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Simultaneous shadowgraph imaging and acceleration pulse measurement of cavitating jet

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ABSTRACT

The variations of cloud structure and erosion characteristics of a cavitating jet are experimentally studied by optical and SEM microscope observations, measurement of erosion characteristics and simultaneous shadowgraph imaging combined with the acceleration pulse measurement. The time difference image analysis of the shadowgraphs allows the detection of the near-wall collapsed bubbles in the periodic development of the cavitating jet, while the simultaneous acceleration pulse measurement indicates the generation of acceleration pulses at the same instant of bubble collapse near specimen surface. These results indicate that the generation of acceleration pulses are highly correlated with the collapsed bubbles behind the cloud in the shrinking motion, which triggers the cavitation bubble collapse and leads to the erosion damage on the specimen. It is found from the image analysis that the erosion distributions on the test specimen are well reproduced in the time-difference images of the shadowgraphs, which indicates the sudden intensity growth near the wall due to the cavitation collapse. This result suggests that the collapse of the cavitation bubbles near the specimen surface is correlated with the erosion distribution on the specimen surface in the cavitating jet.

1. Introduction

Cavitating jet is a submerged water-jet issuing into a still water environment, which is associated with the formation of cavitation bubbles in the shear layer of the jet. When the cavitation bubbles collapse in the high pressure region downstream of the cavitating jet, the pressure pulses are generated from the collapsed cavitation bubbles and trigger the erosion damage on the metal materials placed in the cavitating jet. Due to such highly erosive nature of the cavitating jet, it has been widely applied to the engineering field for fabrication, cutting and peening of metal materials [1], while the detailed mechanism of erosion is still not clear.

The erosive nature of the cavitating jet is known to be improved by the introduction of converging and diverging nozzle, which has a certain length of straight orifice section between the converging and diverging section of the nozzle [2–4]. The role of this nozzle is to generate the periodic motion in the cavitating jet and magnify the number of cavitation bubbles in the jet. As the nozzle geometry is closely related to the aggressiveness of the cavitation erosion, the optimum design configuration of the nozzle has been studied for generating the highly erosive cavitating jet [5].

The shadowgraph imaging combined with the high-speed observations of the flow through the converging and diverging nozzle [6,7] is an effective visualization technique that allows the study of unsteady cavitation behavior near the entrance of the orifice section in the converging and diverging nozzle. The formation of periodic cavitation cloud in the entrance of the orifice section downstream of the converging nozzle is an important phenomenon related to the erosion characteristics of the cavitating jet. The mechanism of periodic growth of the cavitation cloud is known to be due to the occurrence of reentrant jet in the development of the cavitation cloud [8–10]. When the cavitation cloud develops along the shear layer from the orifice section of the nozzle, the reentrant jet starts against the flow through the orifice, which results in the pinching off behavior of the cavity and is shed from the entrance of the orifice section. As the cloud is shed a new cavitation cloud forms at the entrance of the orifice and begins to grow along the shear layer from the entrance, which results in the periodic formation of the cavitation cloud downstream of the nozzle. The cavitation cloud eventually disappears in the relatively high pressure region downstream of the diverging section of the nozzle and the acceleration pulses are generated to damage the target metal materials in the cavitating jet [9,10]. Thus, the role of the cavitation nozzle is to activate the erosion by enhancing the periodic motion of the cavitation cloud. In recent years, the periodic motion of flow has been analyzed statistically using the

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proper orthogonal decomposition (POD) [11–14]. The application of POD to the cavitating jet allows the reproduction of periodic structure of the cavitating jet reconstructed from the lower POD modes [15], which indicates the presence of growth, shrinking, separation and shedding of the cavitation cloud.

The impact force due to the impingement of the cavitating jet has been measured by piezoelectric sensors, such as polyvinylidene fluoride (PVDF) film [16,17], piezoelectric ceramics [18] and piezoelectric acceleration sensor [19], which have higher frequency response than that of the cavitation event having a few tens of kHz [19]. These experimental results in literature show that the impact forces due to the cavitation collapse measured by these sensors are closely related to the erosion characteristics, which have been studied experimentally in literature [20–24]. However, it is still not clear about the relation between the behavior of the cavitation cloud and the erosion characteristics of the metal materials.

The relationship between the cavitation structures and the erosion characteristics is an important topic of interests for predicting the erosion rate of metal materials [25–32]. For this purpose, the cavitation structures are observed by a high-speed camera on the suction side of the hydrofoil in a cavitation tunnel, while the simultaneous observation of the pit formation on the surface is made by a thin aluminum-film attached to the hydrofoil [30,31]. The experimental result suggests that the process of the pit formation is triggered by the cavitation bubble collapse, which might cause an acceleration pulse in the fluid and triggers the cavitation erosion on the wall surface. This might result in the micro jet impact damage on the wall surface. Furthermore, the simultaneous observation of cavitation structures and the number of pits was carried out and the cavitation structure responsible for the erosion is found to be due to the cavitation cloud of irregular shape on the hydrofoil surface [30,31], while the relationship between them has not been studied in the cavitating jet, which is a topic of interest in this research.

The purpose of this paper is to study the erosion mechanism of the cavitating jet by simultaneous shadowgraph imaging and acceleration pulse measurement. The collapsed cavitation bubbles are observed by the shadowgraph imaging combined with the time-difference image analysis and the results are compared with the simultaneous acceleration pulse measurement and erosion distributions on the metal materials. Furthermore, the distribution of image intensity variation, the erosion rate on the metal material and the optical and SEM microscope observations are carried out to understand the relationship between the cavitation cloud structure and the erosion characteristics on the wall.

2. Experimental method and procedure

2.1. Experimental setup for cavitating jet

The experiments were carried out using an enclosure of square horizontal cross-sectional area of 400 mm × 400 mm having a height of 400 mm, which is illustrated in Fig. 1(a). Note that the enclosure is made of acrylic material for flow visualization purpose. The cavitating jet of water issuing from a nozzle is injected into a still water environment. The working fluid of distilled water is kept at temperature 20 °C. The nozzle used in the present experiment for cavitating jet is shown in Fig. 1(b), which is a converging and diverging nozzle designed in reference to the study of cavitating jet erosion by Soyama [5]. It consists of a converging and diverging sections separated by an orifice section of 2.4 mm thick with 0.8 mm in diameter. The nozzle is located at 50 mm deep from the water surface, so that the cavitation coefficient $\sigma\,(=(p-p_v)/\rho U^2)=0.012$ (p: pressure, p_v: vapor pressure, U: velocity at nozzle, ρ: density of water). Note that the nozzle is connected to a plunger pump through a filter to eliminate the dust in working fluid water. Although the maximum operating pressure of the plunger pump is 13 MPa, most of the experiments are carried out at 8 MPa. The mean velocity at the nozzle exit is found to be 100 m/s, which is evaluated from the discharge coefficient of the nozzle 0.8 and the volume flow rate of water.

2.2. Erosion characteristics

The measurement of erosion rate on the specimen surface was carried out using a circular Aluminum plate (A1070) of 40 mm diameter with 8 mm thick, which is placed normal to the jet axis for various distances from the nozzle $y_s=10$–40 mm. The erosion experiment was carried out at the nozzle pressure 8 MPa for every 10 min of duration time for observation and the total erosion weight was measured using the high precision weight meter having a resolution of 0.1 mg. Then, the non-dimensional erosion rate V_m was evaluated from the following equation [33];

$$V_m=\frac{dE_v}{Q\,dt} \tag{1}$$

where E_v is an erosion volume in a unit time t and Q is a volume flow rate of the cavitating jet. The non-dimensional erosion rate V_m is directly evaluated from the gradient of the erosion volume E_v versus the flow volume Qt of the cavitating jet. It should be mentioned that the non-dimensional erosion rate with respect to flow rate Qt is derived from the result of liquid droplet impingement erosion [34].

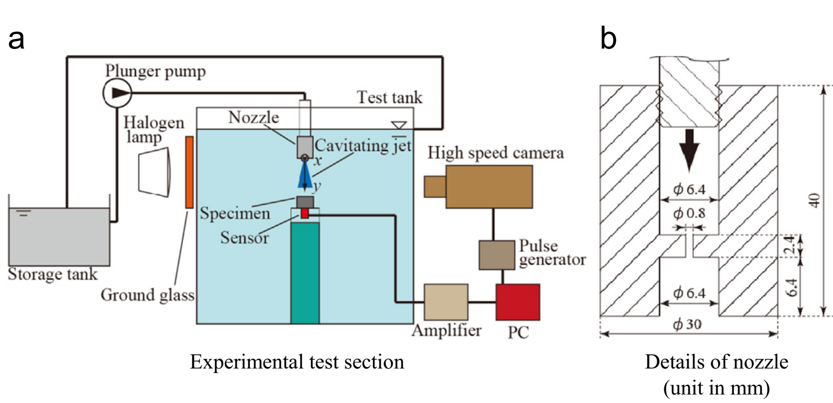

Fig. 1. Experimental apparatus.