Method for calculating the longitudinal dimensions of hydrodynamic cavitation devices with a pressure jump

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Abstract. Cavitation technologies are widely used in many industries: from heavy machine building to the food industry. Such a wide range of different industries testifies to the variety of tasks that can be solved using these technologies: to disinfect wastewater, carry out various processes of dispersion, mixing, homogenization and many other processes. Depending on the source-cause of cavitation, ultrasonic and hydrodynamic are distinguished. The working process of hydrodynamic cavitation is rather complicated, but the development of a correct closed mathematical model allows one to calculate the parameters of cavitation devices. The applied calculation method is important in this. The article describes the workflow of a hydrodynamic cavitation device with a pressure jump and proposes a method for calculating such devices. The calculation problem is solved by the method of successive approximations and allows one to determine the longitudinal dimensions of the device. The industrial approbation of the device, calculated by this method, showed good convergence of theoretical and experimental data.

1. Introduction
The task of ensuring the quality and safety of food raw materials and food products is relevant from the point of view of the development of priority areas of the food industry [1–3]. This task cannot be solved in isolation from the tasks of improving existing and introducing modern innovative technologies for food production [4–6]. For the last 10–20 years, cavitation technologies for the treatment of liquid media have been widely used in various fields and industries: heat power engineering and mechanical engineering, in the chemical and paint and varnish industries, in biotechnology and food technologies. Moreover, scientific research is carried out both in the search for new solutions and optimization of the cavitation technology itself, and in the improvement of devices that implement this technology [7, 8].

Depending on the production method, ultrasonic and hydrodynamic cavitation are distinguished. Ultrasonic cavitation occurs in a liquid medium when it is exposed to an ultrasound source (for example, a reactor). Hydrodynamic cavitation occurs if the geometry of the flow of a liquid medium is changed in such a way that a local acceleration of the flow occurs to a speed at which the pressure drops to the pressure of saturated vapor [9, 10]. Thanks to the latter, conditions are created for the development of
cavitation. When bubbles collapse in a short period of time (about 1...10 ns), a significant increase in pressure and temperature occurs - up to 5000 atm and $1.5 \times 10^4$ K, respectively [8, 11]. Such multiple point micro-impacts cause dispersion of the components of the liquid medium. This mechanism is at the heart of the cavitation technology.

At the local section of the flow, where the pressure drops to the saturated vapor pressure, a two-phase flow is formed, consisting of a droplet (low-compressible) liquid with a relatively high density and a compressible gas or vapor, as evidenced by numerous experimental and theoretical studies [12-15]. It is known that the speed of sound of a two-phase flow also depends on the flow regime of such a flow and the model of the phase transition. Figure 1 shows the curve of the change in the speed of sound as a function of the volumetric gas content $\beta$ [12] and the experimental data [13]. Experimental graphs of changes in the speed of sound in the presence and absence of a phase transition in a sound wave are shown in figure 2 [16].

Similar theoretical data indicating rather low speeds of sound in vapor-gas-liquid mixtures can be obtained using Wood's formula - the graph is shown in figure 3.

The analysis of theoretical and confirmed experimental data of low values of sound speed in two-phase flows led to a logical conclusion: cavitation promotes the formation of a two-phase flow, therefore, if the speed, at which a supersonic flow is formed, is calculated, then under the conditions of friction of the working chamber of a hydrodynamic cavitation device, the supersonic flow will inevitably turn into subsonic through a pressure jump, which will be an additional powerful factor affecting the flow. An analysis of the operation of hydrodynamic cavitation devices of this type is given in works [17, 18]. To implement the mechanism of the flow of the working process in the direction indicated above, an adequate mathematical model is required that describes the working process of a two-phase flow and the implementation of a pressure jump - is given in works [17, 18]. In this case, an equally important condition for correct calculations is the calculation method. This article is devoted to the development of a method for calculating the longitudinal dimensions of the device.
Figure 2. Graphs of changes in the speed of sound in the presence and absence of phase transitions in the sound wave.

Figure 3. Theoretical curves of sound velocity changes as a function of volume gas content $\beta$ (in accord with Wood).
2. Method for calculating hydrodynamic cavitation devices that implement the mechanism of transition through a pressure jump

Figure 4 schematically shows the working process of the hydrodynamic cavitation device, which implements the mechanism of the transition of the working fluid flow through the pressure jump.

The fluid flow enters the hydrodynamic device through the confuser for the purpose of its preliminary acceleration, then to the cavitator (this can be a nozzle or a hydrodynamic cascade), which provides an increase in velocity (at the nozzle exit in the jet boundary layer or in the vortex wake behind the hydrodynamic cascade) and pressure up to saturated steam pressure. A two-phase flow is formed and, if the critical flow parameters (Mach number, critical pressure) are calculated, then it is possible to judge the presence or absence of supersonic flow. The threshold-like ledge at the end of the working chamber serves to initiate the transition in the working chamber, the damper - to “soften” the turbulence of the flow at the entrance to the diffuser, in which the kinetic energy is partially transformed into potential energy.

![Flow diagram of a cavitation device with a pressure jump.](image)

Figure 4. Flow diagram of a cavitation device with a pressure jump.

When calculating the cavitation device in accordance with the initial data of the working fluid (composition, temperature, pressure, flow rate), the type of the cavitator, its resistance coefficient and the selected resistance coefficients of the flow path of the device, the optimal (with minimum pressure losses on the cavitation device) transverse dimensions of the device are determined. The works [17, 18] provide information on the development of a mathematical model for determining the dimensions of a hydrodynamic cavitation device with a pressure jump. устройства со скачком давления.

Having determined the flow parameters, the pressure loss on the device is checked, the amount of vapor released is calculated, since the behavior of the two-phase flow largely depends on the vapor content in it. In the working chamber behind the cavitation inducers (behind a multi-jet nozzle or a hydrodynamic grid), the maximum vapor evolution is limited by the space free from liquid jets. In this case, the source of the heat of vaporization is the loss of mechanical energy of the flow when flowing around the cavitators, as well as a part of the thermal energy of the liquid flow itself. Checking the
temperature of the mixture flow serves as a condition for moving to the next step of the calculation - determining the steam content in the flow or to one more iteration. Determination of the steam content in the flow is necessary to determine the critical parameters, in particular, the critical pressure $P_c$, which allows one to determine the critical length $\ell_c$ of the section of the working chamber of the device with a turbulent two-phase flow, at which the critical flow state is reached in the end section of the section (pressure $P=P_c$). Having determined $\ell_c$, we determine the length of the working chamber (or the longitudinal dimensions of the cavitation device).

Figure 5. Method for calculating.

3. Results and their analysis
Comparing two methods of initiating cavitation phenomena in devices of various types (acoustic and hydrodynamic), we can say that hydrodynamic cavitation has incomparable advantages - hydrodynamic cavitation devices are easily integrated into a continuous technological line, showing high productivity and lower energy consumption compared to acoustic ones [19, 20]. However, these devices have not yet found wide practical application, despite the simplicity of their design (sequentially – confuser, cavitator, working chamber in the form of a cylindrical pipe, at the end of which there is a threshold-shaped ledge and a damper in the form of a lattice, then a diffuser). The calculation of such devices is rather complicated, it requires a detailed development of a workflow and an appropriate mathematical model that takes into account the physics of a two-phase medium flow. The fact that the achievement of supersonic flows in a two-phase medium is not only possible, but also easily achievable, is proposed a cavitation device with a supersonic flow of the working fluid, which turns into subsonic through a powerful pressure jump, which is an additional dispersing effect on the flow. Industrial testing of the
cavitation device calculated by this method has shown good convergence of theoretical and experimental data. Thus, the developed methodology can be applied to the calculation of devices of this type, has practical significance and relevance.

References

[1] Velazquez J B 2011 Innovations in food technology Special Issue Food Bioprocess Technol 4 831–32

[2] Akhmetova S, Suleimenova M and Rebezov M 2019 Mechanism of an improvement of business processes management system for food production: case of meat products enterprise Entrepreneurship and sustainability issues 7 (2) 1015–35 DOI: 10.9770/jesi.2019.7.2(16)

[3] Zinina O V, Borisovich R M and Vaiscrobova E S 2016 A microstructure of the modelling systems on the basis of the ferment raw material with a high collagen content Pakistan Journal of Nutrition 15 (3) 249–54 DOI: 10.3923/pjn.2016.249.254

[4] Zinina O, Merenkovna S, Rebezov M, Tazeddinova D, Yessimbekov Z and Vietoris V 2019 Optimization of cattle by-products amino acid composition formula Agronomy Research 17 (5) 2127–38 DOI: 10.15159/AR.19.159

[5] Vladimirovna Z O and Borisovich R M 2016 A biotechnological processing of collagen containing by-products of bovine animals Research Journal of Pharmaceutical, Biological and Chemical Sciences 7 (1) 1530–34

[6] Tretyak L, Rebezov M, Keniz N, Khayrullin M, Gribkova V and Goncharov A 2020 Controlled glycolysis as the basis of beer technology with specified consumer properties Sys Rev Pharm 11 (5) 166–75 DOI: 10.5530/srp.2019.2.04

[7] Cvetković M, Kompare B and Klemenčič A K 2015 Application of hydrodynamic cavitation in ballast water treatment Environ Sci Pollut Res 22 7422–38

[8] Long X, Wang Q, Xiao L, Zhang J, Xu M, Wu W and Ji B 2017 Numerical analysis of bubble dynamics in the diffuser of a jet pump under variable ambient pressure Journal of Hydrodynamics 29 (3) 510–19

[9] Badmus K, Tijani JO, Massima E and Petrik L 2018 Treatment of persistent organic pollutants in wastewater using hydrodynamic cavitation in synergy with advanced oxidation process Environmental Science and Pollution Research 25 7299–7314

[10] Ashokkumar M, Rink R and Shestakov S 2011 Hydrodynamic cavitation – an alternative to ultrasonic food processing Electronic Journal ”Technical Acoustics” 9 1–10

[11] Gogate P and Kabadi A 2009 A review of applications of cavitation in biochemical engineering/biotechnology Biochemical Engineering Journal 44 (1) 60–72

[12] Fisenko V 1978 Critical two-phase flows (Moscow: Atomizdat) p 160

[13] Deutsch M 1968 Gas dynamics of two phase media (Moscow: Energy) p 328

[14] Collingham R E 1968 Indust and Engng Chem Process Design and Development 2 (3) 197

[15] Böck P 1975 Ausbreitungsgeschwindigkeit einer Druckstörung und kritischer Durchflub in Flüssigkeits Gas Gemischen Chemie Ing. Techn. 7 309

[16] Semenov N 1964 Results of a study of the speed of sound in moving gas-liquid mixtures Heat power engineering 6 46–51

[17] Prokhasko L, Zinina O, Rebezov M, Zalilov R, Yessimbekov Zh, Dolmatova I, SomovaYu, Peryatinskiy A, Zotov S and Tumbasova E 2018 Mathematical model of a hydrodynamic cavitation device used for treatment of food materials Journal of Engineering and Applied Sciences 13 (24) 9766–73

[18] Prokhasko L, Rebezov M, Zinina O, Zalilov R, Dick E, Arslanbekova S, Tsyganov A, Ilyina O, Somova Yu and Sychygov D 2019 Development of the mathematical model of a hydrodynamic cavitations device International Journal of Recent Technology and Engineering 8 (1) 1113–20

[19] Ashokkumar M, Rink R and Shestakov S 2011 Hydrodynamic cavitation – an alternative to
ultrasonic food processing *Electronic Journal Technical Acoustics* 9 1–10

[20] Gogate P R and Pandit A B 2005 A review and assessment of hydrodynamic cavitation as a technology for the future *Ultrason. Sonochem.* 12 21–27