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Recent Topics on Cavitation Research

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Abstract

This article presents the unique characteristics of cavitation, those are very high pressure and very high temperature even in a very short time. Such the high-pressure causes the destruction of material, which sometimes brings a severe problem to fluid machinery. However, if we look the cavitation from the different direction, such the high pressure can be used to various applications. The author presents two examples of the utilization of cavitation recently done at the Toyo University. Those are "dispersion of spilled oil" and "killing planktons".

1. What is cavitation?

Cavitation is a vaporization phenomenon caused by sudden decrease in static pressure in a flow system. It is the same phenomenon as boiling. Boiling occurs when the liquid temperature becomes higher than the vaporization temperature by heating. In contrast, cavitation occurs by sudden decrease in static pressure as mentioned above. This difference is illustrated in Fig. 1.

Bubbling of beer or champagne is very similar to cavitation, but it is totally different phenomenon. It is not vaporization, but degassing of carbon dioxide according to Henry's law.

Cavitation was discovered about a century ago, when naval architects designed marine propellers for a high-speed ship. The thrust of the propeller didn't reach the amount, which the designer expected because of cavitation.

Cavitation causes performance reduction, generation of noise and vibration, and erosion. Cavitation is generated in any liquid, from water to liquid hydrogen. From sea water to lubrication oil in a bearing .

Recently, it was reported that the cavitation caused the destruction of the hydrogen feed pump of the Japanese space rocket H2, resulting in failure of the mission. This gave a big shock to Japanese people.

As mentioned later, the collapse of a cavitation bubble generates a very high pressure, which destroys blades of pumps and marine propellers. Therefore, cavitation should be avoided in such a case. However, cavitation can be a strong tool for cutting materials. Cavitation can be also used in cleaning, mixing, or accelerating chemical reaction, killing planktons, and so on.

In this review, the author describes the unique characteristics of cavitation, which are responsible wide utilization of cavitation.

2. Unique characteristics of cavitation

When a foil section is in a uniform flow, the region of low pressure generates at the backside of the section as illustrated in Fig. 2. If the pressure becomes lower than the vapor pressure, cavitation generates at the region. The cavitation bubbles flow downstream and collapse at the high-pressure region.

The collapse of a cavitation bubble is associated with the condensation of vapor, and the internal pressure does not increase. It is a big difference from a gas bubble, whose pressure increases as the bubble shrinks. In the case of cavitation bubble, the surrounding liquid flows in the center of the bubble at a very high speed, which causes the concentration of energy, resulting in the generation of very high pressure (more than 1Gpa) at the moment of final collapsing stage. In some cases the temperature inside the bubble becomes very high (a few thousands degree).

Another unique characteristic of cavitation is the generation of cloud cavitation. The type of caviation is classified by its appearance, such as; sheet cavitation, bubble cavitation, cloud cavitation, and so on. It is closely related to the characteristics of the boundary layer where cavitation generates.

The sheet cavitation is associated with the separation of the boundary layer. When the pressure increases suddenly, the sheet cavitation breaks into many small cavitation bubbles, which are called cloud cavitation, because of its appearance. The collapse of cloud cavitation sometimes causes severe noise, vibration, and erosion. Therefore, a designer should avoid the cloud cavitation when he designs fluid machinery. The collapse of cloud cavitation generates a higher impact pressure than the collapse of a single bubble.

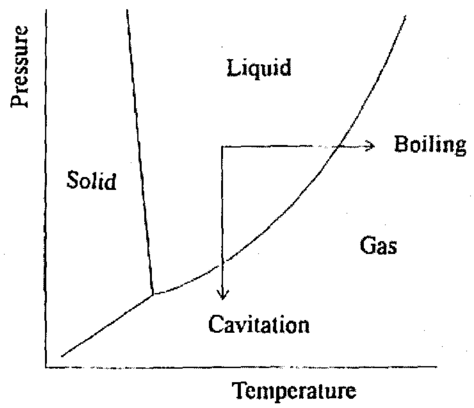

Fig. 1 Cavitation and boiling

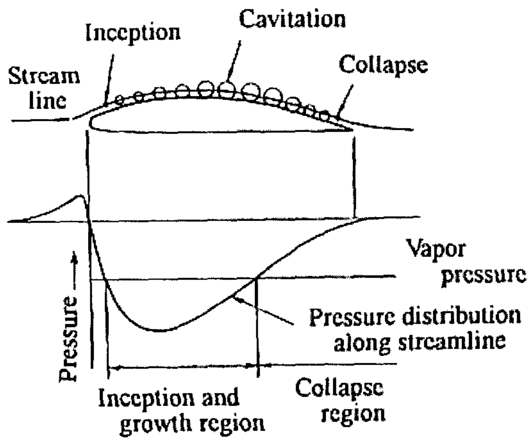

Fig. 2 Cavitation on a foil section

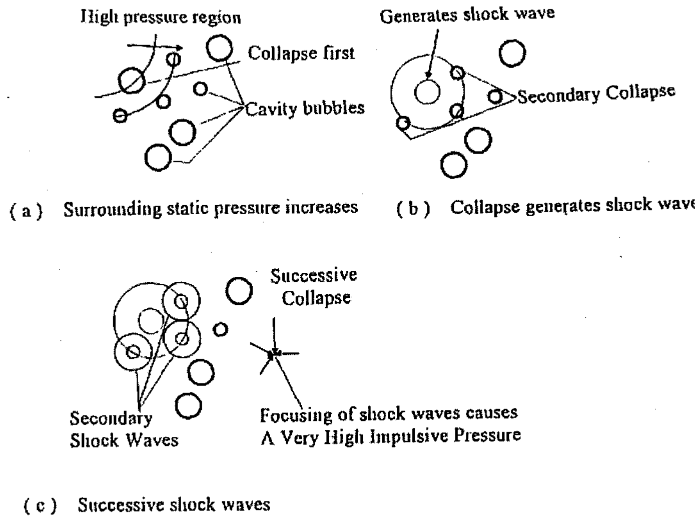

Fig. 3 Successive collapse of cloud cavitation bubbles

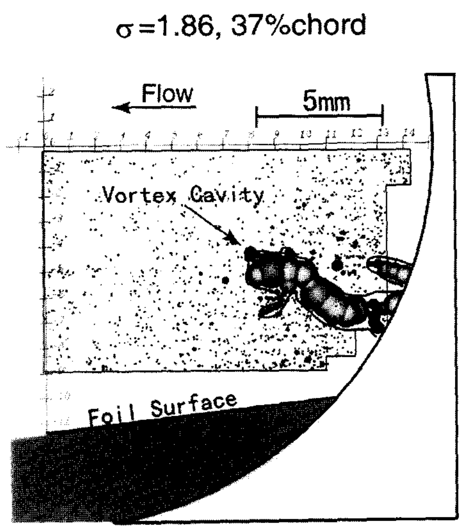

Fig. 4 Reconstructed image of cloud cavitation on a foil section

3. Why cloud cavitation is so harmful?

Why does the collapse of cloud cavitation generate such a high impulsive pressure? Figure 3 shows the answer schematically. When a high-pressure wave propagates into the cloud cavitation region, some cavitation bubbles collapse first (Fig. 3(a)). This collapse generates spherical shock waves (Fig. 3(b)) that cause the surrounding cavitation bubbles to collapse violently. These secondary collapses and shock waves cause other surrounding cavitation bubbles to collapse more violently. Therefore, a very high impulsive pressure is generated in cloud cavitation by focusing shock waves (Fig. 3(c)). This procedure is sometimes called the "avalanche effect".

The mechanism of the high-pressure generation was also studied by analytical methods. Assuming a spherical bubble cloud surrounded by an unbounded pure liquid, the growth and collapse of individual bubbles were analyzed by coupling Euler or Navier-Stokes equation and the equation of individual bubble motion (Rayleigh-Plesset equation) with bubble interaction effects. The highest pressure peak of more than 1 GPa, generates at the center of the cavity cloud.

4. Two experiments on cloud cavitation

We made the experiment of cloud cavitation on a foil section whether such the analytical result is true in the real field. The first experiment was the observation of cloud cavitation. We observed cloud cavitation on a foil section using off-axis hologram. Figure 4 is an example of reconstructed image. From those observations it was found that the cloud cavitation consists of a vortex cavitation surrounded by many small cavity bubbles.

The second experiment was the measurement of impulsive force caused by the collapse of cloud cavitation. We embedded 4 impulsive force sensors made of PVDF piezoelectric polymer film on a 2D NACA0015 foil section. Observation of cloud cavitation was made by a high-speed video camera (FASTCAM by PHOTRON Ltd.) at a speed of 40,500 fps. The impulsive force measurement was simultaneously made with the observation.

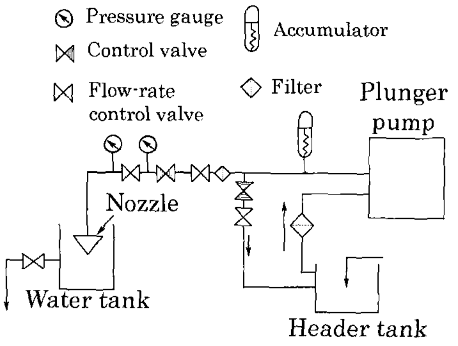

Fig. 5 Test loop for dispersion of spilled oil

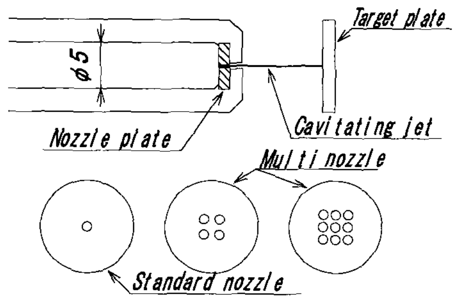

Fig. 6 Three types of nozzles

According to the analytical result, shock wave generates at the moment of complete collapse of cavitation cloud. Whereas, the impulsive force was generated a few frames before the complete collapse. The average time difference was 95 microseconds. We cannot explain this time difference by a simple cloud cavitation model.

5. Utilization of cavitation

As mentioned in the previous section, cavitation has many unique characteristics, which were thought as harmful phenomena for last 100 years. However, such the characteristics as generating a very high pressure easily, can be used to more positive direction. Table 1 is the summary of cavitation utilizations including future applications. The characteristics are classified into three categories; those are high pressure, high speed, and high temperature.

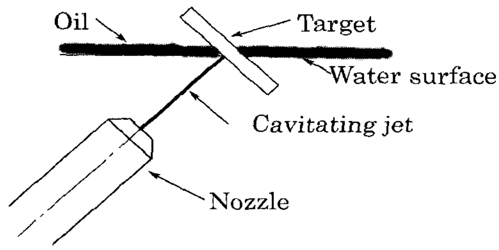

Fig. 7 Cavitating jet hits oil-water interface

The leftmost vertical column shows the fields to which cavitation is applied, such as mechanical engineering, civil engineering, naval architecture and ocean engineering, nuclear engineering, electronics, chemical engineering, medicine, food technology, and environmental protection. Here the author introduces you recent experimental results at the Toyo University, for the environmental protection by cavitation; those are dispersion of spilled oil and killing planktons in seawater.

5.1 Dispersion of spilled oil

Oil spill accidents sometimes give detrimental effects to the ocean environment. In January 1997 a Russian tanker Nakhodka sank at the Japan Sea, whose spilled heavy oil reached to Japanese coastline. It gave big social problems and issues to Japanese people. Soon later, a large crude oil tanker spilled her cargo oil out at the southern coast of Korea.

The best countermeasure is, off course, the mechanical recovery of the oil using oil recovery system. However, it becomes impossible for reasons such as bad weather. The second best countermeasure is to disperse spilled oil by dispersant. The use of dispersant has a critical issue, because persons are afraid of its poisonous effect to the environment. If we can disperse oil by cavitating jet, it has a big advantage to dispersant, because we use only water (sea water). It gives the feeling of safety to people.

Figure 5 shows the experimental apparatus used for dispersing oil. A plunger pump with three cylinders generates high pressure water up to 5.6MPa. Water is ejected from a nozzle, forming cavitating jet flow. Nozzles tested are shown in Fig. 6; those are three single hole nozzles of 0.4mm, 0.8mm, and 1.2mm in diameter, and two multi-hole nozzles (4 and 9 holes).

The cavitating jet hits the water-oil (C-heavy oil) interface as

Table 1 Utilization of Cavitation

Application	High Pressure (~ 1 GPa)	High Speed (~100 m/s)	High Temperature (~ 1000 deg)
Mechanical, Civil, Ocean, & Nuclear Engineerings	Cleaning, Cutting, Peening Improve Fatigue Strength	Bubble Jet Printer	Anti-corrosion Nuclear Fusion
Electronics	Cleaning, Gettering		
Chemistry	Recrystallization Fine Powder Formation	Decomposition of Polymer Emulsifacation	Acceleration of Reaction Amorphous Material
Medicine	Surgical Knife		Destruction of Cancer Cells
Food Technology	Cleaning, Cutting, Sterilization	Mellowing of Sake	
Environmental Protection	**Killing Planktons**	**Spilled Oil Dispersion**	**Decomposition of Chemicals**

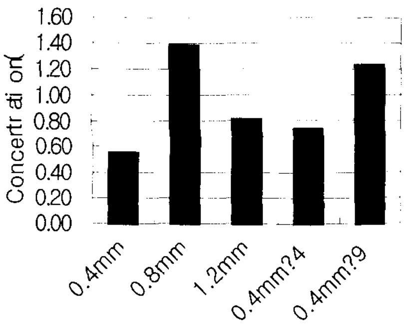

Fig. 8 Effect of NozzleType on Oil Dispersion (V=50m/s)

shown in Fig. 7. A target plate is set at the interface, where cavity bubbles collapse, and disperse oil by small high-speed flow accompanied with the collapsing motion.

Dispersed oil becomes many small oil droplets in water. Water with oil droplets are sampled and observed by a microscope. Most droplets were smaller than 30 microns, which is smaller than 50 microns, the limit of dispersion. The distance between the nozzle and the target plate is an important factor for the effective dispersion. It was found that the best condition was non-dimensional distance of ca. 50. Figure 8 is the comparison of the different nozzles, where the distance of the target plate limited within 30mm. In the present experimental condition, the 0.8mm nozzle was the best, and the oil concentration reached about 1.4 %. We tested also the effect of dispersant for the comparison. We selected a typical dispersant, S-7. Added 2 ml of S-7 into 10 ml of C-heavy oil, stirred 30 seconds, and sampled the water. The mean concentration of oil was 0.14%, which was much less than the case of cavitating jet.

It was found that the cavitating jet with a target plate was a promising method and further researches are necessary for the practical use.

5.2 Killing planktons by cavitation

Enormous amount of planktons sometimes generates in a semi-closed sea, such as Tokyo Bay, resulting in the destruction of the environment.

Another important issue is planktons in ballast water. 10 billion tons of ballast water has been discharged all over the world a year. Planktons, eggs of fish, and other micro organisms are also discharged at the place thousands miles away where the planktons are living. If the planktons and fish are harmful to the new environment, it causes a serious damage of the environment. The International Maritime Organization (IMO) has started the argument to find the effective countermeasure to protect the ocean environment. Several methods have been proposed. Those are filtering, heating, ozone, chemicals, and so on. Among them, Japan proposed hydrodynamic method. The method is so simple that ballast water is ejected through a nozzle(s) when the water is loaded and/or unloaded. The high shear flow with cavitation causes the destruction of planktons.

The similar experiment has been done at the Toyo University. Two experimental apparatus were used; one is the ultra-high

Fig. 9 Brine shrimps used for the experiment

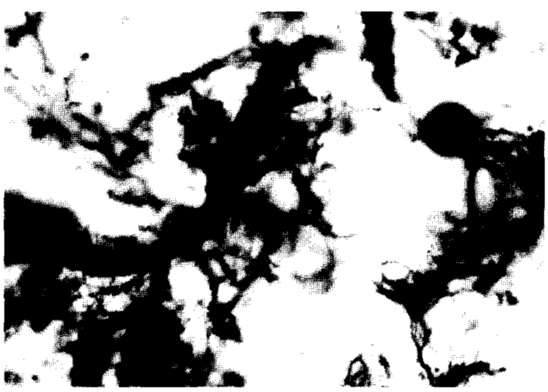

Fig. 10 Micrographs of destructed brine shrimps
(Cavitating-jet device, Nozzle diameter 0.4mm, 2.5 MPa)

pressure experimental apparatus. The amount of test liquid is only 4 cc per stroke but it can generate very high pressure up to 150 MPa. The test section is a circular pipe of 5 mm with two small circular nozzles (0.12 mm/ 0.15 mm, and 0.25mm/0.30mm). The other is the flow loop used for the oil dispersion (Fig. 5).

We tested two different waters with planktons. One is the water taken at a pond at the Kawagoe campus, Toyo University. The other is salt water with brine shrimps, which can easily purchase at a pet shop. Figure 9 is brine shrimps used for the experiment. The size is 0.6-0.7mm in length.

Figure 10 is the micrograph of destructed brine shrimps. The substance looks like roots is the internal organ of the brine shrimps. Eggs are also seen in the photograph. As seen in the figure, the brine shrimps were destructed almost completely. The effect was also shown by measuring the decrease of solid particle size in the water with planktons.

The present results shows that the use of cavitation seems a promising method in the treatment of ballast water.

6. Concluding remarks

As mentioned first, engineers have thought that the cavitation was a harmful phenomenon and should be avoided for almost one century. However, the cavitation has many very unique characteristics, and we can use it much wider applications. The applications will be from environmental protection to nuclear fusion.