Applied Mechanics and Materials Vols. 52-54 (2011) pp 1873-1878
Online available since 2011/Mar/28 at www.scientific.net

doi:10.4028/www.scientific.net/AMM.52-54.1873

Effect of stand-off distance on impact pressure of high-speed water jet injected in water

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Keywords: Impact pressure, High-speed submerged water jet, Impact acceleration method, PVDF pressure sensor, Shadowgraph

Abstract. This study is to measure the impact pressure of high-speed water jet injected in water at the stand-off distance from the nozzle exit. The high-speed water jets are generated by the impact of a projectile, which known as impact acceleration method, launched by Horizontal Single Stage Power Gun. The maximum averaged jet velocity of about 374.24 m/s in water was generated in this experiment. The impact pressure of high-speed water jet in water at the stand-off distance 15, 20, 30 and 40 mm from the nozzle exit was measured by the PVDF pressure sensor. Moreover, the impact phenomena of the jet were visualized by a high-speed video camera with shadowgraph optical arrangement. From the pressure sensor, two peak over-pressures are always observed in this experiment. From visualization, it was found that the two peak over-pressures of 24 GPa and 35 GPa at x = 15 mm were generated by the jet and the bubble impact, respectively. The peak over-pressure decreases exponentially as the stand-off distance between the PVDF pressure sensor to the nozzle exit increases. Moreover, the jet and the bubble impact on the PVDF pressure sensor, shock waves, and bubble deformation were obviously observed in this study.

Introduction

The impact phenomenon of high-speed liquid jet on surface have been studied for many engineering application, such as water jet cleaning and cutting technology [1, 2] wet stream turbine erosion, mining and tunneling, fuel injection and Supersonic Combustion Ram (SCRAM) jets [3-4]. Recently, the jet impact has gained attention in medical applications [5, 6], such as the drug injection, the tissue cutting, and the removing of a cerebral thrombus. Moreover, attention has begun to be focused on industrial applications of jet to underwater work [7], 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. Although, the preliminary investigation on impact phenomena of submerged jet for medical and underwater work application have been studied [8, 9], the submerged jet speed have been quite low in the previous studies. Thus, the impact pressure of liquid jet injected in water in high speed range has not been measured yet.

To generate high-speed water jets injected in water, the impact acceleration method or Bowden and Brunton method [10, 11] was applied in this study. The impact pressure of water jet at various stand-off distances from nozzle exit was measured by the PVDF pressure sensor, which was specially designed, manufactured and calibrated for this experiment. Moreover, high-speed digital video camera with shadowgraph optical arrangement is utilized to clarify the impact phenomena of high-speed water jet on the PVDF pressure sensor surface in water in this experiment.

High speed jet generation

In this study, high-speed water jet is generated by a special technique known as impact acceleration method [10, 11]. By this technique, the liquid retained inside the nozzle cavity is impacted by a high velocity projectile. The liquid obtains the momentum transfer from the projectile and is injected from the nozzle. The high velocity projective in this technique has been generated by the Horizontal

Single Stage Powder Gun (HSSPG) as shown in Fig. 1. The HSSPG consists of launcher, launch tube, pressure relief section, test chamber and test chamber. The launch tube has a diameter of 8 mm and length of 1.5 m. The pressure relief section has a length of 40 cm, which is designed to diminish the blast wave in front of the projectile as shown in Fig. 2. The pressure relief section has 3 slots; which each slot has a diameter of 4 mm and a length of 36 cm. The test chamber has a diameter of 48 cm. It is enclosed by poly methyl methacrylate (PMMA) and 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) as shown in Fig. 3a. This HSSPG has been employed to generate the high-speed water jet velocity ranged from 550 to 2,290 m/s injected into air in each gunpowder weight. The nozzle that is connected to pressure relief section is made of mid-steel, and its dimension is shown in Fig. 3b. Gunpowder of 5 g is used in this study, which can launch the projectile speed of about 952 ± 32 m/s and generate the jet velocity of about 374.24 m/s in water.

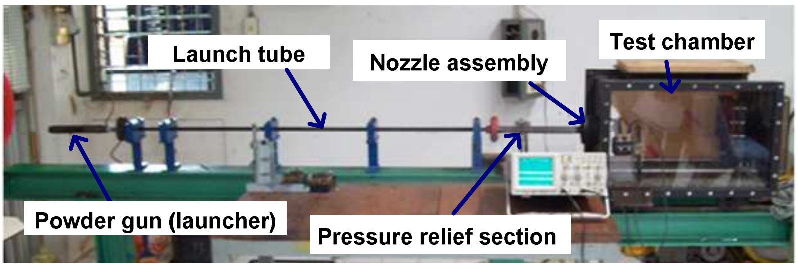


Fig. 1 Horizontal Single-Stage Powder Gun (HSSPG)

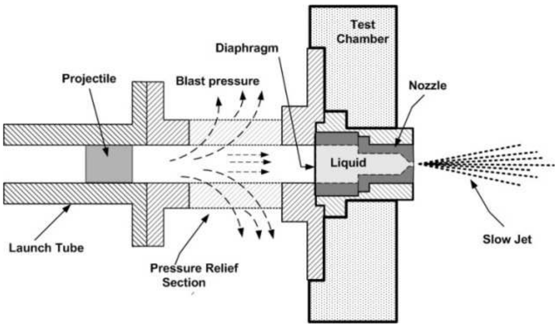
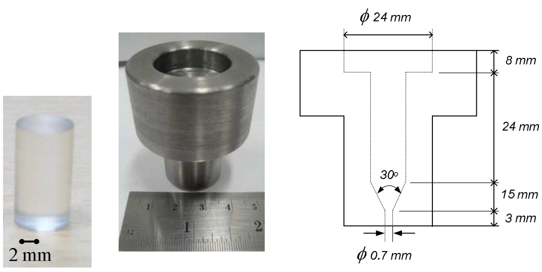


Fig. 2 The blast pressure or shock wave effect cause slow jet



(a) **(b)**

Fig. 3 (a) projectile (b) Nozzle geometry

Visualization method

In this study, a high-speed digital video camera and shadowgraph optical arrangement ware used to visualize the jet impact as shown in Fig. 4. 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 was limited so 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 digital video camera screen. The high-speed digital video camera is a Photron SA5 at frame rate of 30,000 f/s, maximum shutter speed of 1 μs, and 5.46 seconds record time at full resolution.

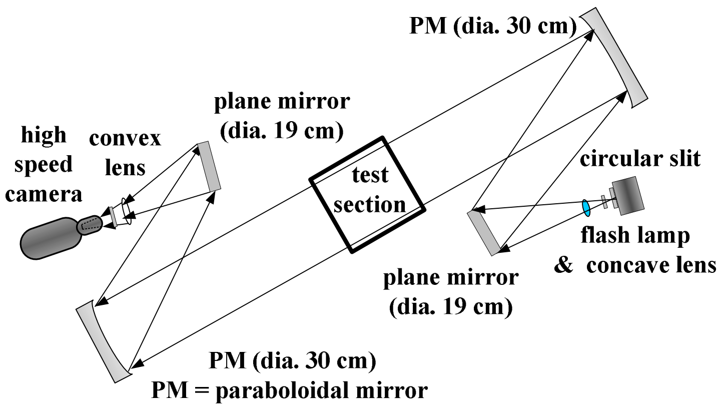


Fig. 4 Shadowgraph optical setup for high-speed digital video recording

Impact pressure measurement

The high-speed water jets generated from HSSPG are impulsive jet. Once the water jet impacts on solid surface, the impact pressure reaches a high value in a very short time. This pressure is dynamics pressure created by impact and is in the high MPa up to GPa range. Hence, it is not possible to measure it by conventional instrumentation.

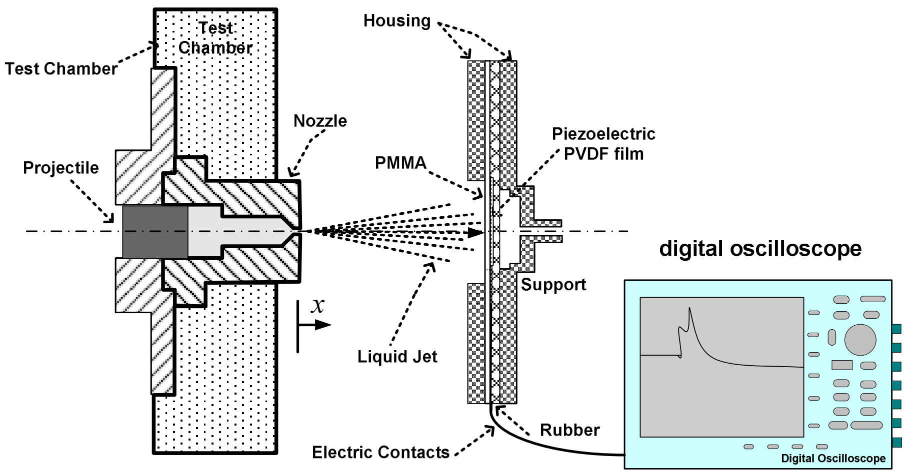


Fig. 5 Experiment setup for impact pressure measurement

To measure these high pressure, the pressure sensor was designed, manufactured and calibrated [12] in this study. The pressure sensor is constructed with Polyvinylidence Fluoride (PVDF) piezoelectric film, a 6 mm thick of PMMA and a 8 mm thick rubber support. It is assembled in 8 mm thick housing with an outer diameter 75 mm as shown in Fig 5. This PVDF film is a flexible component which comprises a 28 μm thick of piezoelectric PVDF polymer film with screen printed Ag-ink electrodes.

The experiment setup for measuring the impact pressure of liquid jets by using a PVDF is shown in Fig. 5. Once the water jet impacts on the PMMA surface, the PVDF film will respond to impact pressure giving a pressure signal that is recorded by oscilloscope. In the experiment, the stand-off distance from nozzle exit to the PVDF pressure sensor is varied changed by adjusting the pressure sensor holder backwards or forwards.

Results and discussion

Figure 6 shows a load-time trace for a water jet impact at 20 mm stand-off distance from the nozzle exit. This is the pressure signal from oscilloscope in voltage signal before calibration to pressure signal. Two peak over-pressures are always observed in this experiment. The two peak over-pressures marked at points A and B correspond to 17.33 GPa and 18.92 GPa, respectively, the time interval between them being about 33.2 µs. To clarify these peak over-pressures, jet impingement on the PVDF pressure sensor surface in Fig. 7b, its impact pressure being detected and recorded by oscilloscope as the first impingement signal. After jet impingement on the surface, the bubble grew and contacting the surface in Fig 7c. Its impingement was also detected and recorded as the second impingement signal. The time interval between Fig. 7b and Fig. 7c is 33 µs. In Fig. 7d-h, the bubble shape was deformed because of bubble impingement in the limited distance between the nozzle exit and the PVDF pressure sensor. From a load-time trace in Fig. 6 and visualization in Fig. 7, the two peak over-pressures marked at points A and B indicate the jet impact and the bubble impact since their time intervals are related, these being 33.2 µs and 33 µs, respectively.

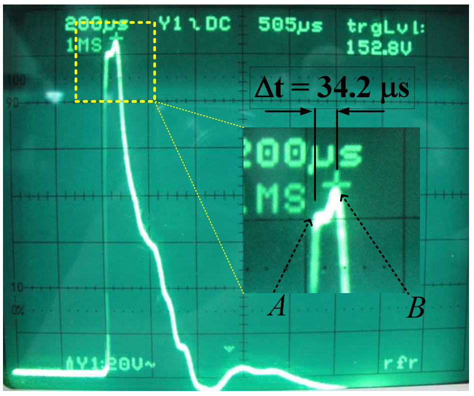


Fig. 6 A load-time trace for a water jet impact at x = 2 cm stand-off distance

Figure 8 shows the impact pressure of the jet and the bubble at 15, 20, 30 and 40 mm stand-off distance from nozzle exit. The ordinate and abscissa designate the jet over-pressure (red down-triangle), bubble impingement (black circle) both in GPa and stand-off distance *x* from nozzle exit in mm, respectively. Experiments were repeated three to four times at each individual positions. The scatter of data points is reasonably small. Due to hydrodynamic drag, the peak over-pressure decreases exponentially to approximately 24 GPa and 35 GPa at x = 15 mm, down to 0.9 GPa and 1.6 GPa at x = 40 mm for the jet impact and the bubble impact, respectively. In Fig. 7, the time interval of the jet and the bubble impact on the PVDF pressure sensor at x = 15 mm is quite long (approximately 33 µs) because the penetration speed of the bubble was slower than that of the jet. Thus, each impact developed individual over-pressure clearly as observed in Fig. 8, while impact at far away from the nozzle exit (x = 40 mm) the impact might be developed by the coupling effects from the jet and the bubble impact. That is because the bubble boundary grew nearly to the jet tip during impact so that the over-pressure of both impacts are about the same at x = 40 mm as observed in Fig. 8.

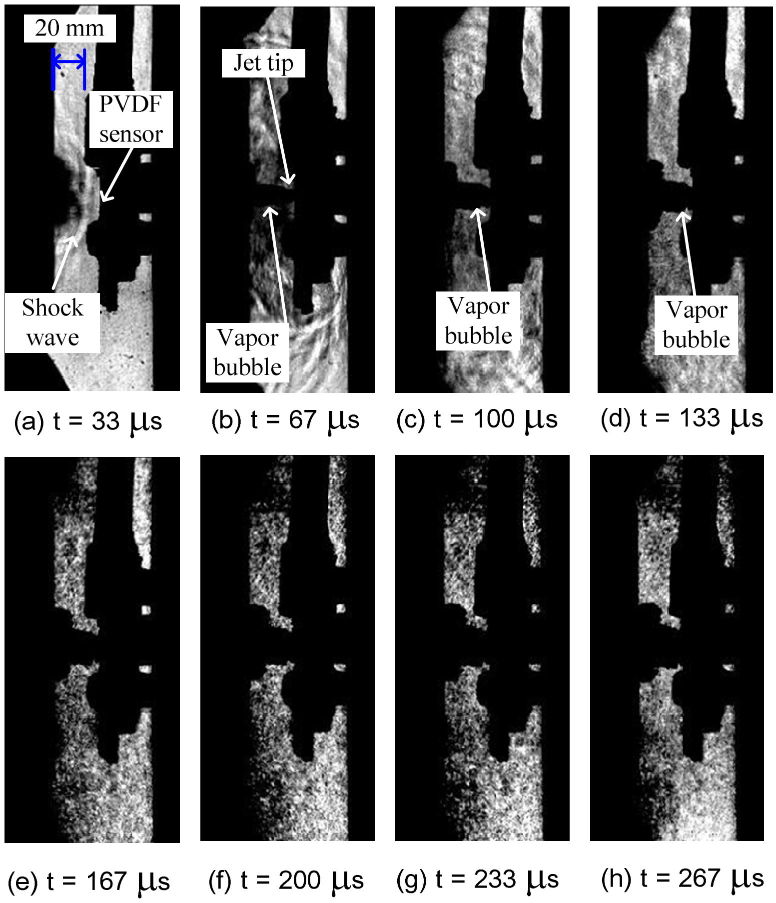


Fig. 7 Jet and bubble impact on the PVDF pressure sensor placed at the stand-off distance 20 mm

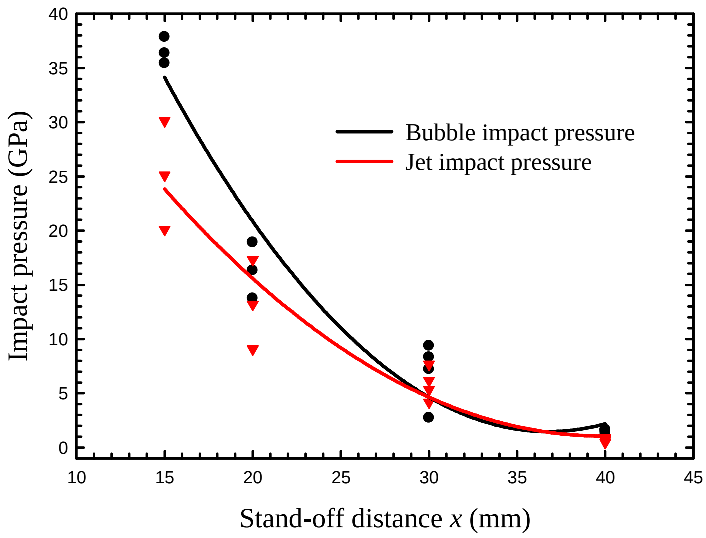


Fig. 8 Impact pressure at stand-off distance from nozzle exit

Concluding remarks

The impact pressure of high-speed water jet injected in water at the stand-off distance 15, 20, 30 and 40 mm from the nozzle exit was measure by the PVDF pressure sensor, which special designed, manufactured and calibrated for this study. From the experiments, two peak over-pressures are always observed in this experiment. To clarify these peak over-pressure, the high-speed water jet impact on the pressure sensor was visualized by high-speed digital video camera with shadowgraph optical arrangement. From visualization, the peak over-pressures of 24 GPa and 35 GPa were generated by the jet and the bubble impact, respectively. The peak over-pressure decreases exponentially to approximately 24 GPa and 35 GPa at x = 15 mm, down to 0.9 GPa and 1.6 GPa at x = 40 mm for the jet and the bubble impact, respectively. Moreover, jet and bubble impact on the PVDF pressure sensor, shock waves, and bubble deformation were obviously observed in this study.

Acknowledgement

The authors are grateful to Thailand Research Fund (TRF, contact No.MRG5180046), Department of Mechanical Engineering, Faculty of Engineering, Ubon Ratchathani University, National Research Council of Thailand (NRCT) and Thailand Toray Science Foundation (TTSF) for financial support.

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Advances in Mechanical Engineering
doi:10.4028/www.scientific.net/AMM.52-54

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doi:10.4028/www.scientific.net/AMM.52-54.1873