Examination of Cavitation-Induced Surface Erosion Pitting of a Mechanical Heart Valve Using a Solenoid-Actuated Apparatus

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Several factors, including peak dp/dt of the ventricular pressure and maximum closing velocity of leaflet have been studied as indices of the cavitation threshold. In the present study, just before closing velocity of the leaflet has been studied as indices of the cavitation threshold, and cavitation erosion on the surface of a mechanical valve was examined by focusing on squeeze flow and the water hammer phenomenon during the closing period of the valve. A simple solenoid-actuated test device that can directly control the valve closing velocity was developed, and opening-closing tests of 3,000 and 40,000 cycles were performed at various closing velocities. There was a closing velocity threshold to occur erosion pitting of valve surface, and its value was about 0.4 m/s in this study. Cavitation-induced erosion pits were observed only in regions where squeeze flow occurred immediately before valve closure. On the other hand, the number of the pits was found to be closely related to an area of water hammer-induced pressure wave below the critical pressure defined by water vapor pressure. Therefore, it was concluded that cavitation is initiated and augmented by the two pressure drops due to squeeze flow and water hammer phenomenon, respectively.

Key Words: Mechanical Heart Valve, Cavitation, Surface Erosion Pit, Closing Velocity, Squeeze Flow

Nomenclature

b : Gap between a disk and stop (m)
L : Half the length of the stop (m)
p : Pressure (Pa)
u : Squeeze flow velocity (m/s)
v : Closing velocity of the disk (m/s)
ρ : Density of water (kg/m^3)

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1. Introduction

Since the discovery in the 1980s of erosion pit-induced fractures in implanted mechanical heart valves (Klepetko, 1989), cavitation on the surface of mechanical heart valves has been studied as a possible cause of pitting. Cavitation is the rapid formation and collapse of vapor-filled cavities when a fluid is exposed to rapid changes in pressure below liquid vapor pressure. When cavitation occurs near a material surface of a mechanical heart valve (MHV), this rapid collapse may cause the generation of a high-speed microjet, resulting in the formation of erosion pits on the surface of the MHV. Therefore, it is very important to investigate the mechanisms underlying cavitation and pitting in a MHV.

Recently, several factors, such as the peak dp/dt of ventricular pressure and the closing velocity of a disk, have been studied as indices of the cavitation threshold. Lee and Shu et al. examined the cavitation threshold of dp/dt for different commercially available MHVs using stroboscopic photography (Lee, 1994, 1996; Shu, 1994). Richard et al. examined the cavitation thresholds of dp/dt in three different MHVs and observed the generation of erosion and pitting (Richard, 1994). Graf et al. measured the critical disk closing velocity inducing cavitation, mainly focusing on the pressure drop due to the deceleration of a disk (Graf, 1994). As a disk comes into contact with a stop, a region of low pressure can be formed by squeeze flow, and hence much interest has been shown in closing velocity, which is directly related to squeeze flow (Lee, 1994; Lee, 1996; Makhijani, 1994). Wu et al. reported an optical apparatus for measuring the instantaneous closing velocity of Medtronic Hall valves during the final 3-degree period before closure as a cavitation index (Wu, 1994). From the results of the above mentioned studies, squeeze flow from a gap between a disk and a stop has been recognized as an important factor for the generation of cavitation. The results of our previous study (Lee, 2000) also suggested that the closing velocity of a disk immediately before closure has significant effects on pitting erosion.

All of the studies mentioned above were conducted using a pulsatile pressure-driven device such as a mock circulatory loop or a pressurized chamber. In the present study, a simple solenoid-actuated device that can directly control the closing velocity was developed, and the threshold of closing velocity was examined by observing the formation of cavitation pits after opening-closing tests of 3,000 and 40,000 cycles. The mechanism by which cavitation is generated was also investigated from measured pressure waveforms and microscopic observations of the pits.

2. Materials and Methods

2.1 Experimental system

As shown in Fig. 1, the experimental system

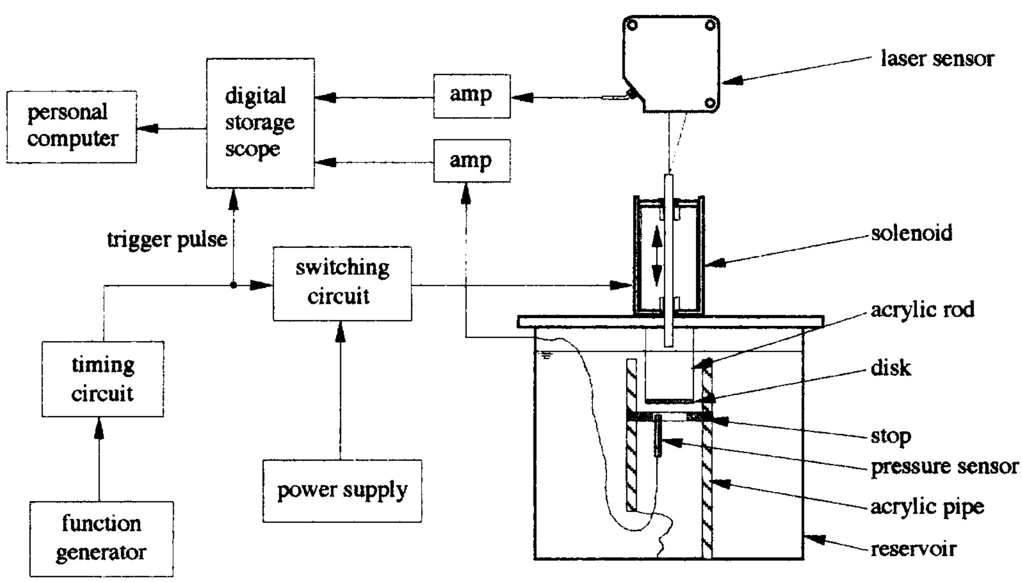


Fig. 1 Schematic diagram of the solenoid-actuated experimental system. The disk was directly actuated by the solenoid, and movement of the disk was measured using a laser displacement sensor

was a simple in construction ; there were no circulating circuits or pressurized chambers conventionally used in a valve testing system. A disk was connected to a solenoid (SS-093K-701, Shinmei Electric) through a rod and directly actuated by this solenoid. The disk and the stop were made of duralumin and stainless steel, the surface polished to observe the surface pitting, and their dimensions are shown in Fig. 2. The stop was mounted to the housing, made of acrylic pipe, and the housing was fixed to the bottom of a reservoir with dimensions of 15, 15 and 13 cm in width, length and height, respectively. The reservoir was filled with tap water, and experiments were performed at room temperature.

The opening and closing actions of the disk were controlled by the back and forth motion of the solenoid. Changing the power supply voltage to the solenoid controlled its closing velocity. To measure the closing velocity, we used a laser displacement sensor (LB-045, Keyence Ltd.; resolution, 4 μm), which was placed on the upper side of the solenoid and measured the movement of the disk during a closing period. Displacement signals from the sensor were stored in a digital storage scope (HP54510B, Hewlett-Packard) at a sampling frequency of 100 kHz and transferred to a personal computer via GPIB. A signal for triggering the digital storage scope was obtained from the timing circuit.

To measure the change in pressure near the disk surface during a closing period, a piezoelectric pressure transducer (105B02, PCB Piezotronics Inc.) with a tip diameter of 2.5 mm and a natural frequency of 250 kHz was used. The tip of the pressure transducer was placed approximately 1 mm from the surface of the closed disk. Pressure signals were also recorded by the digital storage scope at a sampling frequency of 1 MHz and transferred to the computer.

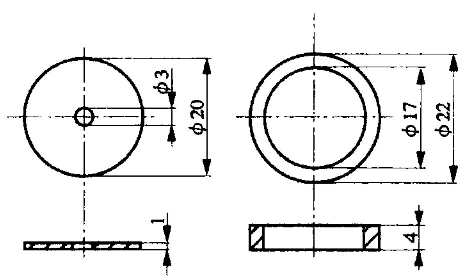


Fig. 2 Dimensions of the disk and the stop, which were made of duralumin and stainless steel, respectively

2.2 Examination of surface pit erosion

The experimental system was operated at 60 cycles per minute. The surface pits were investigated after opening-closing tests of 3,000 and 40,000 cycles had been performed at five different closing velocities. Three to five disks were used in each test. In order to quantitatively evaluate the surface erosion of the disk, pits were counted in an area of 1.5 mm squares at four different locations on the surface of each disk. After each test, pictures of the disk surface were taken using a reflected light microscope (SMZ-10, Nikon), and pits with a diameter of more than 30 μm were counted.

3. Results

3.1 Closing velocity of a disk

An example of disk movement during a closing period is shown in Fig. 3. The closing distance of

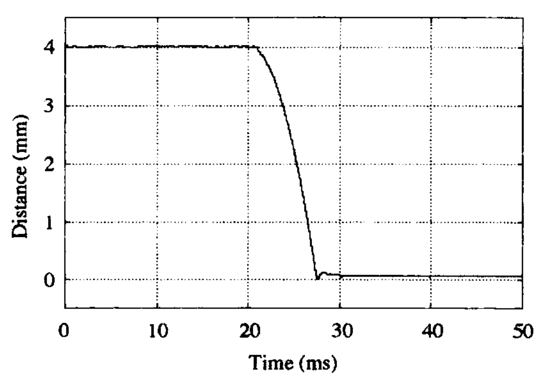


Fig. 3 A trace of disk movement when the solenoid was driven by 20 volts. The distance between the disk and the stop was set to 4 mm. The disk was accelerated and made contact with the stop at an almost constant speed and then rebounded. The mean velocity of the disk during the last 0. 3-mm interval before valve closure was defined as disk closing velocity

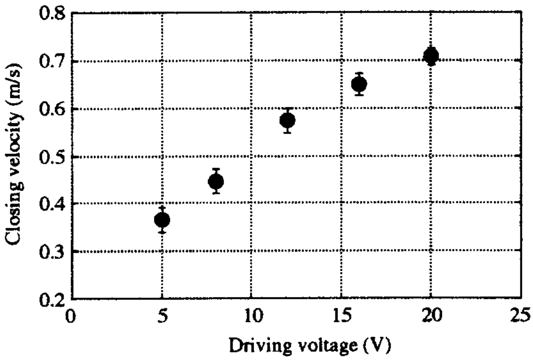


Fig. 4 Relationship between closing velocity of a disk and driving voltage of the solenoid

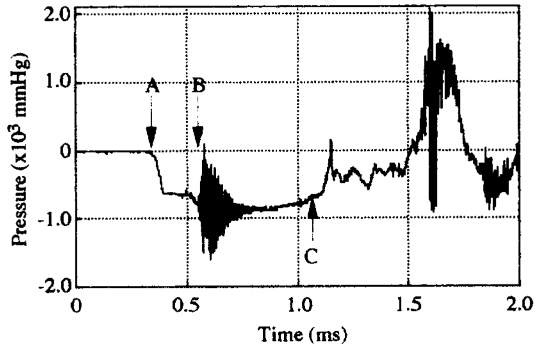


Fig. 5 A pressure waveform measured beside the stop at a closing velocity of 0.71 m/s. The section A～B indicates the pressure drop due to squeeze flow. The disk makes contact with the stop at point B, resulting in generation of impact sound. The pressure drop of section B～C is due to the water hammer phenomenon caused by the sudden stopping and rebound of the disk. Point C denotes the level of critical pressure defined by water vapor pressure

the disk was set on 4 mm. As shown by the slope of the curve, the speed of the disk increased with time after the solenoid had been actuated and that of the disk was reduced before valve closure. In this study, the mean velocity of the disk during the last 0.3-mm interval before valve closure was defined as closing velocity of the disk. The closing velocities of a disk at various driving voltages of the solenoid are shown in Fig. 4. The driving voltage of the solenoid varied from 5 to 20 volts, and the corresponding closing velocities varied from 0.37 to 0.71 m/s. The reproducibility of velocity at each driving voltage was good, as indicated by the error bars that were obtained from twenty measurements.

3.2 Pressure waveform

An example of the pressure waveforms measured near the disk surface during a closing period is shown in Fig. 5. Point B in Fig. 5 indicates the moment that the disk made contact with the stop, resulting in the generation of impact sound. Negative pressure due to squeeze flow was generated and was almost constant for about 0.1～0.2 ms immediately before the contact (section A～B in the Fig. 5). Then the negative pressure due to a water hammer phenomenon (flow deceleration induced by the disk suddenly stopping) gradually increased and decreased for about 0.5 ms even after the valve had closed. Thus, the pressure drops due to squeeze flow and due to the water hammer phenomenon were fairly well separated.

Pressure waveforms measured at the various closing velocities are shown in Fig. 6. The negative pressure due to squeeze flow (closed circles) gradually increased with increase in closing velocity of the disk but was not strongly dependent on the closing velocity. The measured pressure drop did not reach the critical pressure (−736 mmHg at 25℃) that is determined by saturated water vapor pressure, because the pressure drop was measured at 1 mm from the disk surface. Therefore, the actual pressure at the surface was likely have decreased more than the measured pressure as is discussed in detail in a later section. Compared to the pressure drop due to squeeze flow, pressure drop due to the water hammer effect should not be significantly dependent on the distance from the disk surface because the pressure drop is determined by mass of fluid column below the disk and deceleration of water : the 1 mm separation from the disk surface to the sensor tip was much smaller than the length of the water column. Therefore, we concluded that the changes in pressure generated by the water hammer effect were correctly measured. The pressure drops were greater than the critical

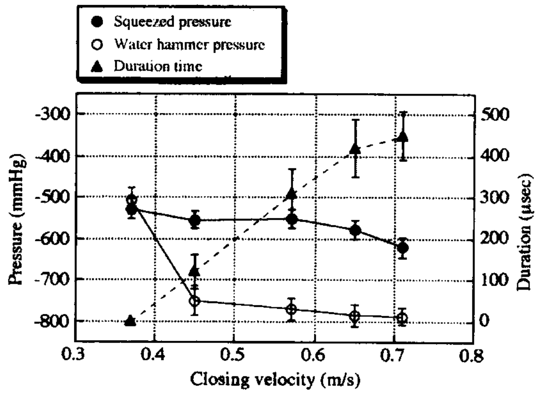
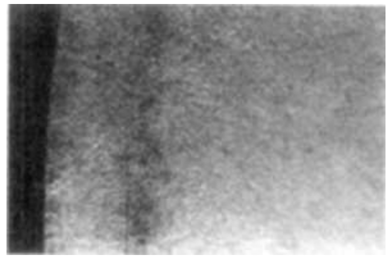


Fig. 6 Negative pressure drops due to squeeze flow (closed circles) and water hammer phenomenon (open circles), and negative pressure duration (triangles) below the critical pressure, at various closing velocities of disks. Pressure drops due to the water hammer phenomenon were greater than the critical pressure except for at a disk closing velocity of 0.37 m/s. The duration below the critical pressure increased with increase in disk closing velocity

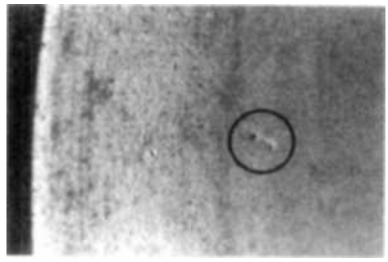
pressure except for that at the closing velocity of 0.37 m/s. In accordance with the increased closing velocity of the disk, not only the magnitude of negative pressure but also the duration of negative pressure below the critical pressure (section B~C) significantly increased.

3.3 Surface erosion pits

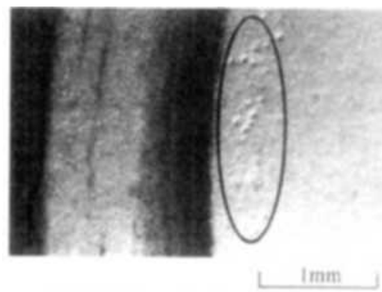
After tests of 3,000 opening-closing cycles, erosion pits were observed on the surface of a disk when the disk had been actuated at closing velocities faster than 0.45 m/s (Figs. 7(b) ~ (c)). No pits were observed at 0.37 m/s. In the photographs, the dots inside the circle are erosion pits made by cavitation bubble. No pits were observed even after 40,000 cycles, when the disk had been actuated at 0.37 m/s. Thus, there was a threshold velocity inducing erosion pits around 0.4 m/s. Photographs of the surface of the disk after 40,000 opening-closing cycles with closing velocities above this threshold are shown in Fig. 8. An enlarged photograph of a pit is also given, in Fig. 9, with a cross-sectional profile that was



(a) closing velocity : 0.37 m/s



(b) closing velocity : 0.45 m/s

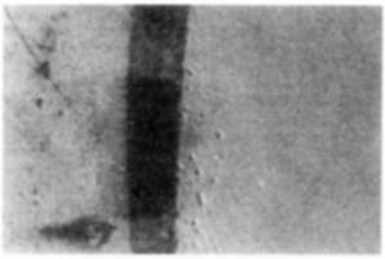


(c) closing velocity : 0.57 m/s

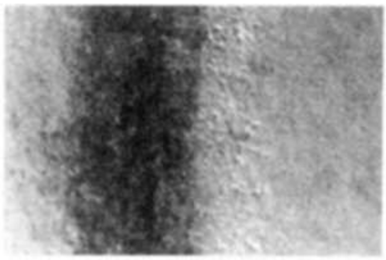
Fig. 7 Photographs of a disk surface near the edge of contact with the stop after an opening-closing test of 3,000 cycles. No pits were observed at a closing velocity of 0.37 m/s (a). In the case of closing velocities of more than 0.45 m/s, pitting occurred as indicated by the circles. Arch-shaped black portions are areas of contact with the stop

measured using a microscope profilometer (VF-7510, Keyence). The black portion on the surface of the valves shown in Fig. 8 is the area of contact with the stop. The area in which erosion pits were generated was restricted to near the inside edge of contact with the stop. In the case of closing velocities of 0.45, 0.57, 0.65 and 0.71 m/s, erosion pits were found in ranges of 0.3, 0.36, 0.5 and 0.78 mm, respectively, far from the edge of the stop.

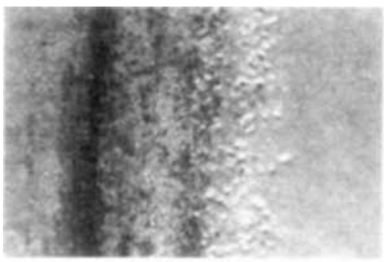
The number of pits with diameters of more than



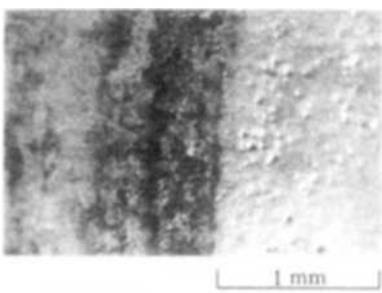
(a) closing velocity : 0.45 m/s



(b) closing velocity : 0.57 m/s



(c) closing velocity : 0.65 m/s



(d) closing velocity : 0.71 m/s

Fig. 8 Photographs of a disk surface near the edge of contact with the stop after an opening-closing test of 40,000 cycles at disk closing velocities of more than 0.45 m/s. Arch-shaped black portions are areas of contact with the stop

30 μm that were produced at different closing velocities is shown in Fig. 10. After both 3,000 and 40,000 opening-closing cycles, the number of pits exponentially increased with an increase in the closing velocity of the disk.

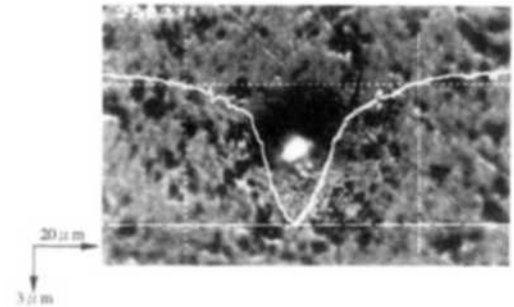


Fig. 9 Enlarged microscopic image of a pit. The curve shows the cross-sectional profile of the pit. A scale of 3 μm in depth is indicated by the vertical arrow. The pit diameter and depth were 62 and 8 μm, respectively, and the area surrounding the pit was also deformed

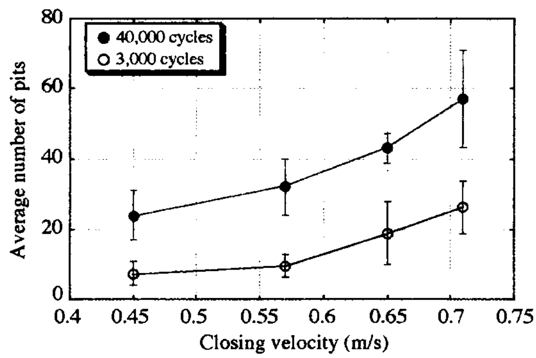


Fig. 10 Average number of pits with a diameter of more than 30 μm plotted against disk closing velocities after opening-closing tests of 3,000 cycles (open circles) and those of 40, 000 cycles (closed circles). Pits on the disk surface were counted in an area of 1.5 mm squares. Counts at four different locations of 3～5 disks, using in each test, were averaged

4. Discussion

As shown in Fig. 5, the pressure drops due to squeeze flow and due to the water hammer phenomenon were fairly well separated. However, the pressure drop due to squeeze flow did not reach the critical pressure (Fig. 6). As described in the section on results of pressure waveform, this is because the tip of the pressure sensor was placed 1 mm from the surface of a closed disk. Jet flow squeezed from a narrow gap is restricted to

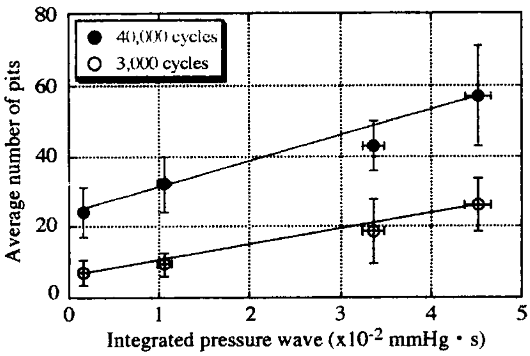


Fig. 11 Average number of pits with a diameter of more than 30 μm plotted against integrated pressure wave below critical pressure. The number of pits increased with increase in magnitude and duration of pressure drop and was proportional to the area of the pressure wave below critical pressure

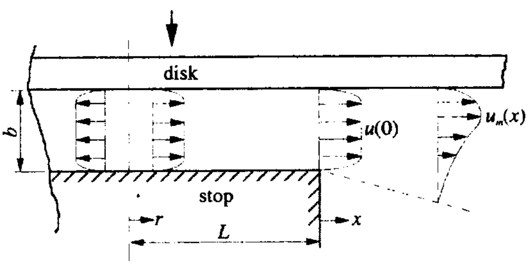


Fig. 12 A model of jet flow squeeze from a narrow gap between a disk and a stop. b : gap ; L : half the length of the stop ; $u(0)$: uniform velocity at $x=0$; $u_m(x)$: peak velocity at x

an area near the disk surface, and flow velocity decreases rapidly with increase in the distance from the disk surface (Fig. 12). Therefore, the actual pressure drop induced by $u_m(x)$ near the disk surface was likely to have been much greater than the pressure drop measured, as estimated below. Where $u_m(x)$ is maximum velocity at disrance x.

Assuming a uniform flow from a gap, we obtain the following simple equation with respect to squeeze flow velocity u :

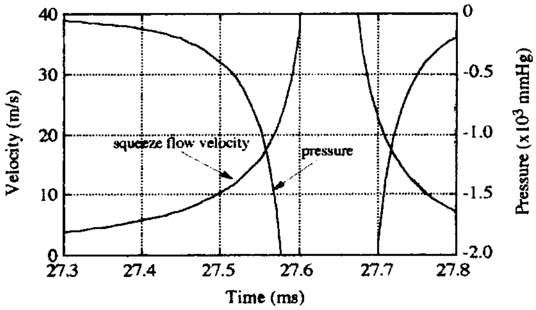
$$u(r)=\frac{r}{2b}v=\frac{r}{2b}\frac{db}{dt} \quad (0<r<L),$$
$$u(0)=\frac{L}{2b}\frac{db}{dt} \tag{1}$$

where b is the gap between a disk and stop, L is half the length of the stop ($2L=1.5\times10^{-3}$ m), and v is the closing velocity of the disk. From the Bernoulli equation, the pressure drop due to squeeze flow can be written as follows :

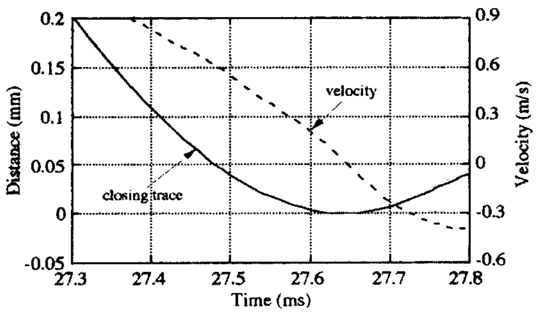
$$p=-\frac{1}{2}\rho u^2=-\frac{1}{2}\rho\left(\frac{r}{2b}\frac{db}{dt}\right)^2 \tag{2}$$

where ρ is the density of water. When a flow velocity u is faster than 14 m/s ($u=(2p/\rho)^{1/2}=$ 14 m/s), the pressure falls to the critical pressure. This flow velocity is widely used in the field of cavitation engineering as a critical fluid velocity at which cavitation bubbles may be generated. In the present study, we measured the movement of disks. This enabled us to obtain the instantaneous velocity of disks by differentiating their movement traces. An example of the instantaneous velocity around the moment of contact is shown in Fig. 13. Immediately before the contact, the disk did not approach the stop at a constant speed but at a decelerating speed, probably due to acceleration of squeeze flow and/or viscosity of water as it neared the contact, then rebounded. Substituting the instantaneous gap and velocity experimentally obtained into eq. (2), we obtained pressure drop as shown in Fig. 13(b). Curves of other closing velocities were also examined in the same manner.

The pressure rapidly fell to the critical pressure at 0.1～0.2 ms before contact (Fig. 13(b)). This estimated duration of pressure drop due to squeeze flow agrees well with the experimental results (section A～B in Fig. 5). The gaps in which critical squeeze flow was attained were read from the movement traces and were 15, 16, 17, 20 and 22 μm in the case of mean closing velocities of 0.37, 0.45, 0.57, 0.65 and 0.71 m/s, respectively. In spite of the decreasing velocity of a closing disk, it was estimated that the pressure can easily drop to the critical pressure at gaps of a few tens of micrometers and that the pressure drop is accelerated as the gap approaches complete closure. However, a maximum pressure drop at the moment of contact cannot be obtained from equation 1 because the equation is divergent when $b=0$. As for the behavior of a valve at contact,



(a) closing trace and velociy just before closure



(b) closing trace and theoretical pressure drop

Fig. 13 Calculated dynamic behavior around the moment of contact. Instantaneous closing velocity of a disk (a), squeeze flow velocity (b) and pressure drop (b) were calculated from the measured movement (a) of the closing disk using eqs. 1 and 2

Makhijani et al. reported, based on results of numerical analyses, that a valve does not completely close but rebounds with a gap of several μm even at the moment of "contact" (Makhijani, 1994). When there is a small gap, the pressure drop theoretically estimated by Eq. (1) is limited to a certain finite value. Although the exact magnitude of pressure drop was not able to be obtained in this study, it was concluded that the pressure drops sufficiently below the critical pressure, resulting in formation of bubbles and cavitation.

Graf et al. has reported that the closing velocity of the commercial MHVs was about 1.5~2.0 m/s as cavitation threshold (Graf, 1994). In this study, there was a closing velocity threshold to occur erosion pitting of valve surface, and its value was about 0.4 m/s. This difference value of critical closing velocity contributed to differ from the geometrical shape of leaflet.

Erosion pits formed only in a region close to the inside edge of the stop, and the area in which pits were observed increased with increase in closing velocity. These results also suggest that cavitation is induced by squeeze flow. If cavitation were induced only by the water hammer phenomenon, erosion pits would be observed over the whole surface of a disk. However, pit formation was restricted to an area beside the edge. Therefore, squeeze flow is a very important factor for initiating cavitation. On the other hand, the pressure drop caused by the water hammer phenomenon is also thought to have an important effect on cavitation because the integrated pressure was correlated well with the number of pits (Fig. 11). This speculation is also supported by the fact that no pits were observed when the pressure drop due to the water hammer phenomenon did not reach the critical pressure as shown in Figs. 6. As shown in Fig. 6, not only the magnitude of negative pressure but also the duration below the critical pressure increased with increase in closing velocity. Therefore, we hypothesize that an integrated pressure wave area below the critical pressure is significantly related to the number of pits. Figure 11 shows results plotted against the integrated pressure wave area. An approximately linear relationship was obtained.

Based on the above mentioned results and their interpretations, we propose the following possible mechanism by which cavitation is generated in a mechanical heart valve.

(1) When pressure drops below the critical pressure due to squeeze flow just before the closure of a disk, bubbles are formed (section A~B in Fig. 5).

(2) If negative pressure below the critical pressure is sustained by the water hammer phenomenon, the growth of bubbles occurs (section B~C in Fig. 5).

(3) When the bubbles are exposed to positive pressure, the bubbles suddenly collapse, and micro-jets are generated. These micro-jets may cause the pits on the surface of the disk.

As shown in Fig. 10, the number of pits was not proportional to the number of opening-closing cycles. Even when the difference between opening-closing cycles was more than 10 fold, the difference in the number of pits formed was only two to three fold. Furthermore, the results of additional evaluation of surface erosion showed that no pits of more than 60 μm in diameter were formed after the 3,000 cycles test, whereas many pits larger than this size were formed after the 40,000 cycles test. These results suggest that overlapped multiple pitting occurred at the same site and that there is a possibility that deeper and wider erosion pits are formed in the case of long-term exposure to cavitation.

As discussion above, both squeeze flow and water hammer phenomenon have significant effects on the formation of pits in MHVs. The closing velocity of disk closely related to these two factors, and hence the closing velocity is one of the most important parameter for determining cavitation threshold. Despite limited applicability to commercially available MHVs, the solenoid-actuated apparatus developed in this study can directly control the closing velocity and is a useful experimental system for collecting basic data for improvement of an MHV design so as to suppress the occurrence of cavitation.

5. Conclusion

Surface erosion pitting of a mechanical heart valve was examined using a simple solenoid-actuated apparatus that can directly control the closing velocity of a disk. Pit generation due to cavitation was restricted to an area on the disk surface beside the edge of the stop where squeeze flow occurred, and pits were observed. These results demonstrate that both squeeze flow and water hammer phenomenon are essential factors for formation of erosion pits in a mechanical heart valve. The closing velocity of a disk, which is closely related to these two factors, is one of the most important parameters for determining a cavitation or pitting threshold. It was also demonstrated that the number of pits is proportional to the area of the pressure wave below the critical pressure. Because experimental system we used was a simple, there was no circulation of fluid, so that our results may differ with that of circulation system. In future, we have to perform with commercial mechanical heart valve in circulation system.

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