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Metal Berthelot Tubes with Windows for Observing Cavitation under Static Negative Pressure

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***Abstract*—**Cavitation under static negative pressure is not revealed well. The Berthelot method to generate such negative pressure can be a means to study cavitation inception. In this study, metal Berthelot tubes built in observation windows are newly developed and are checked whether high static negative pressure is generated or not. Negative pressure in the tube with a pair of a corundum plate and an aluminum gasket increased with temperature cycles. The trend was similar to that as reported before.

***Keywords*—** Berthelot method, negative pressure, cavitation.

I. Introduction

WHEN pressure of a liquid is reduced, negative pressure can build up. Negative pressure is in metastable state thermodynamically [1]. Therefore, cavitation occurs, and pressure becomes almost zero. Cavitation causes serious damages to fluid machines and is useful to cleaning apparatus, and so on [2]. Therefore, there have been many studies about cavitation. However, cavitation which occurs under static negative pressure has not been cleared yet. If a technique to generate and measure static high negative pressure is established, it can be a means to study cavitation inception.

A method to generate such negative pressure is the Berthelot method using metal tube [3]. This method uses difference of thermal expansion between a liquid and a container, and it generate static negative pressures. In previous studies, by metal tubes, negative pressures for distilled water of ca. -18 MPa [4] and some organic liquids of ca. -20 MPa [5] could be attained.

Unfortunately, there have been no metal Berthelot tubes to observe cavitation directly. If such tubes are designed, detailed information about cavitation inception will be provided. Thus, some metal Berthelot tubes built in observation windows are examined whether high negative pressure is generated or not. Cavitation is viewed for a metal Berthelot tube with a plate of corundum crystal and an aluminum gasket.

II. Experimental procedure

Fig. 1 shows the Berthelot method with a pressure (*P*)-temperature (*T*) graph and a schematic diagram. As shown in (a) of the Fig. 1 (i), when the system composed of a sample liquid sealed in a tube is heated, the pressure of the sample increases because it cannot expand sufficiently for a lower isobaric expansion coefficient of the tube. Next, the system is cooled, and the pressure decreases to (b) of the figure. If cavitation nuclei, namely gases in crevices on the wall of the tube contacting with the sample [4], is pre-reduced, the pressure becomes negative as shown in (c) of the figure. When negative pressure is high, cavitation occurs, and the sample is in vapor-liquid co-existing state. By re-heating the system, the pressure increases gradually to (b) for dissolving a vapor phase to a liquid one and steeply from (b) to (a).

The *P-T* graph of the Fig. 1 (ii) shows a relation between pressures and temperatures. Each point in the graph corresponds to that in the Fig. 1 (i). At (c) of the graph, the pressure jumps up to the saturation vapor pressure of the temperature. At a period from (d) to (b), the saturation pressure increases gradually. At (b), a liquid phase starts to occupy the whole inner volume of the tube, and the pressure increases steeply to (a). A process of (abcdba) is called temperature cycle. A temperature of (b) where $P=0$ (0.1 MPa) was called T_0.

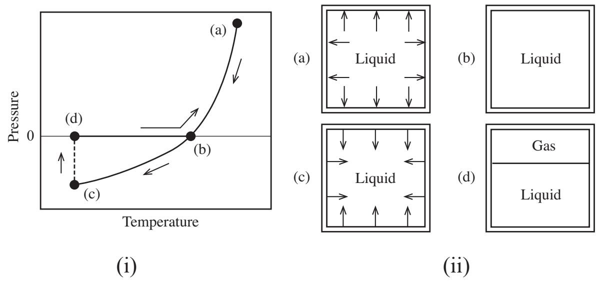

Fig. 1 Berthelot method: *P-T* graph (i) and liquid in tube (ii)

In the metal Berthelot tubes, a specimen liquid in a container was sealed by plastic deformation of a metal plug softer than the container. The plug was forced on a top edge of the container by fastening a flare nut until the plug was deformed plastically [5].

In this study, in order to build in an observation window to the tube, two kinds of materials were tested instead of the plug. They were transparent circular plates made of acrylic resin (PMMA) and corundum crystal (Al_2O_3), respectively. The acrylic plate was intended to be deformed plastically like the plug, while the corundum crystal itself was not deformed and deformed another material located between the crystal and the top of the container.

Fig. 2 shows observation tubes. The tube in Fig. 2 (a) consisted of a pressure transducer (Kyowa Elec. Inst. Co., PHL-A) having a specimen chamber in its upper part, an acrylic plate, a flare nut, and so on. The plate was circular and had a radius of ca.4 mm and a height of ca.4 mm. The chamber had a volume of ca. 40 mm^3. Cavitation in the tubes was able to be observed from their top views.

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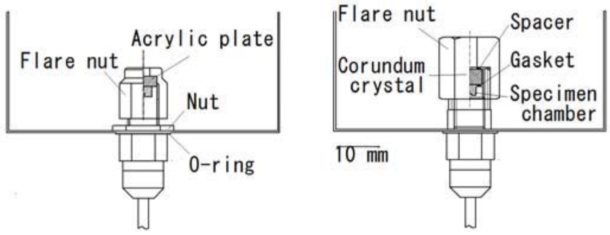

Fig. 2 Metal Berthelot tubes built in observation windows

The tube in Fig. 2 (b) consisted of more parts, namely a transducer, a gasket, a crystal plate, a spacer, a flare nut, a socket, and so on. Because the corundum plate cannot be deformed almost plastically, the material softer in Mohs hardness than both the plate and the top of the transducer was located among the both. It was deformed plastically by fastening the nut through a spacer. As such seal material, a sheet of polytetrafluoroethylene (PTFE) and metal plane gaskets made of copper, nickel, and aluminum, were examined. They had outer diameters of ca. 8 mm, inner diameters of ca. 5 mm, and thicknesses from ca. 0.1 mm) to ca. 1.0 mm.

In the tube of Fig. 2 (b), the liquid was sealed as follows. At first the socket was attached to the transducer, and a distilled water of ca. 60 °C was poured in the socket to its upper part. Then, a seal material, an observation window and a spacer were put in the socket sequentially. Finally, the nut was tightened, and the seal material was deformed plastically.

In order to confirm whether seal of liquids was performed properly or not, the tubes were put in a hot bath. The bath temperature was kept constant for a period with a thermostat, and a positive pressure signal of the transducer was recorded for the period. If the signal decreased within the period, authors judged that seal performance was not good. The bath temperature was ca. 54 °C initially, and was raised to ca. 69 °C by 3 °C finally. A holding time at each temperature was ca. 20 minutes.

A negative pressure generator is shown in Fig. 3. When the tube was soaked in a hot bath and a cool bath in turn, positive and negative pressures occurred in the baths, respectively. If a cavitation event happened in the cool bath, the tube was moved in the hot bath. Movement of the tube was controlled with a sequence controller, and temperature cycles were carried out automatically. Negative pressure was measured by repeating these temperature cycles. The tube was often held in air, causing cavitation to occur in air for adjusting experimental conditions.

After negative pressure was achieved relatively high with temperature cycles, cavitation events were observed using a microscope with a high-speed camera (Keyence VW9000).

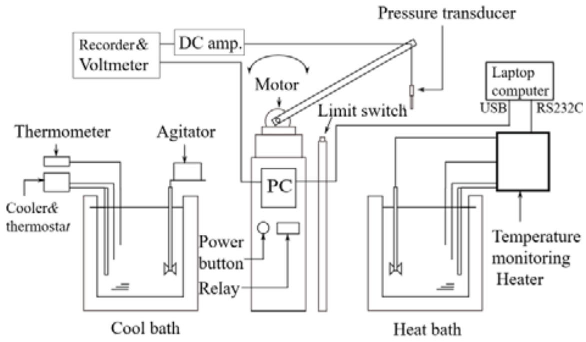

Fig. 3 Experimental apparatus

III. Results and Discussion

Relations between temperature cycles and the magnitude of negative pressure are shown in Fig. 4. The negative pressure for the acrylic plate and the corundum plates with the PTFE sheet and the aluminum gasket were able to be generated; the containers were sealed up. On the contrary, those for the corundum plates with the nickel and the copper gaskets were not able to be sealed up.

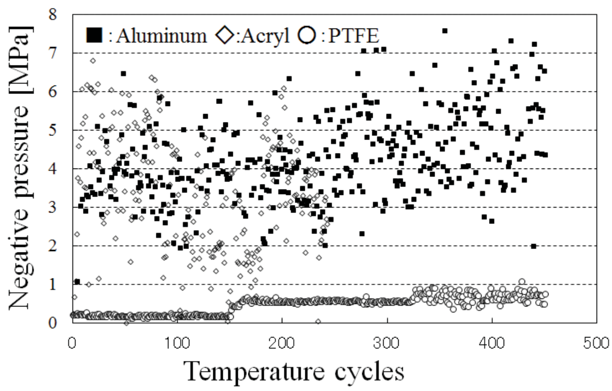

Fig. 4 Relation between negative pressure and temperature cycles for corundum plates of Al gasket and PTFE sheet, and PMMA plate

The negative pressure for the PTFE sheet was the lowest. As temperature cycles were repeated, corresponding positive pressure in the hot bath decreased. Therefore, the flare nut was often fastened.

The negative pressure for the acrylic plate, though it were scattered widely, increase to ca. 7.0 MPa within ca. 20 cycles, levelled off to ca.80 cycles, decreased to ca. 2.0 MPa to ca. 180 cycles, and increase to ca. 4.0 MPa with wide scatters. Positive pressure decreased as well as that for the PTFE sheet, and therefore, the nut was often fastened similarly.

Fig. 5 shows relations between positive pressures and holding times at constant temperatures for the acrylic plate and the corundum one. When the temperatures were lower than 63 °C, corresponding pressures for the both materials increased stepwise with an increase of temperatures. At temperatures higher than 66 °C, the pressures for the both materials indicated different trends. The pressures for the acrylic plate increased steeply initially and then decreased gradually, while those for

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the corundum one increased stepwise.

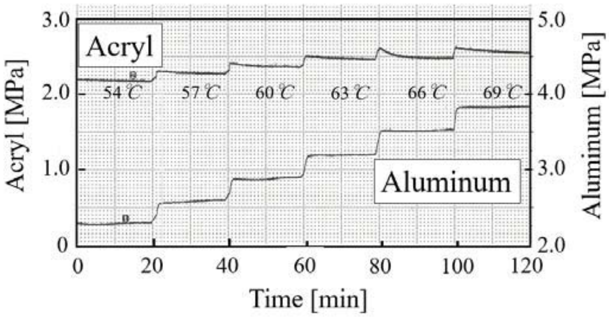


Fig. 5 Relation between positive pressures and holding times at constant temperatures for the acrylic plate and the corundum one

The acryl and the PTFE are classified as thermoplastic resin; the resin could be deformed easily when they are heated and are pressurized. In this experiment, the acrylic sheet and the PTFE plate were pressurized by fastening the nuts, and then underwent temperature cycles in temperature ranges from ca. 40 °C to ca. 70 °C. Therefore, they could be deformed plastically not only on sealing the water but also on repeating temperature cycles. Their deformations could be severe under positive pressures at high temperatures.

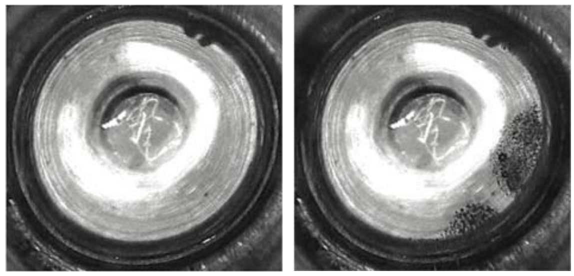
In the Berthelot method, pressures are generated on a basis of difference of thermal expansion coefficients between a liquid and a surrounding container. When the liquid sealed in the container is heated, positive pressures are generated because the liquid cannot expand sufficiently. The liquid forces an inner wall of the surrounding container outward. In this experiment, sealing materials of thermoplastic resins were used as parts of the containers. The materials could be deformed outward, and therefore, positive pressures could be decreased. This was confirmed by the decreasing trends in positive pressures at high temperatures of the acrylic plate in Fig. 5.

In Fig. 4, negative pressure for the aluminum gasket increased through two stages; an initial steep stage to ca. 6.0 MPa within ca. 100 cycles, and a subsequent stage to ca. 9.0 MPa. The two stage increasing trend was similar to those obtained for previous metal tubes without observation windows.

In previous studies of metal Berthelot tubes [3], negative pressure within initial temperature cycles was restricted by gaseous nuclei trapped within crevices on metal surfaces contacting with a specimen liquid. The nuclei were able to be removed by pre-pressurization treatments to metal surfaces. Initial negative pressures were not generated unless positive pressure was applied sufficiently

In this experiment, three different trends in Fig. 4 indicate that negative pressures depended on the sealing materials explicitly and on positive pressures implicitly. Thus, cavitation events seemed to be caused by gaseous nuclei within crevices on the materials' surfaces.

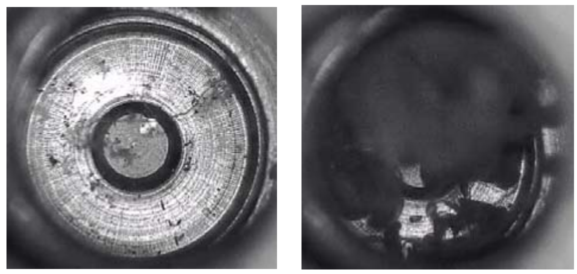
Cavitation for the corundum plate with the aluminum gasket was photographed with a microscope built in a high-speed camera. Photos are shown in Fig. 6. A large number of small bubbles existed in water as a result that cavitation occurred. Some photos were able to be obtained with temperature cycles.



(a) (b)

Fig. 6 Photos of water in the Berthelot tube built in the corundum plate with the Al gasket; (a) before cavitation, and (b) after cavitation

Fig. 7 shows photos for a water and methyl pyridine solution. Apparently, cavitation for the solution was different in aspect from that for water. More and smaller bubbles occurred.



(a) (b)

Fig. 7 Photos of a water and methyl pyridine solution in the Berthelot tube built in the corundum plate with the Al gasket; (a) before cavitation, and (b) after cavitation

Such photos were not obtained for the acrylic plate. It is known that the resin is harmed by organics [6]. Therefore, when the plate was soaked in the solution, it got opaque.

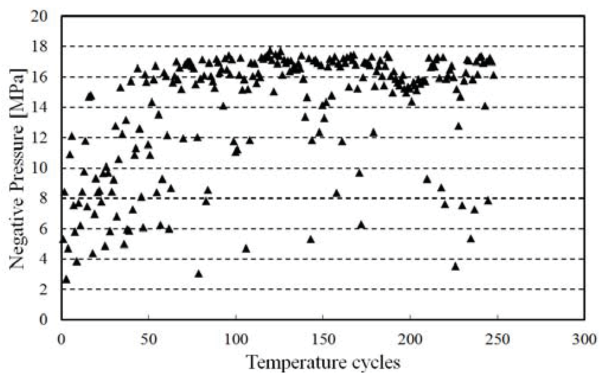


Fig. 8 Relation between negative pressure and temperature cycles for a water and methyl pyridine solution with corundum plates and Al gasket

Fig. 8 shows relations between temperature cycles and the magnitude of negative pressure. The negative pressure increased through two stages; an initial steep stage to ca. 15.0 MPa within ca. 50 cycles, and a subsequent stage to ca. 17.0 MPa. As well as the trend obtained for water, the two stage increasing trend was similar to those for previous metal tubes without observation windows.

A few photos were able to be also obtained for the acrylic plate, but the corundum plate was superior to the acrylic one because of repeated observations for liquids such as organics without restrictions of temperatures. In future, in order to investigate cavitation inception more exactly, change of liquid density with cavitation will be observable by applying the Schlieren method to the Berthelot tube built in the corundum plate with the aluminum gasket.

IV. Conclusions

In order to observe cavitation under negative pressure, metal Berthelot tubes built in observation windows were tested. Negative pressure for water in the tube including a corundum plate with an aluminum gasket increased with temperature cycles, and cavitation was able to be photographed without restrictions of temperatures.

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