundary of the cavitation bubble are the main factor that determines the influence of temperature on cavitation. The established more than 2-times variation of optimal exposure intensities at a small temperature change (no more than 25 %) indicates the need to develop a more advanced, highly sensitive to changes in acoustic load system for automatic dosing of input energy and maintaining the optimal exposure intensity. Taking into account the results obtained will allow creating systems for monitoring the erosion strength of materials and coatings operating in cryogenic liquid media at low temperatures.

1. Introduction

Today, liquids operating near phase transitions are very widely used. These are radiators for cooling and heat transfer systems, systems for stabilization of friction surface temperature, etc. Also, it can be cryogenic liquids like liquid nitrogen, freons, and in many cases just evaporating liquids from surfaces (similar to water). A single approach to study the strength of materials operating with such liquids (for example, materials for channels, technological volumes, high–pressure cylinders) is creating of cavitation near the phase transition [1]

Now, cavitation effects in cryogenic liquids are the least studied. Only some experiments (cavitation in liquid nitrogen, ultrasonic spraying of liquid nitrogen, which has a cavitation nature) is known which is obtained mainly by the authors of this article.

It is necessary to develop a physical and mathematical model for a detailed understanding of the process and rational planning of the experiment. The physical and mathematical models must consider phase transitions because cryogenic liquids have a low specific heat of vaporization (>10 times less of water). Now, there are many models and numerical methods for studying (based on lattice Boltzmann equations, variational principles, averaging methods etc.) the parameters changing of gas impurity in a liquid [2, 3, 4]. However, the existing models and methods are extremely computationally difficult to determine the behavior of the bubble under periodic changes in external pressure.

Therefore, it is important to obtain a system of simplified equations that allow for an acceptable time to calculate the dynamics of a bubble and an ensemble of bubbles in a cryogenic liquid consider phase
transitions. Also, it’s allowed to make a priori estimates of the various factors that influence the occurrence and evolution of cavitation.

The calculations result from this system and the results of its analysis are described in the following sections.

2. Theoretical research of an standalone bubble behaviour pattern

The occurrence and evolution of the cavitation region are primarily determined by the behavior of a standalone bubble. The study of the behavior of a standalone bubble is carried out in a two-phase “liquid–gas” system. The liquid phase is located in the area \( R_b \leq \| \mathbf{r} \|_2 < \infty \); the gas phase is located in the area \( 0 \leq \| \mathbf{r} \|_2 < R_b \), where \( \| \cdot \|_2 \) – the Euclidean norm of the vector; \( R_b \) – the instantaneous radius of the cavitation bubble, m; \( \mathbf{r} \) – the coordinate vector of the observed point, m.

Vapors of the liquid phase with mass \( m(t) \) (\( t \) – time, s) is in the gas phase (inside the bubble). The change in the vapors mass of the liquid phase inside the bubble obeys the experimentally established Dalton law [5]:

\[
\frac{dm}{dt} = 4\pi KR_b^2 \frac{p_{sat} - p_v}{p_v}; \tag{1}
\]

where \( p_{sat} \) is the saturated vapor pressure of the cryogenic liquid at a given temperature, Pa; \( p_v \) is the partial vapor pressure of the cryogenic liquid inside the bubble, Pa; \( K \) is the coefficient depending on the specific heat of vaporization of the cryogenic liquid, and hydrodynamic conditions on the wall of the cavitation bubble, kg/(m²·s).

The pressure difference condition is valid on the wall between the liquid and gas phases, due to the presence of an organic impurity film [6]. This film prevents the bubble size decreasing to zero in the absence of an external ultrasonic field. We neglect the surface tension because it is more than 8 times less in cryogenic liquids than in water (according to reference):

\[
p(R_b(t), t) - p_v(t) \approx \frac{R_b(0)}{R_b(t)}(p_0 - p_v(0)); \tag{2}
\]

The motion of the liquid phase obeys the continuity equation \( \text{div}(\mathbf{v}) = 0 \). It has a spherically symmetric solution \( \mathbf{v} = C(t) \frac{\mathbf{r}}{\| \mathbf{r} \|_2} \); and the law of conservation of impulse

\[
\rho \frac{\mathbf{r}}{\| \mathbf{r} \|_2^3} \frac{\partial C(t)}{\partial t} + \rho \text{div} \left( \frac{C^2(t)}{\| \mathbf{r} \|_2^6} (\mathbf{r} \otimes \mathbf{r}) \right) = - \frac{\mathbf{r}}{\| \mathbf{r} \|_2} \frac{\partial p}{\partial r}; \tag{3}
\]

Improper integration of the equation of conservation of impulse (3) volume of liquid \( V = \{ \mathbf{r} \in \mathbb{R}^3 \mid R_b \leq \| \mathbf{r} \|_2 < \infty \} \) and the additional use of the mass balance of fluid in the volume surrounding the cavitation bubble \( \frac{4}{3} \pi \rho (\| \mathbf{x} \|_2^3 - R_b^3) + m = \text{const} \left( \frac{dx}{dt} \cdot \mathbf{x} \right) = C(t) \| \mathbf{x} \|_2^3 \) gives the final system of equations describing the behavior of a standalone bubble in cryogenic liquids considering phase transitions:
\[
\frac{dm}{dt} = 4\pi KR_B^2 \frac{P_{sat} - p_v}{p_v} \\
\frac{dR_B}{dt} = C(t) + \frac{K}{p_v} \frac{p_{sat} - p_v}{p_v} \\
\frac{dC(t)}{dt} = C^2(t) + \frac{K}{2p_v} \left( \frac{R_B(0) - p_v(0)}{R_B(t)} + p_v(t) - p_\infty \right)
\]

Next, the dependence of a cavitation bubble radius of liquid (liquid nitrogen) (figure 1) contained in the bubble from time \( t \) at different intensities of ultrasonic exposure \( I \).

**Figure 1.** The dependences of the cavitation bubble radius on time at different exposure intensities and temperatures.
The temperature has a rather weak effect on the maximum radius of the bubble reached during the expansion stage as follows from the presented dependences. The partial vapor pressure inside the bubble remains quite small compared to the external pressure despite the processes of evaporation and condensation. Because, the expansion time of the bubble does not exceed 40 microseconds.

The dependences of the vapor mass of the cryogenic liquid (figure 2) contained inside the bubble on time, exposure intensity, and temperature are analyzed for determine the final energy released as shock waves when the bubble collapses.

**Figure 2.** The dependences of the vapor mass-radius in the bubble (in ng) on time at different exposure intensities and temperatures.

The obtained dependences indicate a significant influence of temperature on the vapor content inside the bubble in a wide range of intensities. Obviously, this will cause the temperature to affect the pressure of the shock wave formed when the bubble collapses. Since, it is the pressure of gas (steam) inside the bubble that is the main factor that forms the shock wave.

Next, the energy of shock waves formed during collapse is estimated as part of the study of an ensemble of cavitation bubbles.
3. Theoretical study of parameters of cavitation bubbles ensemble

The peak specific power of shock waves at the moment of maximum collapse of the bubble has is most important at controlling the strength of a material. It determines whether cavitation can overcome the potential barrier of the binding energy of material crystal lattice or not. If the peak power is unable to overcome the strength of the material, then all other phases of the shock wave that have less power will become useless.

Peak specific power of shock waves (figure 3) was estimated in the following way:

$$ P \sim 4\pi \left( \min_{t \in [0;1]} R_h(t) \right)^2 n_{hub} \frac{P_{shw,\text{max}}^2(m)}{2\rho c}; $$

where the concentration of cavitation bubbles $n_{hub}$ was determined by the author's well-known models of the dynamics of a bubbles ensemble [7]. Maximum pressure of standalone shock wave was determined from the theories Gilmore and Eknadiosyants [5, 6].

![Figure 3. The dependence of the peak specific power of shock waves on the intensity at different temperatures.](image)

The presented dependences indicate that the peak specific power of shock waves reaches a plateau at certain intensities of ultrasonic exposure and the power of shock waves does not increase at a further increase in intensity.

Therefore, the minimum intensity (at which the plateau is reached) can be considered the optimal intensity of the ultrasonic exposure. It was found that the optimal intensity is 6.5 W/cm$^2$ at a temperature of 77.36 K, and the optimal intensity is 3 W/cm$^2$ at a lower temperature close to the critical point (63.15 K).

The established more than 2-times variation of optimal exposure intensities at a small temperature change (no more than 25%) indicates the need to develop a more advanced, highly sensitive to changes in acoustic load system for automatic dosing of input energy and maintaining the optimal exposure intensity [8].
4. Conclusion
Thus, a model for the formation of a cavitation area in cryogenic liquids (including a standalone bubble and an ensemble of cavitation bubbles) is proposed as a result of the research. Analysis of the proposed model allowed us to establish that the evaporation and condensation processes of cryogenic liquid at the boundary of the cavitation bubble are the main factor that determines the influence of temperature on cavitation.

The established more than 2-times variation of optimal exposure intensities at a small temperature change (no more than 25 %) indicates the need to develop a more advanced, highly sensitive to changes in acoustic load system for automatic dosing of input energy and maintaining the optimal exposure intensity. Taking into account the results obtained will allow creating systems for monitoring the erosion strength of materials and coatings operating in cryogenic liquid media at low temperatures.

Acknowledgements
The reported study was supported by RFBR, research project No. 20-21-00017 “Research of the formation and development of cavitation processes at abnormally high temperatures in liquid media in contact with various materials and coatings to create a method and means to control their erosion strength” Rosatom.

References
[1] Petkovsek M and Dular M 2018 Wear April 400
[2] Kupershtokh A L, Medvedev D A and Gribovov I I 2018 Physical Review E 98(2) 023308
[3] Schmidmayer K, Petitpas F, Daniel E, Favrie N and Gavrilyuk S 2017 Journal of Computational Physics 334 468
[4] Hantke M and Warnecke G 2014 Continuum Mechanics and Thermodynamics 29
[5] Rozenberg L D 1970 Physical principles of ultrasonic technology (Moscow: Science) p 689
[6] Rozenberg L D 1968 Powerful Ultrasound Fields (Moscow: Science) p 268 (In Russian)
[7] Khmelev S S, Khmelev V N and Golykh R N 2015 Romanian Journal of Acoustics and Vibration 1 20
[8] Khmelev V N, Barsukov R V, Genne D V, Shalunov A V, Abramenko D S and Ilchenko E V 2011 International Conference of Young Specialists on Micro/Nanotechnologies and Electron Devices EDM 2011 (Novosibirsk, Russia) p 241