Article citation info:
Vitenko T, Droździel P, Horodyskyi N. Erosive impact of vapor-gas phase on the working surface in hydrodynamic type cavitation mode. Diagnostyka. 2016;17(1):3-8

DIAGNOSTYKA, 2016, Vol. 17, No. 1

ISSN 1641-6414
e-ISSN 2449-5220

EROSIVE IMPACT OF VAPOR-GAS PHASE ON THE WORKING SURFACE IN HYDRODYNAMIC TYPE CAVITATION MODE

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Summary

In this article is analyzed the possible mechanism of cavitation bubbles erosive impact on the working surfaces of equipment. The volume and the size of vapor-gas phase generated in hydrodynamic type mode was theoretically determined and experimentally verified. Here are presented the results of studies of cavitation-erosion resistance of food steel, in particular, that the process of destruction has cyclical pattern.

Keywords: cavitation, Venturi tube, erosion.

ODDZIAŁYWANIA EROZYJNE PAROWO-GAZOWEJ FAZY NA POWIERZCHNIĘ ELEMENTÓW MASZYNOWYCH W HYDRODYNAMICZNYM STANIE KAWITACJI

Streszczenie

W artykule przedstawiono oddziaływanie erozji na powierzchnię elementów maszynowych powstałej pod wpływem pęcherzyków kawitacyjnych. Ilość oraz wielkość fazy gazowej w stanie hydrodynamicznym została teoretycznie obliczona oraz doświadczalnie zweryfikowana. Artykuł prezentuje wyniki badań odporności na erozję kawitacyjną stali stosowanej przy produkcji żywności, że szczególnym uwzględnieniem cyklicznego procesujej destrukcji.

Słowa kluczowe: zwężka Venturiego, erozja.

1. INTRODUCTION

An important issue for mechanical engineering - along with efficiency, ergonomics and structural perfection - today is the sufficient reliability and durability of the equipment. The industry suffers huge losses due to the lack of produced machines capacity. There is no doubt that the repair and restoration of equipment requires additional time. Therefore, it is extremely important to minimize and save time, i.e. to maintain efficiency under given technical conditions for a specified period of time. This property in engineering machinery is called machine reliability. The reliability is put in during the design phase, provided during manufacture and brought into effect during operation. The most important indicators of reliability are failure-free performance and durability. This largely applies to hydrodynamic type cavitation devices that are actively offered for the intensification heat and mass transfer processes. In these devices cavitation phenomenon is created specifically for the implementation of certain processes, including: dispersing and emulsifying of hard mixing agents, dissolution, extraction, activation of chemical reactions and so on.

Thus, the products technological design, operating under conditions of hydrodynamic loads, aims at increasing their cavitation resistance. To achieve this is developed the optimum design of parts, are selected and developed cavitation- and corrosion-resistant materials such as composite materials, including those on the basis of nano-carbon structures, are selected technological modes in order to obtain fine-grained and homogeneous material structure, optimal surface roughness of details.

Today exist various mathematical and analytical modes using computer modeling that help to describe the phenomenon of cavitation. They allow to determine the conditions under which cavitation occurs, calculate the value of sound pressure and other parameters and to determine conditions under which cavitation can cause negative effects on systems or can result in processes intensification.

In the USA for cavitation studies were created computer models, which use computational hydrodynamics theoretical methods. Scientists reproduced the processes arising from turbulent flow passing through various operating flap and joint configurations. Such models were used to calculate pressure, density and flow rate and to determine conditions under which cavitation occurs, to predict and evaluate its impact on equipment. For descriptive reasons was applied graphic 3D-modeling. Moreover, the results obtained with the help of computer simulation were compared with actual data obtained during tests.

The first method under cavitation modeling is the method of mathematicalmodel creation, which calculates the value of pressure in individual areas of turbulent flow. This model can be effectively applied to assess the possibility of cavitation occurrence, but does not take into account the spontaneity of its occurrence in individual areas. The second method of cavitation description is the method of pressure fluctuations, using approximate values of speed and density of substances enabling to calculate the pressure in each point of the studying area. This particular method proved to be the most effective in cases, when the difference of pressure in different points of the flow is significant.

Many authors note in their works that large amounts of energy that dissipate during the collapse of cavitation bubbles can cause damage to working surfaces. The scale of the phenomenon (hydraulic erosion) can be different: from zero-dimensional surface erosion after many years of service to the catastrophic failure of large designs. A typical type of parts wear is shown in (fig. 1).

Fig. 1. Typical types of cavitational parts` wear

It was found [1, 2] that the main cause of working surfaces cavitational erosion is cavitation bubbles implosion near them. Without going into the details of bubbles inception, we should note that during implosion bubbles provide certain energy impact on the environment in which they are located. In such a case the kinetics of material destruction process is described as an erosion curve (the loss of weight or volume over time), on which similarly to the process of fatigue, are outlined stages of formation and development of erosion damage. The traditional criterion for material erosion resistance is the loss of its mass (volume) over a certain period of time. This criterion does not account for load conditions, the physics of the process and material properties [3 - 5].

Back in the forties of the previous century, American scientist Knapp suggested a method of cavitation bubbles impact assessment using a thin tin or aluminum foil [3]. When bubble collides with foil in the latest are formed holes or visible hollows (craters). This technique allows sufficiently objectively evaluate the cavitation bubbles field erosion capacity. However, the behavior of cavitation bubbles – single ones and their scopes – and the mechanism of their impact on the working surfaces is still under research [5, 6].The aim of this work was to study the process of cavitation bubbles dynamics and its possible impact on the working surface of hydrodynamic type cavitation module.

2. MAIN RESULTS OF THE RESEARCH

The scheme of the module is shown in Figure 2. The basis of the design is Venturi tube. This design is easy to produce and operate, and the efficiency of its work is high. Under certain conditions of cavitation module performance can be achieved various forms of cavitation, in particular: bubble, developed and super cavitation.

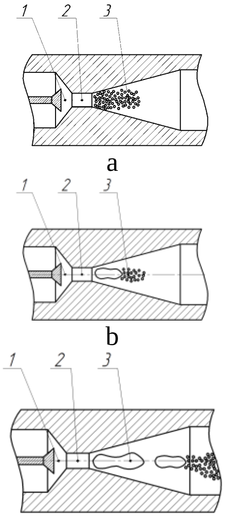

Fig. 2. Module scheme: confuser part - 1; narrow-width part - 2; diffuser part – 3 (a – bubble cavitation; b – developed cavitation; c – mixed cavitation)

The module consists of three parts: input part - 1, narrow-width part - 2 and the diffuser part - 3.

The cone cavitator is installed at the entrance to a narrow-width cylindrical area. The design provides backward-forward movement of the rod with cavitator.The flow of liquid that passes through

Venturi nozzle significantly increases its speed in the narrow part - 2. The pressure in the area of cavitator reduces and cavitation bubbles start to form. When liquid passes through the diffuser, on the walls start to form cavities that generate the bulk amount of cavitation bubbles. When liquid passes through the nozzle, pressure increases (it leads to the collapse of cavitation bubbles).

To calculate the pressure distribution, and the possible content of gas-vapor phase along the working area was used application software package SolidWorks, and, in particular, its module for modeling the flow of liquids and gases - Flow simulation. The software module simulates the flow of liquid based on the Navier-Stokes equation, which is an interpretation of laws of mass conservation, momentum and energy conservation for liquid flow (flows of liquids and gases). The equations are supplemented with expressions of liquid state (that define its nature) and empirical dependences of density, viscosity and thermal conductivity of the liquid from temperature. Incompressible non-Newtonian fluids are considered in terms of the dependence of their dynamic viscosity from shear-strain rate and temperature, and compressible fluids are considered in terms of the change of their density from pressure. Another part of the equation is responsible for the flow geometry, boundary and initial conditions.

The laws of mass conservation, momentum and energy conservation for liquid flow in a Cartesian coordinate system (that rotates with angular velocity Ω about an axis passing through the origin of the coordinate system) can be written as the following:

$$\frac{\partial\rho}{\mathrm{dt}}+\frac{\partial}{\partial x_i}(\rho\cdot u_i)=0$$

$$\frac{\partial\rho\cdot u_i}{\mathrm{dt}}+\frac{\partial}{\partial x_j}(\rho\cdot u_i\cdot u_j)+\frac{\partial\rho}{\partial x_i}=\frac{\partial}{\partial x_j}(\tau_{ij}\cdot\tau_{ij}^R)+S_i \quad (1)$$

$$\frac{\partial\rho H}{\mathrm{dt}}+\frac{\partial\rho u_i H}{\partial x_i}=\frac{\partial}{\partial x_i}(u_j(\tau_{ji}\cdot\tau_{ji}^R)+q_i)+\frac{\partial\rho}{\partial \mathrm{t}}-\tau_{ji}^R\frac{\partial u_i}{\partial x_{ji}}+\rho\varepsilon+S_i u_i+Q_H$$

$$H=h+\frac{u^2}{2}$$

To perform the calculation analysis using Flow Simulation was created solid model of cavitation module in SolidWorks, were given boundary conditions, and were conducted calculations and analysis of results. Were obtained theoretical results on the distribution of pressure along the working area, changes of the speed, temperature and steam phase content under the same initial conditions (Q=2.4·10-3m^3/s, P$_{out}$= 0,11MPa) and the expansion angle of 45°, shown in (fig. 3).

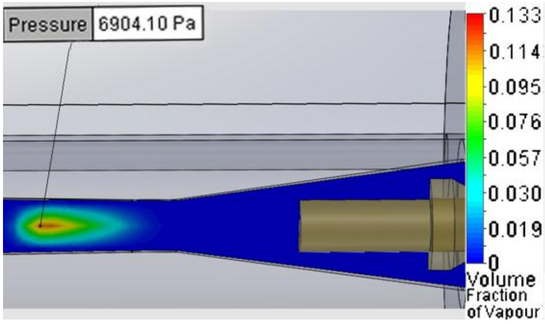

Fig. 3. The results of calculation of basic hydrodynamic module parameters

High-speed digital recording made it possible to estimate the size of cavitation bubbles by measuring their diameters $d_{б}$ in the phase of the greatest expansion and determine their average values (frame frequency 20000 pic./s).Figure 4 shows a photograph of one of the areas. As it can be seen from the photo, the bubbles are about of the same size.

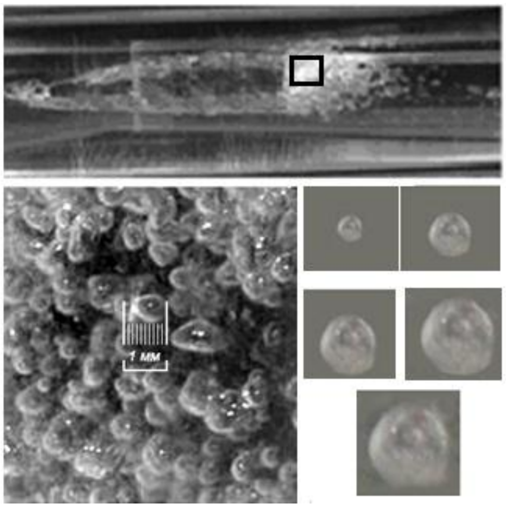

Fig. 4. The photograph of the working area on cavitation stage 2,0 (Exposure time200 microseconds)

The filming and preliminary calculations (on the volume of vapor-gas phase) allowed to determine the total number of bubbles. The distribution of bubbles according to their size is shown in Figure 5. Mathematical synthesis of these data allowed to obtain analytical dependences. With sufficient reliability in all experiments bubbles composition is described as a normal distribution in the form [12]:

$$f(d)=\frac{1}{\sqrt{2\cdot\pi\cdot\sigma}}e^{\frac{(d-a)^2}{2\sigma^2}} \qquad (2)$$

where:
a - sample mean,
σ- corrected sample dispersion (standard notation).

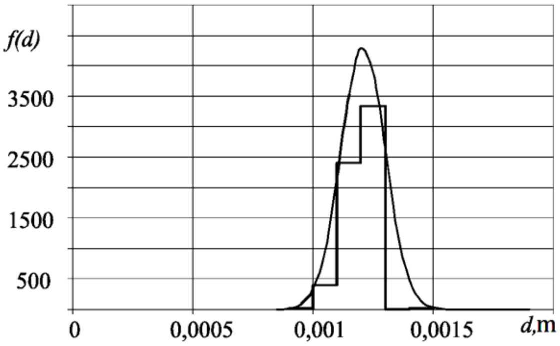

Fig. 5. Distribution of steam bubbles depending on their diameter under cavitation stage 2,0

Let`s consider the impact mechanism of these bubbles on the working surface. As it was mentioned above within the low pressure area cavities (bubbles) are formed from cavitation nuclei present in any liquid. These cavities are distributed directly on the working surface and away from it. When bubbles get in the area of high pressure they compress and consequently form micro-streaming which mechanically affect the work piece surface during implosion. During periodic impact of these micro-streaming occurs transfer of material mass with erosion holes formation on the surface, leading to a gradual deterioration of equipment working surface.

Most models that describe the mechanism of cavitation impact are based on cumulative hypothesis. According to this hypothesis, the degree of cavitation impact depends on the rate of cumulative micro-streaming (fig. 6), which in turn is related to the dynamics of steam bubbles [7, 8].

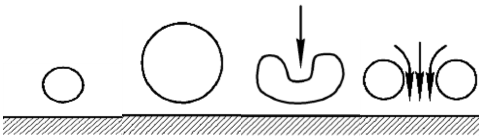

Fig. 6. The scheme of vapor-gas phase impact onto working surface [9]

During small bubbles implosion, formed cumulative streaming can have much higher speeds $v_k$at the same minimum radius of a bubble, as in this case quite small angles of leakage are possible [10], which in turn leads to significant cumulative effects.

Let`s consider a single bubble in a section that is characterized by a certain pressure, including the velocity of its borders. According to the results of the work [14], the equation describing the motion of bubble boundaries (containing gas in its volume) has a form:

$$\left(\frac{d}{dt}r\right)=\left(\frac{2}{3}\right)\cdot\left(\frac{p_s-p}{\rho}\right)\cdot\left[1-\left(\frac{R_0}{r}\right)^3\right]+\left(\frac{2}{3}\right)\cdot\left[\frac{p_{g0}}{\rho\cdot(1-\gamma)}\right]\cdot \tag{3}$$

$$\cdot\left[\left(\frac{R_0}{r}\right)^{3\cdot\gamma}-\left(\frac{R_0}{r}\right)^3\right]-\left(\frac{2\cdot\sigma}{\rho\cdot R_0}\right)\cdot\left[\frac{R_0}{r}-\left(\frac{R_0}{r}\right)^3\right].$$

where:
r – unstable radius of the bubble,
p - pressure on the boundary of the bubble,
ρ - density of the liquid,
p_{g0} - undisclosed gas pressure inside the bubble under the condition that $r = R_0$;
p_s - the vapor pressure in the liquid,
σ - the surface tension coefficient,
R_0 - initial radius of the bubble,
γ - adiabatic index.

The results of the calculations of this equation are shown in (fig. 7). Here can be observed an increasing rate of bubble`s growth and implosion under the condition of increasing pressure around bubbles. However, the maximum radius reduces under these conditions.

During the movement of cavitation bubbles in a liquid, at first occurs its increase in the volume of the area where the pressure in the liquid is lesser than vapor pressure due to liquid evaporation inside the bubbles. Further, when bubbles get in the area with the pressure higher than saturation pressure occur bubble implosion (collapse).

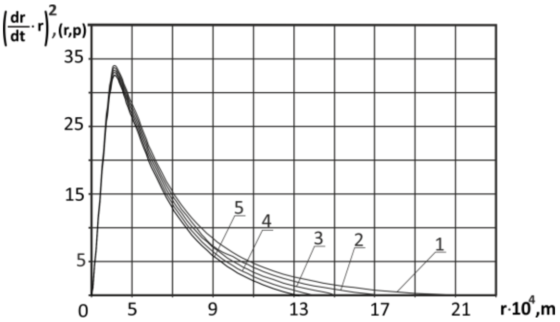

Fig. 7. The dependence of squared velocity of cavitation bubble boundary from its unstable radius: 1-p=0,4 MPa; 2-p_2- p=0,5 MPa; 3- p=0,6 MPa; 4-p=0,7 MPa; 5- p=0,8 MPa

Due to pressure in the liquid bubbles start to move towards the center and their speed is accelerated. Due to thermodynamic gas processes inside cavitation bubbles can be observed increasing pressure and temperature. Cavitation bubble stores kinetic energy required to overcome the increasing pressure. With increasing pressure bubble`s content begins to condense on the inside of the bubble`s walls, which reduces the pressure in the bubble. It means that bubble`s radius can reduce further. In the last stage the bubble closes and kinetic energy evolves.

Pressure field, which is formed during the collapse of cavitation bubbles can be defined by the equation [14]:

$$\frac{P_c}{p}=1+\left(\frac{1}{3}\right)\cdot\left[\frac{7}{l_1^2}-4\cdot l_1-l_1\cdot\left(1-l_1^3\right)\right]\cdot L^{-1} \tag{4}$$

where

$$L = \frac{r}{R_{c\max}};$$

$$l_1 = \frac{r_c}{R_{c\max}}.$$

And kinetic energy by the equation [14]:

$$T = \frac{4}{3} \cdot \pi \cdot p_0 \cdot R_{\max}^3 \qquad (5)$$

The results of the calculation (equation 4) are shown in (fig. 8).

It is logical that along with the change of the initial bubble radius and pressure around it the pulse energy transferred to the bubble walls will also be variable. In the works devoted to ultrasonic cavitation is indicated the growth of momentum from 0 to 7.10^{-7} kg·m/s under changing initial radius from $1\cdot10^{-5}$ to$9\cdot10^{-5}$m.

The obtained results are confirmed by the results of studies on the deterioration of samples made of stainless food steel. The researches on samples durability showed that during the period of the research the sample weight decreased by 28%. The samples were placed at a certain distance from the vapor-gas phase concentrator area with pressure 0,11MPa.

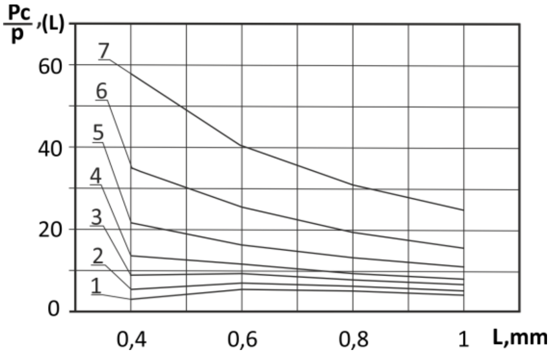

Fig. 8. The dependence of dimensionless pressure from the size of a bubble: 1-l_1=0,769; 2-l_1=0,692; 3-l_1=0,615; 4-l_1=0,538; 5-l_1=0,462; 6-l_1=0,385; 7-l_1=0,308

As a working environment was used clarified tap water, with the temperature 20±1°C controlled with thermometer. The intensity of wear was determined gravimetrically by weight loss at fixed intervals with the help of laboratory electronic scales Radwag 210, within the accuracy up to 0.0001g. Before weighing the samples were washed in distilled water and in ethanol, then placed in drying oven (at T=70...80°C for 5 min.), cooled and stored in anexsiccator.

The rate of wear was determined by the ratio of ΔG/Δτ, where ΔG total mass loss of the sample during the test Δτ. For all of the studied samples (Fig. 9) we can see a definite pattern: the wear has a cyclical pattern (better seen when cavitation effect is the hardest, i.e. the size of vapor-gas bubbles is the smallest), regardless of the speed of the working environment the samples wear has similar pattern.

It should be noted that under stated value of cavitation stage during the research is observed cyclical nature of samples wear rate change that demonstrates the cyclical development of fatigue cracks and implementation of destruction mechanism due to changes in dislocations density in the surface layer.

Such properties change pattern of samples` surface layers was observed during hydroabrasive wear [11].

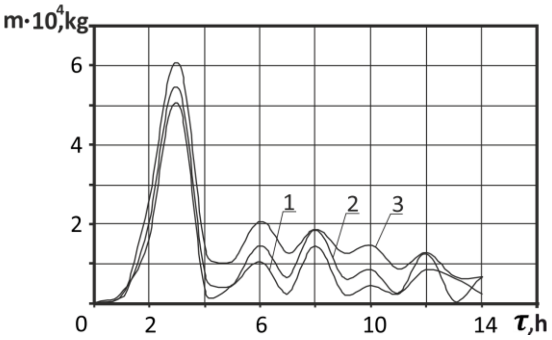

Fig. 9. The dependence of wear rate from time: 1 – Steel brand 12X13; 2– Steel brand –08X13; 3 – Steel brand 40X13

3. CONCLUSION

By analyzing the possible mechanism of cavitational impact of vapor-gas phase we can state that the main cause of cavitation erosion of working surfaces is cavitation bubbles implosion near them. When bubbles get in the area withhigh pressure they compress and consequently form micro-streaming which mechanically affect the work piece surface during implosion. During periodic impact of micro-streaming occurs material mass transfer with the formation of erosion holes on the surface, leading to a gradual deterioration of equipment working surface. According to the researches, food steel is promising for work under the conditions of cavitation-erosion wear. It was determined that the process of its destruction is cyclical in nature, and the study of its patterns is of significant scientific and practical importance.

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Received 2015-09-01
Accepted 2016-02-15
Available online 2016-02-22

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