EXPERIMENTAL STUDY ON CAVITATION STARTING AT AND FLOW CHARACTERISTICS CLOSE TO THE POINT OF SEPARATION

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ABSTRACT

Microscopic bubbles stably existing everywhere in liquid are the core idea of the traditional nucleus theory for cavitation. However, the idea conflicts with the following two facts; one is diffusion, the universal physical law in nature. The other, which has experimentally been confirmed, is that a tensile stress generated in liquid does not cause any anticipated changes in liquid such as explosive growth of bubbles and reduction of sound velocity when it is propagated as a wave [1]. The present paper introduces the cavitation study in oil flows carried out by the present authors with the intention of answering these questions. Some interesting results discovered through observations of cavitation starting at the point of separation are provided together with their physical interpretations, which may be quite unfamiliar to many but are conceivably no less plausible than the nucleus theory as a hypothesis. The newest one is that the singularity of a flow separating from a wall can be the real cause of cavitation.

INTRODUCTION

The idea of omni-present bubble nuclei long formed the basis for the traditional cavitation nucleus theory. However, there have been doubts cast on the central idea, because cavitation does occur even when the liquid does not contain bubble nuclei, and the idea of minute gas bubbles existing stably in liquid, such being the established image of cavitation nuclei, conflicts with the universal physical law of diffusion. Although the nucleus theory was widely accepted and seemingly unassailable, the present authors wished to settle these doubts and started to investigate from scratch the mechanism of cavitation more than a decade ago.

They conducted microscopic observations of cavitation at the point of separation in oil flows through a long rectangular constriction first [2] and passing over a needle projection second [3], using unusual experimental tools such as a microscope, a laser beam transmission, a photo-multiplier and an electrical charge detector. The findings were intriguing as follows; 1) cavitation starts with a micro-cavity which suddenly emerges on the wall at the point of separation. There are several bases to believe that this incipient cavity does not result from a so-called stream nucleus. 2) The newborn micro-cavity stays on the wall near the separation point and grows as gas dissolved in surrounding liquid diffuses into it. 3) When the cavity grows bigger, it is partially torn away by the flow and supplies so-called cavitation nuclei to the downstream. 4) Vigorous cavitation is usually accompanied by electric charge both on the wall and in the liquid in addition to light emission often visible to the human eye. 5) What looks like a gleam to the human eye is actually a series of instantaneous flashes, probably electric discharge, in the cavity. 6) Electric charges on the wall and in the liquid have opposite signs, and their transient variations are synchronized with the light flashes.

In those observations, incipient cavities kept staying in the vicinity of the point of separation. Presumably that was because those flows separated from “projected edges” which could shelter newborn cavities on their downstream sides from the surrounding flow. In order to see what happens if there is no such sheltering space on the wall, a flow separating from a smooth wall was next observed, using a high-speed video camera and a thermo-couple in addition to the same tools as employed in the previous observations [4]. The results obtained in this case were as follows; 1) a cavity suddenly emerged on the wall close to the point of separation and took a course of explosive growth, shrinkage and disappearance just in several tenths of one millisecond. 2) Light emission was observed in the growth of a cavity and electric current synchronized with it was detected from the downstream oil. 3) A streamline extending from the point of separation was spontaneously visualized. Temperature measurements across the streamline indicated that heat was generated somewhere near the separation point.

In order to explain all the results consistently, the present authors proposed a new hypothetical picture of how cavitation starts; in a separation flow, a tensile force working on the point of separation increases with the fluid velocity. As it exceeds a certain threshold, the tensile force rips a liquid particle from the wall, which phenomenon can be regarded as “yielding”, so to speak, leaving behind a microscopic rent in the solid-liquid interface. The rent rapidly develops into a cavity by drags of the surrounding liquid. Moreover friction between the wall and the liquid when the cavity grows, which is presumably a sort of flow
The electrification phenomenon, gives rise to electric charges with opposite signs on both sides, respectively. When the cavity is explosively enlarged, the work done by it enhances the electrical potential of the charges, and this consequently discharges in the near-vacuum inside of the cavity.

Naturally, the above-mentioned picture of cavitation is quite foreign to many cavitation researchers and will receive criticisms from the traditional standpoint of the nucleus theory. The present authors would like to introduce some of their experimental findings, mainly from the data obtained through the observation of cavitation on a smooth wall, hoping to have them scrutinized by others.

**NOMENCLATURE**

- $p$: pressure
- $p_U$: pressure upstream of constriction
- $p_D$: pressure downstream of constriction
- $\bar{u}_M$: average flow velocity at minimum section of the constriction
- $u$: velocity component tangential to surface of body in boundary layer flow
- $v$: velocity component normal to surface of body in boundary layer flow
- $x$: coordinate tangential to body surface in boundary layer
- $x_S$: x-coordinate of point of separation on body surface
- $y$: coordinate normal to body surface in boundary layer
- $D_H$: hydraulic diameter of minimum rectangular cross section
- $Re$: Reynolds number ($= \bar{u}_M D_H / v$)
- $\mu$: coefficient of viscosity of oil
- $\nu$: kinetic viscosity of oil
- $\sigma$: cavitation number ($= p_D / (p_U - p_D)$)

2. EXPERIMENTAL APPARATUS AND METHOD

The same test section was used for all the observations. In order to carry out visual and optical observations conveniently, the test section was made of transparent acrylic resin and had a rectangular external shape with an internal passage of 20mm height and 10mm width as shown in Fig.1. The three different shapes of flat blocks of 10mm thickness, which were also made of acrylic, were inserted to realize three different kinds of constriction flows at the test section: 1) a rectangular parallelepiped block to form a one-sided long two-dimensional constriction (Fig.2 (a)), 2) a semicircular cylinder with a needle embedded on its top (Fig.2 (b)), 3) a semicircular cylinder to form a two-dimensional constriction whose cross-section smoothly decreases and then increases in the flow direction (Fig.2 (c)).

The test channel was incorporated into the hydraulic oil circuit (Fig.3), using specially manufactured joints to connect its rectangular passage smoothly to circular pipes at both ends. The working liquid (VG46 machine oil, $\nu = 0.73 \text{cm}^2/\text{s} @ 30^\circ \text{C}$) discharged from the screw pump passes a flow control valve, an orifice flow-meter, a 3µm filter and an accumulator-type pulsation absorber, and then flows into the test channel. The flow rate through and the pressures before and after the constriction were measured with the orifice flow-meter and the strain gauge type pressure transducers (rated pressure of 5MPa), respectively, while the temperature was detected with a thermistor located immediately before the test channel.

Although cavitation researchers usually depended on the naked eye to recognize cavitation inception, the present authors wanted to make it more precise and introduced stereoscopic and long-distance microscopes as novel tools for cavitation research. Various video cameras ((A) state-of-the-art ultra high speed camera with 312*260 pixels at 1,000,000F/s (B) high speed camera of 40,500F/s at the maximum (C) video camera with high optical sensitivity (D) ordinary home-video camera of 30F/s) as well as conventional and digital still cameras were mounted in turn on the microscopes to visually record transient microscopic phenomena occurring at an incipient stage of cavitation. For the still cameras and the high-speed videos, a stroboscopic flash light (flashing duration of 1.1 µs) and an ordinary white spotlight were used for illumination, respectively.

In order to otherwise detect fast-moving microscopic cavities and bubbles in a flow, a combination of a laser beam focused down to 0.1 mm $\phi$ in nominal at its narrowest and a PIN photo-diode was effectively employed. A beam transmitted close to the point where an incipient cavity comes out was used...
as a trigger signal of stroboscopic flash or for the high-speed video cameras.

Needless to say, it is essential for experimental study on cavitation to monitor carefully stream nuclei and not to let bubbles produced by cavitation circulate in hydraulic circuits. Generally speaking, small bubbles neither stay long nor circulate in oil hydraulic circuits, because they quickly dissolve into oil due to diffusion, especially when exposed to high pressure at the pump discharge port. Moreover above-mentioned laser transmission, which has proved to be able to detect at least a bubble of 10 µm in diameter [3], can probably judge well if the oil flow under observation is truly free of stream nuclei. The possibility for micro bubbles smaller than 10 µm in diameter to survive for some time must be very small, considering that diffusion allows them to exist only for milliseconds in oil pressurized at several MPa, which is the case of the present test.

3. CAVITATION STARTING AT POINT OF SEPARATION

3.1 Preliminary discussions on points at issue

Traditionally, cavitation researchers have adopted the first moment when bubble nuclei are expanded in turbulence and become visible with the naked eye, as the criterion of cavitation inception. On the other hand, the present authors have found out that a microscopic cavity invisible to the naked eye emerges on the wall near the point of flow separation before cavitation become recognizable in the downstream turbulence. The newly born cavity grows bigger and is split into pieces which act as cavitation nuclei in the downstream. If that is a fact, the first emergence of microscopic cavities at the point of separation should be regarded as the real start of cavitation.

Figure 4 shows a side-view photograph of a whole cavitating flow through the cylindrical constriction (Fig. 2 (c)). The direction of flow is from left to right, which is the same in all photographs hereafter. At around 20mm downstream of the narrowest section cavitation bubbles have developed large enough for the naked eye to recognize. It is this cluster of “visible” bubbles that the traditional cavitation research mainly paid attention to. Against this, the present authors assert that another cavitation has already occurred at some upstream point where the flow separates from the wall, ahead of this “visible” cavitation.

Fig. 5 shows a top-view photograph of a whole cavitating flow through the cylindrical constriction (Fig. 2 (c)). The direction of flow is from left to right, which is the same in all photographs hereafter. At around 20mm downstream of the narrowest section cavitation bubbles have developed large enough for the naked eye to recognize. It is this cluster of “visible” bubbles that the traditional cavitation research mainly paid attention to. Against this, the present authors assert that another cavitation has already occurred at some upstream point where the flow separates from the wall, ahead of this “visible” cavitation.

Fig. 5 Transitional metamorphosis of incipient cavity emerging at point of separation on a cylindrical surface; photographs with corresponding records of laser beam transmission (top-view, constriction (c))
What also attracts attention in Fig.4 is the spontaneously visualized separation streamline recorded in the photograph. This phenomenon, which seemingly demonstrates the peculiar characteristics of flow separation, will be discussed towards the end of the present paper.

3.2 Cavitation starting on a smooth wall

Interesting results obtained in microscopic observation of cavitation starting on the cylindrical surface (Fig.2(c)) are exhibited in Fig.5. The figure provides the PIN photo-diode outputs of lasers A and B, which were transmitted perpendicularly to the cylindrical wall somewhat upstream of and close to the separation point, respectively, and the top-view photographs taken by stroboscopic illumination triggered by laser B at four different timings (T) behind its sharp change.

These results have revealed the following picture of cavitation inception on a smooth surface; in a flow separating from a smooth wall, a small cavity suddenly emerges near the point of separation. The newborn cavity undergoes drastic metamorphosis, that is, a transition of explosive growth, fission and final disappearance within a very short time, and does not form a stationary cavity. Many minute bubbles are left after the transition is over.

The same cavitation was recorded using the newly introduced ultra high-speed video camera with a max speed of 1,000,000 F/s. A number of frames picked out from the original video images are displayed in chronological order in Figs.6 and 7, which demonstrate the beginning and ending stages of the transitional cavitation, respectively, in more detail. The first several images in Fig.6 are enlarged in Fig.8, in order to see the emerging process of an incipient cavity more closely. In Fig.8, the second frame has caught the just-born cavity which occupies only a few pixels on CCD and is smaller than 20μm in length.

Side-view pictures of an incipient cavity shot by the same video camera are also displayed in Fig.9. Thanks to the mirror images of a cavity recorded by accident, it turns out that the cavity grows to elongate at some angle away from the surface. This interesting result seems to offer some hints for considering how a cavity is generated on a wall at the earliest stage of cavitation. Probably, the elongating cavity points out the
direction in which a tensile force near the separation point takes a maximum value, apparently at about 45 degrees from the tangent.

3.3 Cavitation starting at projected edge

Experimental records of incipient cavities emerging at the tip of the needle (Fig. 2 (b)) are demonstrated in Fig. 10. The cavity suddenly emerged at the point of separation again in this case. However, it didn’t vanish but stayed and repeated a process of growth, bubble discharge and shrinkage, which was much slower than that on the cylindrical surface.

Figure 11 shows another stationary cavities which also suddenly emerged at the entrance edge of the two dimensional long constriction (Fig. 2 (a)) and developed with an increase of fluid velocity. Micro bubbles were intermittently torn off from these stationary cavities, too. While flowing through the long constriction channel, they became too small to be recognized even by stroboscopic photography, but explosively expanded in the downstream turbulence, forming large cavitation bubbles.

4 LIGHT EMISSION AND ELECTRIFICATION

When cavitation in hydraulic oil flows turns vigorous, light emission is commonly perceived by the naked eye. Figure 12 shows an example of its record taken in cavitation on the cylindrical surface, using the video camera with high photosensitivity. When it was watched on the original video film, what looked like a gleam to the human eye turned out to be in reality an intermittent flash (http://keilab.mech.okayama-u.ac.jp/research/cavitation/cavitatione.html).

Electrification of oil was also measured together with light emission using an electrode and a photo-multiplier (Fig. 13). An example of the results is demonstrated in Fig. 14. The thick solid line and the dotted line show the output of the photo-multiplier and the current collected from the oil, respectively. The oil is transiently charged positive in synchronization with the emitted light.

Similar data obtained in vigorous cavitation on the needle are shown in Fig. 15. The currents collected from the needle and
oil have opposite signs and both of them synchronize well with the light emission.

The spectrum of emitted light was measured for a choking flow in the two-dimensional constriction. The result is shown in Fig.16 for reference. Most of the peaks in the spectrum gather around 400 nm, which explains why the observed light looked blue to the human eye. What kind of element corresponds to each prominent peak is yet to be analyzed.

Judging from the observations conducted so far, it is presumed that light emission in hydraulic oil cavitation is caused by electric discharge.
5 SPONTANEOUS VISUALIZATION OF SEPARATION STREAMLINE

As previously pointed out in Fig.4, the streamline separating from the wall was spontaneously visualized. In order to inspect this phenomenon, temperature distribution across the visualized streamline was measured downstream of the constriction, using the experimental setup illustrated in Fig.17. The profiles of temperature distribution thus obtained are plotted in Fig.18, where the ordinate and the abscissa represent the measuring position and the difference between the thermocouple output and the temperature at the upstream reference point, respectively. Obviously the temperature becomes considerably higher nearer the point where the visualized streamline runs, which means that heat is generated near the point of separation.

In order to make this conjecture more certain, wall temperatures around the point of separation were also measured with a different apparatus designed for that specific purpose; an acrylic cylinder with a thermo-couple embedded a little below its surface was made rotatable around the axis. The differences between the thermo-couple output and the reference temperature are plotted against the circumferential position in Fig.19. The temperature elevation peaks a little downstream from the narrowest section (0mm) of the channel, which probably corresponds to the area of flow separation. Moreover, it is as high as 10°C at the maximum, which indicates that substantial heat is generated near the point of separation.

If heat generation near the point of separation is real, what is its mechanism and what does it have to do with cavitation inception? Possible answers are sought next.

6 THEORETICAL CONSIDERATION ON HOW TENSILE FORCE AND HEAT ARE GENERATED AT POINT OF SEPARATION

Possibly, the clue to making clear the mechanism for heat and tensile force to be generated at the point of separation can be found in the analysis offered by L. D. Landau. According to Landau’s analysis, the velocities \( u(x, y) \) and \( v(x, y) \) in a flow near the separation line (Fig.20) are given for \( x < x_s \) as follows [5]:

\[
\begin{align*}
\frac{\partial u}{\partial x} & = \frac{1}{\rho} \left( -\frac{1}{2} \rho \frac{\partial \varepsilon}{\partial x} \right) \\
\frac{\partial v}{\partial x} & = \frac{1}{\rho} \left( -\frac{1}{2} \rho \frac{\partial \varepsilon}{\partial x} \right)
\end{align*}
\]
\[ u(x,y) = u_S(y) + A \frac{du_S(y)}{dy} \sqrt{x_S - x} \]

\[ v(x,y) = \frac{A u_S(y)}{2\sqrt{x_S - x}} \] \( (x < x_S) \) \( (1) \)

where \( A \) is a constant and \( u_S(y) \equiv u(x_S, y) \). Although it does not give the exact solution of a separating flow, Eq.(1) presumably represents the flow qualitatively. Consequently, the normal stresses \( \sigma_x \) and \( \sigma_y \) in \( x \)- and \( y \)-directions can be estimated by the following relations derived from Eq.(1):

\[ \sigma_x = -p + 2\mu \frac{\partial u}{\partial x} = -p - \frac{A}{2\sqrt{x_S - x}} \frac{du_S}{dy} \] \( (x < x_S) \) \( (2) \)

\[ \sigma_y = -p + 2\mu \frac{\partial v}{\partial y} = -p + \frac{A}{2\sqrt{x_S - x}} \frac{du_S}{dy} \]

Since the term \( \frac{A}{2\sqrt{x_S - x}} \frac{du_S}{dy} \) becomes infinity at \( x = x_S \), \( \sigma_x \) and \( \sigma_y \) can take large negative and positive values, respectively, for \( x \) close to and smaller than \( x_S \). Therefore Eq.(2) provides a theoretical basis for considering that within a very small area just upstream of the separation point, a large tensile stress is generated.

The mechanism of heat generation can be discussed on the basis of Eq.(1) as well. Fluid energy is dissipated in a flow by viscosity and is converted to heat. As is well known, the rate of dissipation per unit volume is given by

\[ \mu \left( \frac{\partial u \partial u}{\partial x \partial x} + 2 \frac{\partial u \partial v}{\partial x \partial y} + \frac{\partial v \partial v}{\partial y \partial y} \right) \] \( (3) \)

in which four different velocity gradients are included. When evaluated by Eq.(1), the gradient \( \partial v / \partial x \) expressed as

\[ \frac{\partial v}{\partial x} = \frac{A u_S(y)}{4\sqrt{x_S - x}} \] \( (4) \)

turns out to be by far the most dominant among the four for \( x \) close to \( x_S \). Accordingly, it is presumed that the gradient \( \partial v / \partial x \) plays a major role in heat generation within a small spot just upstream of the separation line. Generated heat is carried over by a flow separating away from the wall and raises the temperature along the streamline, resulting in its visualization.

In conclusion, it can be said that tensile force and heat generation are two indivisible phenomena inherent in the separation of flow.

7 CONCLUSIONS

The present authors advocate the new ideas about cavitation mechanism in hydraulic oil flows as follows:

(1) Incipient cavitation starts at a close vicinity of the point where the flow separates from a wall, in the form of an infinitesimal cavity suddenly emerging there.

(2) Tensile forces acting at the point can be the cause to create the incipient cavity.

(3) Considerable heat is generated in a narrow flow area around the point of flow separation, although how it affects cavitation inception is not clear.

(4) How tensile forces and heat are produced can be theoretically explained by the singularity of a flow near the point of separation, to which Landau has given a mathematical model. In that sense, the singularity of the separation point should be regarded as the primary cause of cavitation.

(5) Cavitation occurring on a solid wall accompanies electrification of oil and the wall with opposite signs. Explosive growth of cavities often results in light emission, probably caused by electrical discharge.

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REFERENCES


DISCUSSIONS

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I have read the article Cav03-OS-003 with very great interest. It gives the new convincing argument that separation can be the main reason of cavitation. The same point of view can be found in my report Cav03-GS-6-004, the details are presented in [14-16]. The main idea of [3, 13-16, 31, 32] is obtaining the axisymmetric and 2D shapes without separation, which can improve the cavitation characteristics as well. The axisymmetric bodies calculated in [3, 13-16, 31, 32] were tested in the wind tunnel of Kyiv Institute of Hydromechanics in the Reynolds number range from 90 000 till 300 000. The flows without separation were obtained for some types of shapes at the larger values of Reynolds number.

It would be very interesting to investigate the cavitation inception characteristics of such unseparated shapes in the water tunnel (unfortunately, there is no appropriate facilities in Ukraine). The principal and very important question could be solved by such tests: are there 3D and 2D shapes, which provide flows without cavitation at arbitrary values of cavitation number? If the answer will be positive, the flows in tubes (such as in the article Cav03-OS-003) could be calculated to prevent separation and cavitation.