CHARACTERISTICS OF SUPERSONIC WATER JET IN SEA WATER

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Abstract— The characteristics of supersonic water jet injected in sea water is preliminarily described in this research. The main focus is to compare the dynamic behaviors of the jet injected in sea water, water and ambient air. The supersonic water jets were generated by impact driven method in a horizontal single-stage power gun being designed and constructed for this study. The jets were visualized by the shadowgraph technique, and the images were recorded by a high-speed digital video camera. From the shadowgraph images, the core jet, water vapor bubble, shock wave in sea water and rebound shock wave generated because of bubble collapse is obviously observed. The maximum averaged velocity of the jet injected in sea water, water and air were 266.80 m/s, 374.24 m/s and 1,669.03 m/s, respectively. The averaged velocity of jet injected in sea water is much slower than that in air because hydrodynamic drag is much higher than aerodynamic drag. Since the density of sea water is higher than that of water, the averaged velocity of jet injected in sea water is lower than that in water. These effect on the penetration distance of jet injected in sea water being shorter than that in water and air, respectively.

Index Terms— Supersonic water jet, Sea water, Shock wave, Shadowgraph technique.

I. INTRODUCTION

High-speed liquid jet has been studied for many engineering applications such as cleaning and cutting technologies, mining and tunneling [1-4]. The high speed liquid jet has also gained attention in combustion [5, 6] and medical applications [7, 8]. Recently, attention has begun to be focused on industrial applications of jet to underwater work [9] such as cutting marine structures and drilling at the bottom of the sea, since the energy density of high-speed jets is sufficiently high for such cutting and drilling.

In 1996, H. Soyama et al. [10] described phenomena occurring around ultrahigh-speed submerged water jet. Continue water jets were generated by a plunger pump, 70 MPa in maximum injection pressure, 22 l/min in flow rate. The water jet accompanied by very severe cavitations was visualized by shadowgraph technique and impulsive pressures around the jets was measured by means of a pressure-sensitive film. The effects of the injection pressure and the nozzle configuration on impulsive pressure of jet were also clarified.

In 2009, K. Ohtani et al. [11] reported the result of preliminary experiments of pulsed Ho:YAG laser-induced jets applied to drill a submerged rock specimen. The laser-induced water jets was visualized by a high-speed digital video camera with shadowgraphs technique. The jet speed was estimated to be about 40 m/s from shadowgraph images. High stagnation pressures generated by jet impingements were also measured. It was found that simultaneously shock waves of about 22.7 MPa were generated at bubble collapse, which effectively cracked the surface of the rock specimens.

In 2013, A. Matthujak et al. [12] describes a preliminary investigation of the characteristics of high speed water jets injected into water. The characteristics of the water jets in water were visualized by the shadowgraph technique, and the images were recorded by a high-speed digital video camera. From the visualization, the processes following such jet injection into water, the jet-induced shock waves, shock wave propagation, the bubble behavior, bubble collapse-induced rebound shock waves were observed. However, the characteristics of high speed water jet injected in sea water for underwater work applications [9] still require the further study.

Therefore, the high speed water jets in supersonic range are generated by the impact driven method [13], [14] in this study. The characteristics of the jets injected in sea water, water and air are visualized by high-speed digital video camera with shadowgraph technique. Moreover, the averaged jet speed and penetration distance of the jets injected in sea water, water and air are investigated in this paper.

II. JET GENERATION

Liquid jets are formed when pressurized liquids confined in a container are discharged through a nozzle hole and jet speeds are determined by the value of pressures. In general, the higher the pressures are, the higher the jet speed becomes. However, static pressures over GPa are hardly maintained in large volume metal vessels.

To generate supersonic jets, Bowden and Brunton [13], [14] enhanced pressures in a liquid filled a container by a momentum transfer created with a sudden impingement of a high-speed projectile as

shown in Fig. 1. Then shock waves are generated inside the container. The shock compression generates high pressures of a several GPa maintained for a few hundred microseconds, which is even more effective than adiabatic compression. Hence to obtain higher jet speeds, impact speeds should be as high as possible technically.

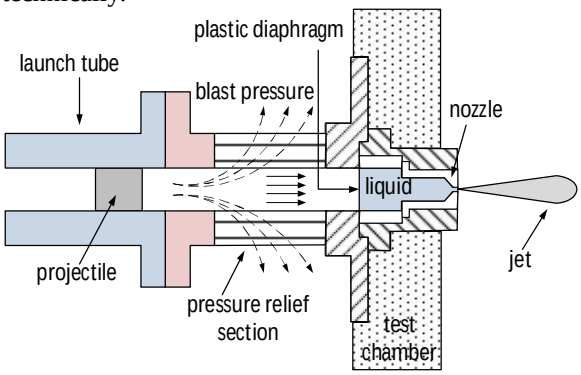


Fig. 1 Experiment setup for impact driven method.

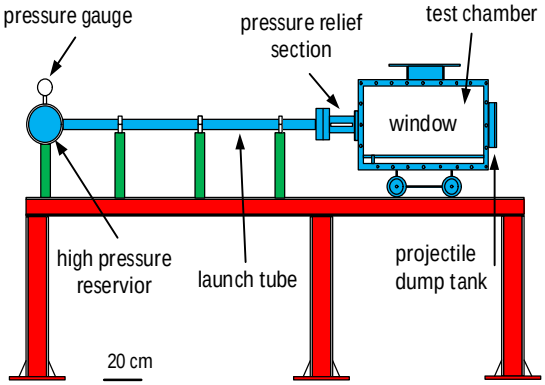


Fig. 2 Horizontal single-stage powder gun (HSSPG).

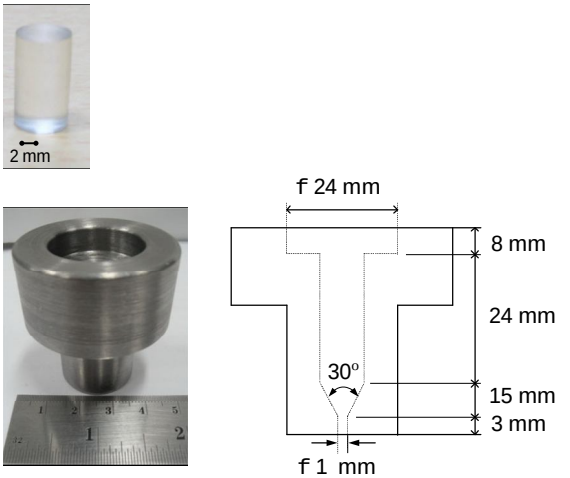


Fig. 3 Nozzle geometry.

The high velocity projectile needed in this technique has been launched by the Horizontal single -stage powder gun (HSSPG) as shown in Figure 2. The HSSPG consists of launcher, launch tube, pressure relief section and test chamber. The launch tube has a diameter of 15 mm and length of 1.5 m. The pressure relief section has a length of 38.5 cm, which is designed to diminish the blast wave in front of the projectile as shown in Fig. 1. The pressure relief section has 4 slots, each slot has 4 mm in width and 345 mm in long. The test chamber is a square tank of 350 X 350 mm in width and 590 mm in long, with two polymethyl methacrylate (PMMA) windows on two sides for visualization. The projectile is made of Polymethyl Methacrylate (PMMA), is cylindrical shape with diameter of 15 mm and length of 8 mm (weight of 0.92 g). The HSSPG has been employed to generate the high-speed liquid jet velocity of 550 to 2,290 m/s in each gunpowder weights. The nozzle that is connected to pressure relief section is made of mid-steel, and its dimension is shown in Figure 3. Gunpowder of 5 g is used for generating the jets in this experiment.

III. VISUALIZATION

In this study, a high-speed video camera and shadowgraph optical arrangement were used for visualization as shown in Fig. 4. The dynamic jet formation was quantitatively measured by sequential observations. A Xenon lamp was used as a light source. The source light was collimated passing through a concave lens and a circular slit. The laboratory space is limited that two plane mirrors of diameter 190 mm were combined. Two paraboloidal schlieren mirrors of diameter 300 mm were used for collimating source light beam passing the test section area. A Nikon 60 mm Macro lens was used to focus the object image on the high-speed video camera screen. The high-speed video camera is a Photron SA5 at frame rate of up to 30,000 f/s, maximum shutter speed of up to 1 □s, and 5.46 seconds record time at full resolution.

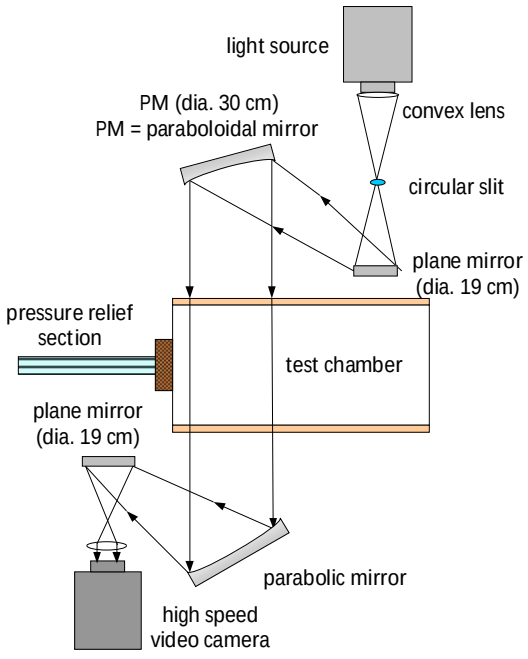
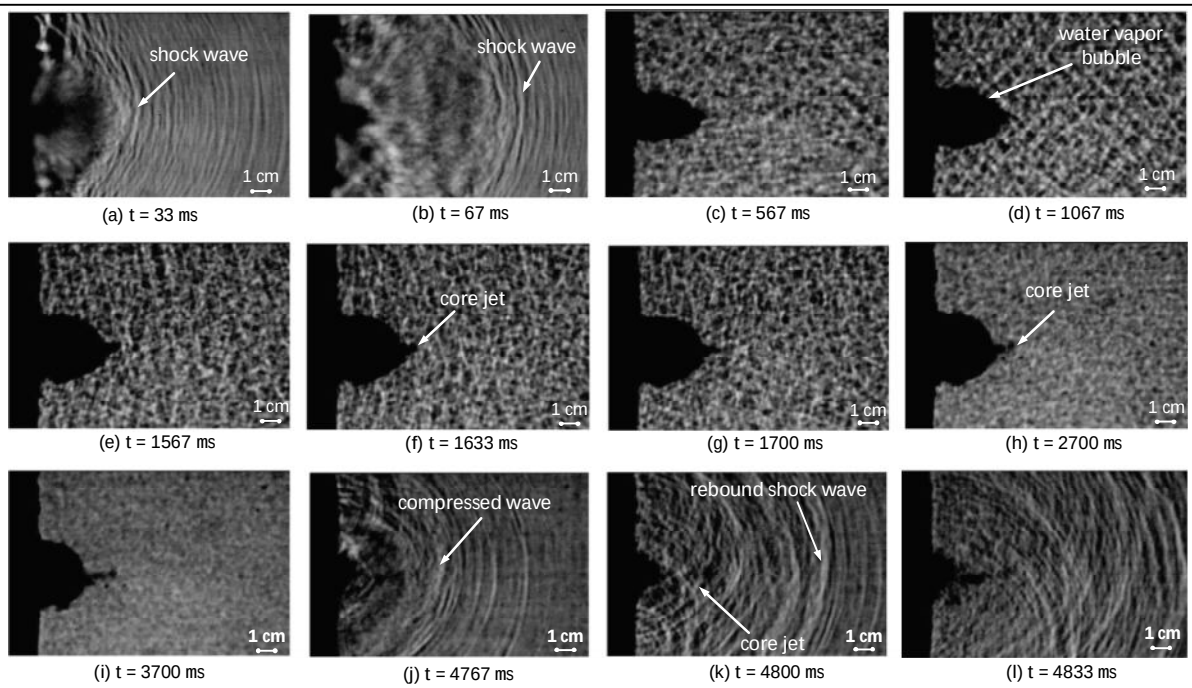


Fig. 4 Shadowgraph optical setup for high-speed digital video recording.

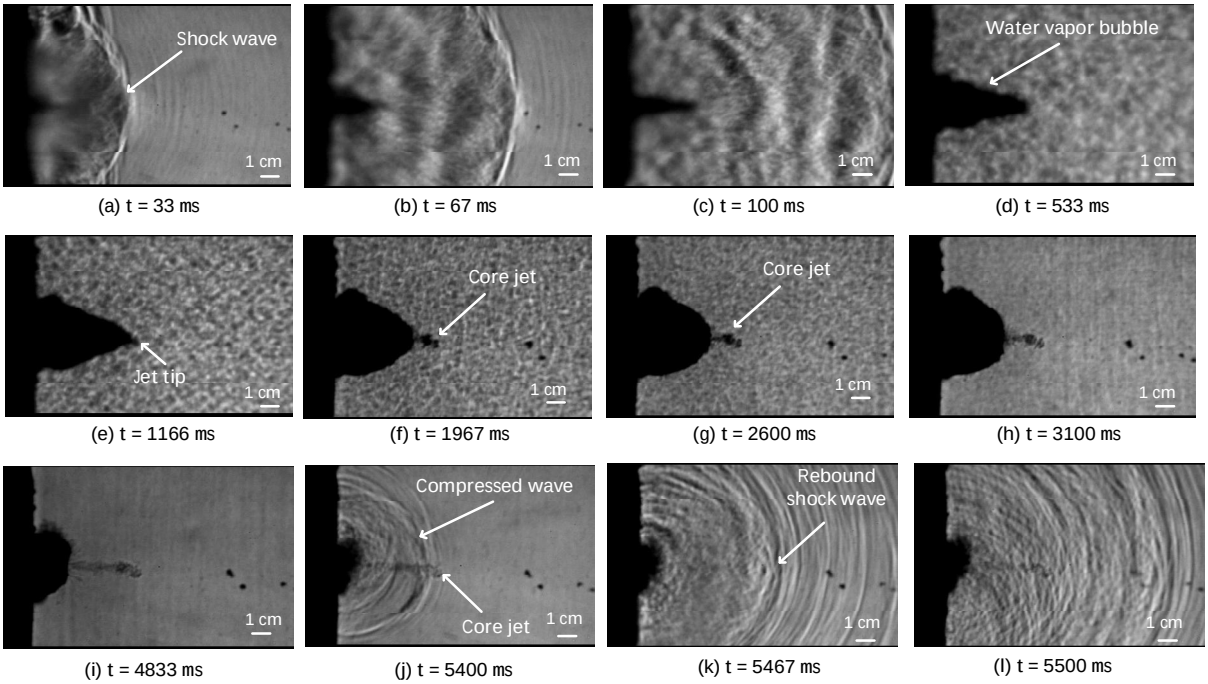


(a) t = 33 ms (b) t = 67 ms (c) t = 567 ms (d) t = 1067 ms

(e) t = 1567 ms (f) t = 1633 ms (g) t = 1700 ms (h) t = 2700 ms

(i) t = 3700 ms (j) t = 4767 ms (k) t = 4800 ms (l) t = 4833 ms

Fig. 5 Sequential observations of water jet formation in sea water.

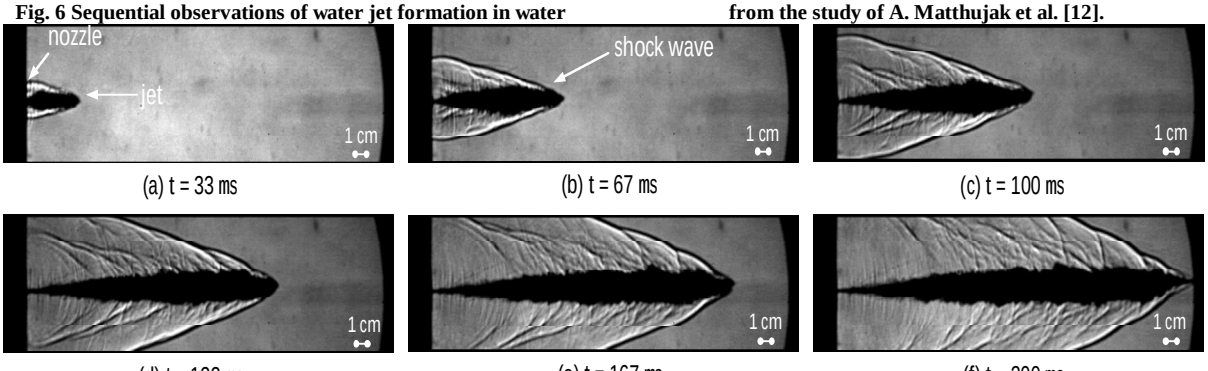


(a) t = 33 ms (b) t = 67 ms (c) t = 100 ms (d) t = 533 ms

(e) t = 1166 ms (f) t = 1967 ms (g) t = 2600 ms (h) t = 3100 ms

(i) t = 4833 ms (j) t = 5400 ms (k) t = 5467 ms (l) t = 5500 ms

Fig. 6 Sequential observations of water jet formation in water from the study of A. Matthujak et al. [12].



(a) t = 33 ms (b) t = 67 ms (c) t = 100 ms

(d) t = 133 ms (e) t = 167 ms (f) t = 200 ms

Fig. 7 Sequential observations of water jet formation in air from the study of A. Matthujak et al. [15].

IV. RESULTS AND DISCUSSION

In this study, using high speed video camera, Photron SA5 could record shadowgraph images at frame rate of up to 30,000 f/s and shutter speed of 1 □s. Such a sequential recording is very useful to observe the jet formation.

Sequential images of water jet injected in sea water are shown in Fig. 5. Only selective 12 images are presented. In Fig. 5a, after the projectile impact at the water contained inside nozzle, the supersonic jet contained water vapor bubble was discharged in quiescent sea water and the observable shock wave in sea water was generated. The maximum averaged velocity of jet injected in sea water is estimated to be 266.80 m/s from the images. The averaged shock speed from high-speed images at 67 □s is estimated to be 1,599.97 m/s and Ms (Mach number) = 1.06.

In Fig. 5b-d, the water-vapor bubble generated due to atomization and vaporization of the water jet expanded quickly as observable in a dark half ellipse shape. It was created by the deflection of the collimated object beam through the bubble. Because of the localized steep density change at the bubble, the collimated object beam is refracted at the bubble boundary, the injected bubble has a dark shape.

In Fig. 5e, the bubble expanded to be the maximum volume at 1,567 □s. After the maximum expansion of the bubble, the bubble started to contract and then the core jet is obviously observed in Fig. 5f-i. At the moment of minimum bubble size, a rebound shock wave was generated due to bubble collapse, which the pressure built up inside the minimum volume bubble would become extremely high. This phenomenon can be described by cavitation mechanism. The rebound shock wave propagates forward at the estimated shock speed of 1,549.10 m/s and Ms = 1.03 as seen in Fig. 5j-l.

Comparing with the supersonic water jet injected in water at the same conditions [12], it was found that characteristics, jet formation and bubble behavior of the supersonic water jet injected in sea water and water are similar as shown in Fig 5 and 6. However, the jet injected in sea water and water is different from the jet injected in air as shown in Fig. 7.

The most different behaviors between the jet injected in liquids (sea water and water) and air is the bubble phenomena. The jet injected in air has not the bubble phenomena while the jet injected in liquids has. The jet formation and characteristics of the supersonic water jet injected in air have been already clarified and reported in the previous researches [15] – [16].

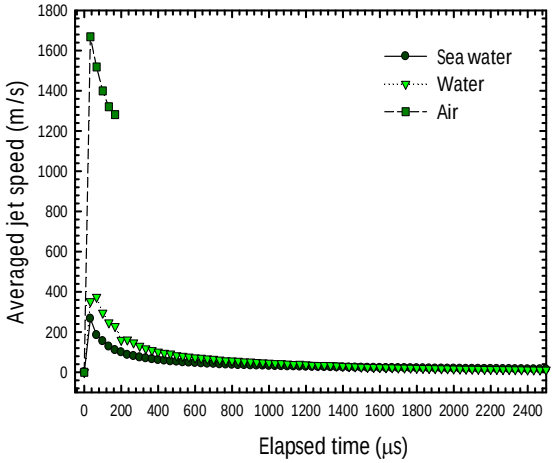


Fig. 8 Comparison of averaged jet speed of water jet injected in sea water, water and air.

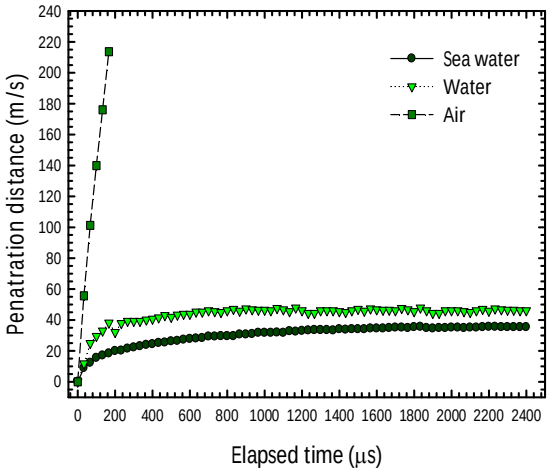


Fig. 9 Comparison of penetration distance of water jet injected in sea water, water and air.

Fig. 8 shows comparison of averaged jet speed of water jet injected in sea water, water and air at each elapsed time. During the maximum velocity point of water jet injected in air at the elapsed time of 33 □s, the velocity of jet drops quickly, as obviously seen in the figure, while the velocity of water jet injected in sea water and water gradually increases and decreases. The maximum averaged velocities of jet injected in sea water, water and air were 266.80 m/s, 374.24 m/s and 1,669.03 m/s at the elapsed time of 33 □s, 66 □s and 33 □s, respectively. The averaged velocities of jet injected in sea water and water are much slower than that in air because hydrodynamic drag is much higher than aerodynamic drag (drag = $0.5C_D \square V^2A$). Since the drag depends on density and the density of sea water (1,025 kg/m^3) is slightly higher than that of water (1,000 kg/m^3), the averaged velocity of the jet injected in sea water is slightly lower than that in water. These effect on the penetration distance of jet injected in sea water being shorter than that in water and air, respectively, as shown in Fig 9.

CONCLUSION

This study reports the characteristics of supersonic water jet injected in sea water comparing with in water and air. Using a high-speed digital video camera with shadowgraph optical arrangement, the dynamic behavior of the jet in sea water have been clearly revealed. From the shadowgraph images, the core jet, water vapor bubble, shock wave in sea water and rebound shock wave generated because of bubble collapse is obviously observed, being similar to the jet injected in water. Nevertheless, the jet injected in sea water and water is much different from the jet injected in air. The maximum averaged velocity of the jet injected in sea water, water and air were 266.80 m/s, 374.24 m/s and 1,669.03 m/s, respectively. The averaged velocity of jet injected in sea water is much slower than that in air because hydrodynamic drag is much higher than aerodynamic drag. Since the density of sea water is higher than that of water, the averaged velocity of jet injected in sea water is lower than that in water. These effect on the penetration distance of jet injected in sea water being shorter than that in water and air, respectively. However, the characteristics and dynamic behaviors of supersonic jets injected in sea water still require intensive clarification in further study.

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