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Effect of sediment size on damage caused by cavitation erosion and abrasive wear in sediment-water mixture

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ABSTRACT

Damage caused by cavitation erosion and abrasive wear is a significant problem for hydraulic machinery in rivers with high concentrations of sediment. In this study, experiments are performed using a vibratory apparatus and a custom-made particle-moving device. The specimens are ASTM 1045 carbon steel, and sediment particles with mean diameters of 0.026–0.531 mm are mixed in water at concentrations of 25 kg/m^3, 50 kg/m^3, and 85 kg/m^3. Experimental results demonstrate that damage is indeed exacerbated with increasing sediment sizes. However, when the size of sediment particles is smaller than a critical number (D_c), the damage caused by the sediment-water mixture is slightly less than the cavitation damage caused by sediment-free water; furthermore, for this small sediment, the damage decreases as the concentration increases. The critical size for the cases in this study is approximately 0.035–0.048 mm. The viscosity of the mixture is likely a key factor to this phenomenon because the viscosities of mixtures with sediment smaller than the critical size increase as the sediment size decreases or the concentration increases. Experiments with mixtures with two sediment sizes further demonstrate that smaller sediment can inhibit the damage by cavitation.

1. Introduction

While sediment-containing fluid flows quickly through hydro-machinery such as piping, pumping equipment, and hydro-turbine, cavitation erosion and abrasive wear usually occur simultaneously, causing serious damage and substantial financial loss [1]. Erosive wear is caused by the impact of solid particles against the surface of a solid. The impacting particles gradually remove material from the surface through repeated deformations and cutting actions [2]. When a liquid is subjected to rapid pressure reductions, bubbles (cavities) form. Upon entering a high-pressure area, these cavities immediately implode [3,4]. If the implosion occurs on the surface of solid, shock waves and/or microjets generated by the collapse of the cavity cause damages to the surface.

The mechanism of cavitation and the resultant damage are complicated, and the physical properties of the liquid–particle flow—e.g., cavitation clouds [5], cavitation nuclei [6], vapor [7], and particles [8]—could induce more complex interactions. For example, particles can be significantly accelerated by growing/expanding cavities [9–11]. However, when the viscosity of a mixture increases, the particle velocity decreases [12]. Thus, solid particles either aggravate or relieve cavitation damage depending on the physical properties of the mixture [13]. Despite prior research on this topic, the effect of sediment particles on damage caused by cavitation erosion is still a poorly understood issue.

Sediment size and concentration are considered to be the crucial parameters that influence damage caused by cavitation erosion and abrasive wear. Researchers have attempted to discern a "harmful size", and it is believed that damage increases with sizes around the harmful size, but there is variation in observed harmful sizes [14–16]. Yao [17] suggested that the harmful size ranges from 0.04mm to 0.14 mm for three types of steels. Satoh et al. [18] proposed that the range should be 0.08–0.17 mm. Yu [19] determined that sediment of 0.01 mm would enhance damage by 4–7 times. Furthermore, Zhong and Minemura [20] suggested that sediment sizes less than 1 mm rarely affect damage, but Xie et al. [21] considered that this is only true for sediment sizes less than 0.25 mm. In contrast, Wu and Gou [22] considered this minimum harmful size to be 0.048 mm.

Making observations during operation of the Chilime Hydro Electric Plant, Bajracharya et al. [23] determined that sediment of 0.2–0.5 mm was harmful for the middle and low water heads of the hydro station, sediment of 0.1–0.2 mm was harmful for the high water head of the hydro station. Wang [24] observed that sediment in the range of 0.05–0.5 mm were harmful. Sediment of 0.04–0.7 mm was harmful for the hydro turbines in the Yanguoxia hydro station.

Zheng [25] and Cheng [26] suggested that sediment can encourage

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damage in silt-laden water at low concentrations, but for high concentration, the sediment restrains the damage; Xing [27] obtained the critical concentration for this phenomenon. Padhy and Saini [28] concluded that the damage rate to a hydro turbine increases with the concentration of the silt irrespective of the silt size. Dunstan and Li [29] and Li [30] simulated the damage and predicted sizes of sediment that should reduce the damage. Hence, there remain disparate conclusions regarding the size and concentration of sediment for damage, which directly relates to the lifetime and safety of hydro-machinery and structures.

The present paper discusses the effects of adding sediment to water. Experiments were performed using a vibratory apparatus and a custom-made particle-moving device to identify the effects of the size (0.026–0.531 mm) and concentration (25–85 kg/m^3) of sediment for ASTM 1045 carbon steel.

2. Test apparatus and procedure

The experiments were conducted in the State Key Laboratory of Hydraulic Engineering Simulation and Safety at Tianjin University. The current study utilizes a vibratory apparatus and a particle-moving device. A diagram of the experimental apparatus is shown in Fig. 1(a).

A vibratory apparatus (KJ-1000; Wuxi Ultrasonic Electronic Equipment Co., Ltd.) is used to produce axial oscillations within each test specimen. The vibrations are generated by a magnetostrictive transducer driven by an electronic oscillator and a power amplifier. The vibratory frequency and amplitude are 19.6 ± 0.5 kHz and 50 µm, respectively. The corresponding output power is 1100 W. The temperature of the mixtures was controlled using cooling water system and maintained at 25 ± 3 °C.

The custom-made particle-moving device keeps sediment moving on the surface of specimen to cause abrasion. The container for the sediment-containing water has three electromotor-propelled stirrers with a speed of 240 r/min, as shown in Fig. 1(b), that agitate the water and sediment in order to maintain a relatively flat water surface and a stable concentration of sediment on the water surface. To further avoid uneven distribution of sediment, the concentration of sediment is confirmed as the concentration of an area on the surface of the liquid around the specimen rather than the concentration of the mixture in the container.

Each test specimen has an exposed radius of 16 mm, and they are held below the horn tip and inserted to a depth of 12.5 ± 0.5 mm in the test liquid. The material of the specimen is ASTM 1045 carbon steel, and its density is 7.85 g/cm^3. The chemical composition of the specimen is shown in Table 1; the microstructure consists of ferrite (69.8%) and pearlite (30.2%).

The mixture comprises distilled water and sediments. The sediments are composed primarily of feldspar and crystals, which have a Mohs hardness of 7 and a density of 2.65 g/cm^3. The sediment composition is shown in Table 2, and the sediment was classified into five classes, as shown in Table 3.

The experiment conforms to the standard test method for cavitation erosion by using a vibratory apparatus [31,32]. The mixture is prepared in advance. Sediment concentration is determined by the concentration at the center of liquid surface, instead of the concentration in the container. The test specimen is carefully cleaned, dried, and weighed on a balance with accuracy of 0.1 mg to determine its mass before the test and to determine the mass loss after test intervals of 30 min. The exposure time of each specimen is 240 min, and each case is repeated by three effective specimens, and the bias is in control of 5%.

The viscosity measurement utilizes a rotational viscometer (NDJ-8S; Shanghai Yueping Scientific Instrument Co., Ltd.). After testing each case, the viscosity of the sediment–water mixture is measured at temperatures of 10 °C, 25 °C, and 35 °C. Each case is repeated five times, and these results are averaged. The experimental cases include two groups, and details are shown in Table 4. The first group is selected to study the effect of a single size of sediment on cavitation damage; the objective of the second group is to study the effect of mixtures with two sediment sizes.

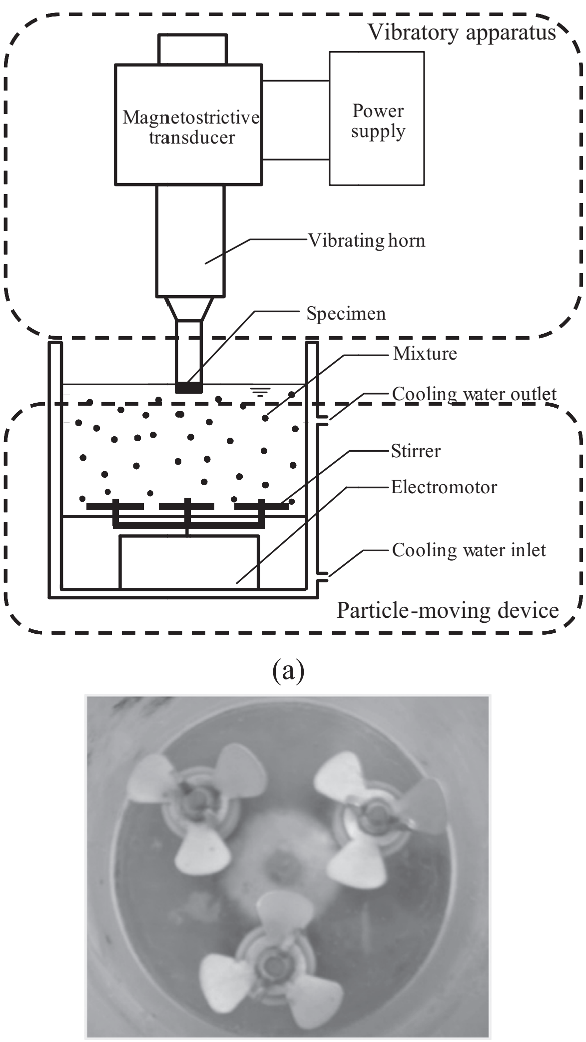

Fig. 1. (a) Schematic of test apparatus and (b) photograph of stirrers with three blades.

3. Results and discussion

In the experiments performed for this study, damage occurs as a result of cavitation in the distilled water or the combined erosion due to cavitation and abrasion in the mixtures with water and sediment. The damage is defined based on the mass loss of the specimen, which varies with exposure duration, particle size and sediment concentration.

Table 1
Chemical composition of specimen (balance is iron).

Chemical composition	*Mass* (%)
C	0.43
Cu	0.23
Mn	0.66
Ni	0.22
P	0.03
S	0.03
Si	0.24