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Comparison-speed liquid jets

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Abstract The performance of a small high-speed liquid jet apparatus is described. Water jets with velocities from 200 to 700 m/s were obtained by firing a deformable lead slug from an air rifle into a stainless steel nozzle containing water sealed with a rubber diaphragm. Nozzle devices using the impact extrusion (IE) and cumulation (CU) methods were designed to generate the jets. The effect of the nozzle diameter and the downstream distance on the jet velocity is examined. The injection sequences are visualized using both shadowgraphy and schlieren photography. The difference between the IE and CU methods of jet generation is found.

1
Introduction

High-speed liquid jets are a typical phenomenon in fluid mechanics. The jets have important industrial applications and academic interest. Therefore, the problem has long been studied worldwide. One can find references from the proceedings of the series of BHR International Conferences on Jetting Technology, the US Water Jet Conference and the Cambridge Conference on Erosion by Liquid and Solid Impact. Recently, Pianthong et al. (2002) and Weeks et al. (2001) listed the applications of jets in rain erosion, cavitation, jet cutting, diesel fuel injection, etc. Momber (2001) and Kennedy and Field (2002) presented new results of abrasive water jet impact force and high-speed liquid impact on natural materials. From an academic point of view, Shi and Takayama (1999) and Shi et al. (2003a) emphasized that a supersonic liquid jet generator can be used as a fundamental tool in aerodynamics studies. Shi and Itoh (1996) reported the design of and experiment with a small high-speed liquid jet apparatus based on Bowden and Brunton's (1958) method of firing a deformable lead slug from an air rifle into a stainless steel nozzle containing water sealed with a rubber diaphragm. Because the slug directly impacts the nozzle to extrude the liquid flowing through a narrow orifice, the method is often called the impact extrusion (IE) method or direct impact method. It is known that the quality and behavior of the jets generated largely depend on the generation method or the design of the nozzle device. In an experiment with a high-pressure helium gas gun, Shi et al. (1996, 2003b) demonstrated that a greater jet velocity can be obtained using the cumulation (CU) method, by which the liquid cylinder is first accelerated by the impact of a projectile and then the liquid is accelerated further after entering a converging nozzle. This paper describes an investigation by jet velocity measurement and flow visualization into the effect on the jet generation when the CU method is applied in a small high-speed liquid jet apparatus.

2
Experimental devices

A general schematic of the small high-speed liquid jet apparatus is shown in Fig. 1a. The total length of the apparatus is 1.2 m. A UD-II Sharp CO_2 rifle with a bore diameter of 5 mm is fixed to steel blocks. The gun muzzle is coupled with the flight chamber and is facing a nozzle assembly. Figure 1b is a photograph of the apparatus.

Figure 2 shows the nozzle device of the IE method. A lead slug of diameter 5 mm , length 6.7 mm, and mass 0.75 g directly impacts a stainless steel nozzle. The test nozzles contain about 150 mm^3 water and have 0.5 mm, 1 mm, and 2 mm diameters respectively. The back end diameters of the nozzles are all 5.5 mm, and the liquid is sealed with a 1-mm-thick rubber diaphragm. The slug impacts the diaphragm and pushes the liquid to flow through the nozzle exit. The arrangement for fixing the nozzle in the nozzle holder is shown in the figure. The nozzle is adjacent to a spacer ring and is pressed by a strangleholder screw. The spacer ring can adjust the distance between the nozzle and the screw. Figure 3 shows the nozzle device in the CU method. Now the nozzle is adjacent to a stainless steel cylinder in which 150 mm^3 water is sealed between a 9-μm-thick Mylar film and a 1-mm-thick rubber diaphragm. The nozzle and the cylinder are fixed in the nozzle holder by the stranglehold screw. The slug impacts on the diaphragm and push the liquid cylinder to enter the nozzle. After traveling through

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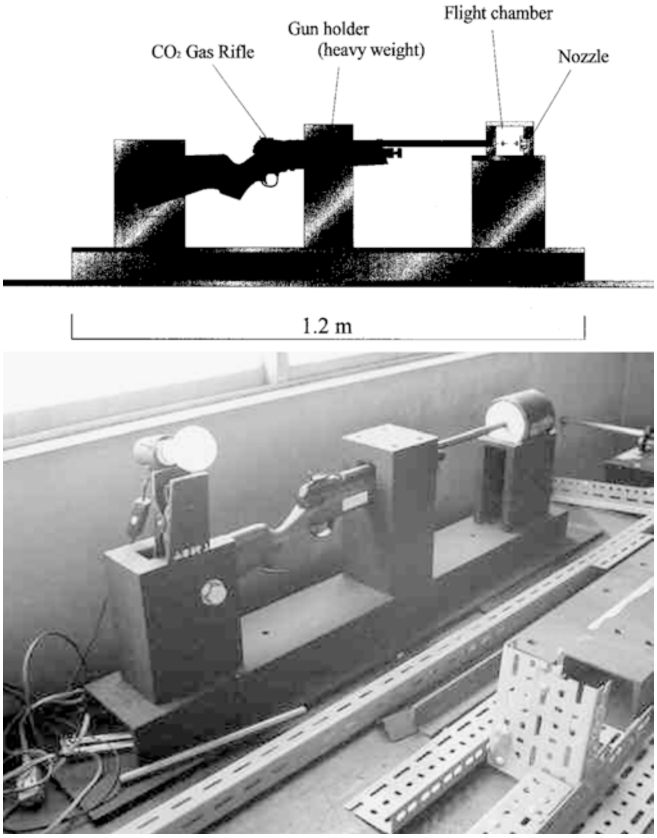


Fig. 1. **a** Schematic of the small high-speed liquid jet apparatus. **b** Photograph of the small high-speed liquid jet apparatus

the nozzle, the liquid flows out of the nozzle exit to form a jet. The design techniques of the IE and CU methods are that, before the experiment, (1) for the IE method, the nozzle is fully filled with water (Fig. 2); (2) for the CU method, water only occupies the back section of the nozzle, whereas the front section (including the converging part) of the nozzle is empty (Fig. 3).

Figure 4 shows the system for measuring the velocities of the slug and the water jet. Two laser beams are set inside the flight chamber to measure the slug velocity. The two laser beams are separated by 40 mm, and the first one is 20 mm from the muzzle exit. The other two laser beams are set at the nozzle exit. The two beams are separated by 15 mm, and the distance between the first one to the nozzle exit X is variable. To examine the effect of the nozzle diameter on the jet velocity, the distance X is kept at 3.5 mm, whereas to examine the jet velocity along the downstream, it is changed from 3.5 mm to 163.5 mm with every 40-mm step. All the laser beams are from semiconductor lasers (wavelength 670 nm, power output 5 mW, beam diameter 3.0 mm, and beam diverging angle 6.0×10^{-3} rad) and the signals from the photodiodes (PIN type, illumination size $\phi0.8$, shutting frequency 500 MHz) are collected into a four-channel digital oscilloscope.

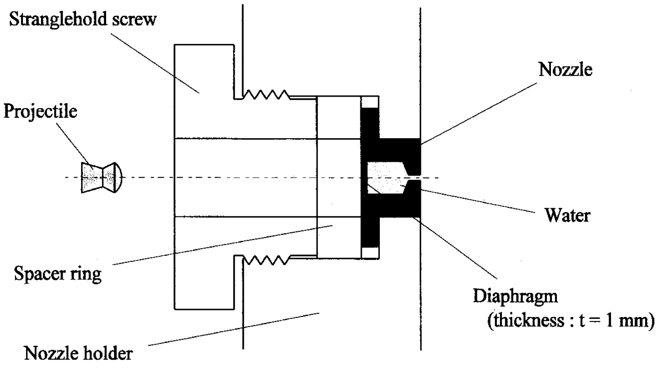


Fig. 2. Nozzle device for the IE method

The optical systems of the shadowgraphy and schlieren photography are given in Figs. 5 and 6 respectively. The shadowgraphy is performed using a xenon flash (nano pulse light, 180 ns exposure time) and an open shutter camera in a dark room. A conducting 0.5-mm-diameter carbon rod is set in the flight chamber, which is 40 mm from the muzzle exit. When the carbon rod is broken by an impacting slug, an electric signal is generated to trigger the xenon flash via the delay unit and the power supply. Adjusting the delay time, the jet events at different injection stages can be photographed. The xenon flash is also used in the schlieren photography (Fig. 6). The two concave mirrors are 150 mm in diameter. The trigger signal of the light source comes from the laser beam, which is set either at the muzzle exit or at the nozzle exit.

3
Results

Figures 7 and 8 give the measured relationships between the jet velocity and the impact slug velocity at three nozzle diameters of 0.5, 1, and 2 mm for the IE and CU generation methods respectively. The measuring point is at a distance of X=3.5 mm. The general trend is that with increasing slug velocity, the jet velocity is increased since the impact pressure is approximated to be $P=\rho CV_{\mathrm{pro}}$, where ρ, C, and V_{pro} are the liquid density, the shock wave velocity, and the slug velocity (Shi et al. 1996). The results of the IE method are close to linear relationships, but the results of the CU method are not. It is obvious from Figure 7 that the smaller the nozzle diameter, the greater the jet velocity. This is because the fluid pressure is higher in a nozzle with a smaller diameter (Shi et al. 1993, 1994). However, Fig. 8 shows that the CU method causes some overlap in the jet velocity, e.g., the jet velocity of 1-mm nozzle is greater than that of 0.5-mm nozzle at the slug velocity of 170∼180 m/s. This is associated with the fact that it is easy for the complicated acceleration process in the nozzle to cause unsteadiness of the jets (Shi et al. 2003b). A comparison of Figs. 7 and 8, shows that the jet velocities of the CU method are generally less than those of the IE method. One exception is that the jet velocity of the CU method is greater than that of the IE method at the slug velocity of 185 m/s for a 2-mm-diameter nozzle. These results are somewhat different from those of Shi et al. (1996, 2003b), but it must be noted that in the high-pressure helium gas gun experiment, Shi et al. (1996, 2003b) used a composed brass/nylon projectile with 1.16 g mass and 200∼300 m/s impact velocity. Therefore, it is understood that the role of the CU method in the acceleration of a water jet depends on the momentum of the projectile, the diameter of the nozzle, and the volume of water. The results of the effect of the liquid volume on the

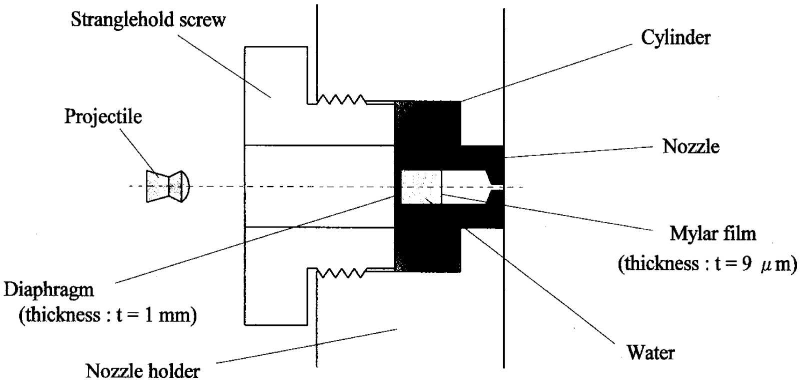


Fig. 3. Nozzle device for the CU method

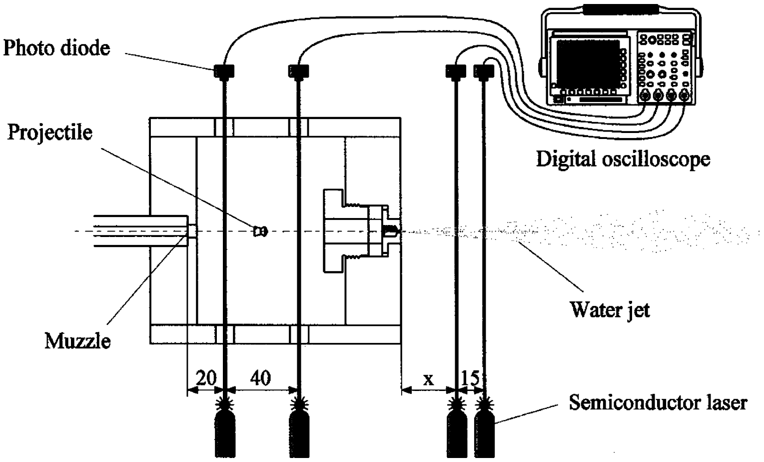


Fig. 4. Optical system for measuring the jet and slug velocities

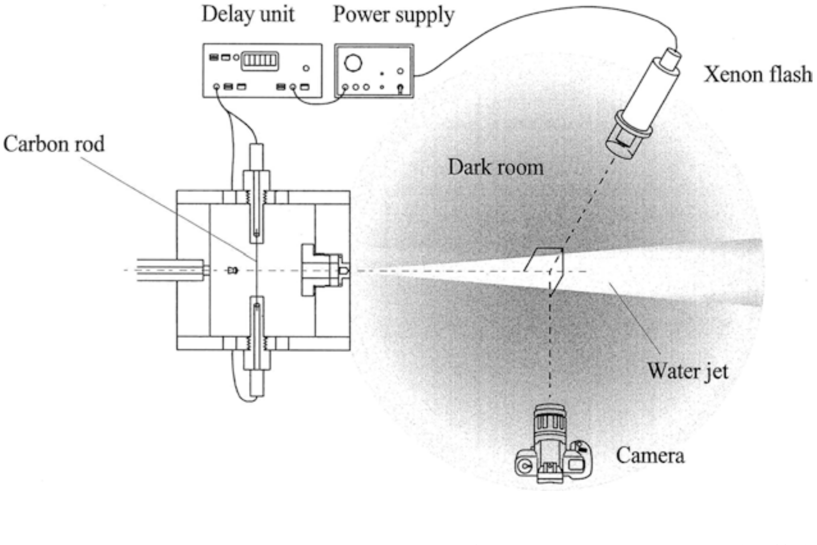


Fig. 5. Optical system of the shadowgraphy for the jets

jet generation can be seen in the study of Shi et al. (1993, 2003b).

Figures 9 and 10 give the measured relationships between the jet velocity and the downstream distance for the IE and CU methods respectively. During the experiment and the schlieren photography, the slug velocities are kept around 185 m/s. For the IE method, the jet velocities of 1- and 2-mm diameter nozzles are relatively stable along the downstream direction. The jet velocity of the 0.5-mm-diameter nozzle decreases greatly along the downstream direction, that is, it becomes half the original value at the stand-off distanceof 120 mm. This is because the 0.5-mm-diameter jet is severely atomized after leaving the nozzle exit. For the CU method, only the jet velocity of 2-mm-diameter nozzle remains stable along the downstream direction. The velocities of the jets from 0.5- and 1-mm-diameter nozzles are decreased significantly with increase in the stand-off distance.

Figures 11 and 12 give the shadowgraphs of supersonic water jets from the 1-mm-diameter nozzle at different stand-off distance for the IE and CU methods respectively. The arrows in the photos mark the position of the nozzle

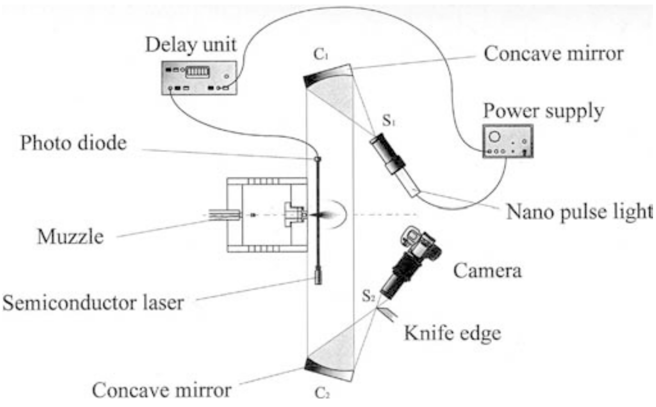


Fig. 6. Optical system of the schlieren photography for the jets

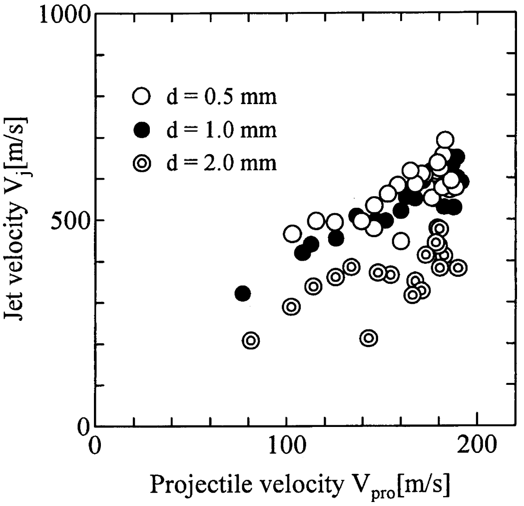


Fig. 7. Relationships between the jet velocity and the slug velocity. IE method. *X*=3.5 mm

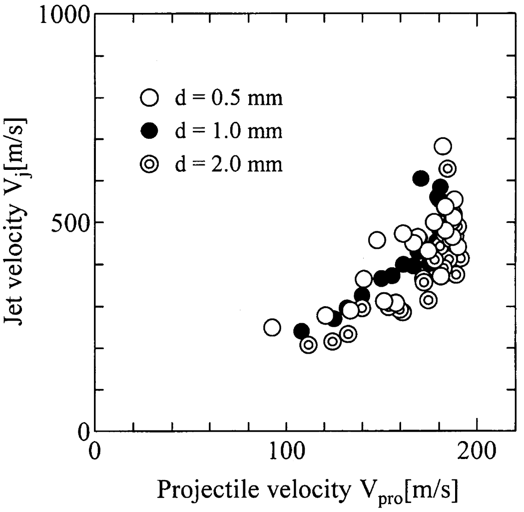


Fig. 8. Relationships between the jet velocity and the slug velocity. CU method. *X*=3.5 mm

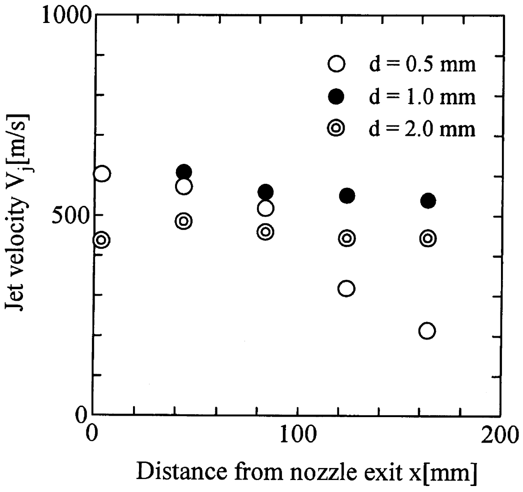


Fig. 9. Relationships between the jet velocity and the stand-off distance. IE method

exit. Figures 13 and 14 give the schlieren photographs of the supersonic water jets from the 1-mm-diameter nozzle at different stand-off distance for the IE and CU methods respectively. We first analyze the jets for the IE method shown in Figs. 11 and 13. In accordance with the jet shape and its stand-off distance, the jets shown in Fig. 11a, b have about a 15 mm stand-off distance and correspond to the cases shown in Fig. 13e–g. The jets in Fig. 11c–d correspond to the cases in Fig. 13i–j. It is shown that, when the jet is fully developed (Figs. 11c–d and 13i–j), the jet has a sharp supersonic tip and a long stretched thin body which is surrounded by the bifurcated jets near the nozzle exit. The combined shadowgraphy and schlieren photography have revealed the mechanism of the formation of the bifurcated jets. Figures 11a–b and 13a–h show that, at the beginning, a thin jet of about 1 mm diameter appears at the nozzle exit (Fig. 13a). Due to the multiple reflection of the shock wave in the nozzle (Shi and Itoh 1999), the successive liquid must flow out of the nozzle (Fig. 13b–c). The successive liquid impacts on the front jet head to cause the liquid to expand radially. As shown in Fig. 11a–b, the diameter of the spray head was 13.3 mm. This is the so-called liquid jet discontinuity (Dunne and Cassen 1956). The radial expansion brings about velocity

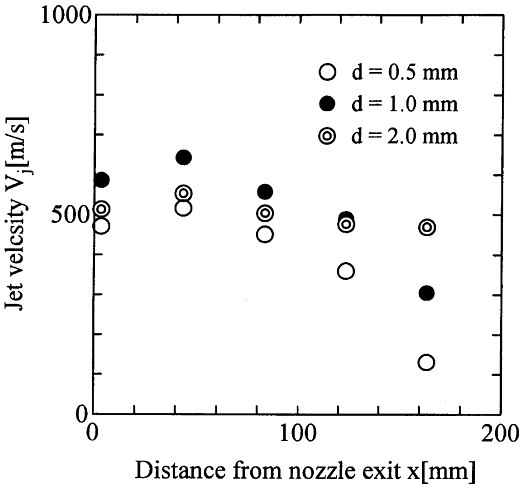
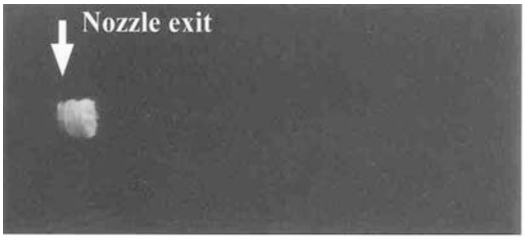
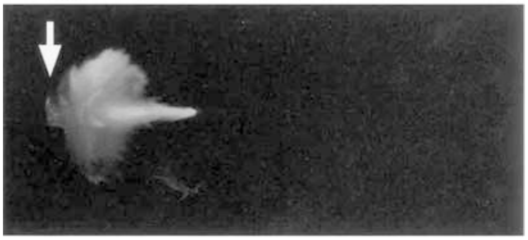


Fig. 10. Relationships between the jet velocity and the stand-off distance. CU method



(a) Delay time 380 μs, V_{pro} = 186 m/s

(b) Delay time 400 μs, V_{pro} = 179 m/s

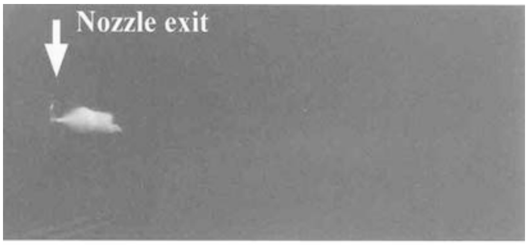


(c) Delay time 450 μs, V_{pro} = 180 m/s

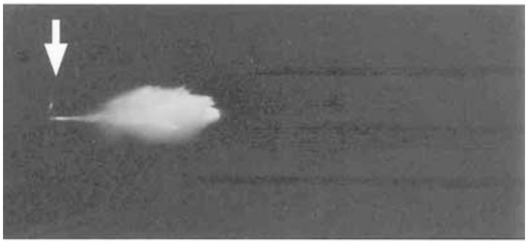
(d) Delay time 500 μs, V_{pro} = 186 m/s

5 cm

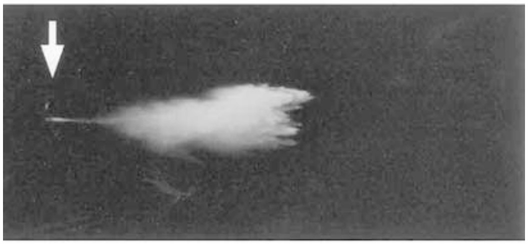
Fig. 11. Shadowgraphs of supersonic water jets from a 1-mm-diameter nozzle. IE method



(a) Delay time 400 μs, V_{pro} = 183 m/s



(b) Delay time 450 μs, V_{pro} = 184 m/s



(c) Delay time 500 μs, V_{pro} = 187 m/s

(d) Delay time 550 μs, V_{pro} = 187 m/s

5 cm

Fig. 12. Shadowgraphs of supersonic water jets from a 1-mm-diameter nozzle. CU method

reduction and quick atomization of the bifurcated jets so that a central jet emerges from the spray (Fig. 13h) and moves forward (Fig. 13i–j). The helical internal vortex shown in Fig. 11d and the wave shape of the jet boundary shown in Fig. 13j are associated with the helical instability and the Kelvin–Helmholtz instability (Andrew 1993; Shi et al. 2001).

When the CU method is applied, the jet bifurcation disappears (see Figs. 12 and 14). Because the liquid has already got initial velocity before emanating from the nozzle exit, all the fluid particles move forward. It is easy for this kind of jet to be atomized and disintegrate. It is evident from Fig. 12a–d that the expanded spray was much larger than the nozzle diameter, which is equal to the diameter of the thin liquid tail behind the spray. In contrast, the diameter of the spray generated by the CU method is larger than that generated by the IE method. This shows the role of the CU method in the liquid disintegration and atomization. The disruption on each jet front is associated with the Rayleigh–Taylor instability (Joseph et al. 1999; Field and Lesser 1977). The schlieren photographs show the complicated shock waves system induced by the jet. In Fig. 14a, the first shock wave to appear is the transmitted shock wave which is caused by the impact on the liquid cylinder (see Fig. 3). Following the first shock wave, the second shock wave appears in Fig. 14b–c, which is a blast wave caused by the sudden motion of the liquid in the nozzle. Then the third shock wave, which is the bow shock around the supersonic liquid jet, appears in Fig. 14d–f. Since the jet overtakes the first and second waves (Fig. 14g–j), the bow shock interacts with these waves. In Fig. 14i, the arrow marks the transmitted shock wave. It is seen from the schlieren photographs that not only does the disruption of the jet head

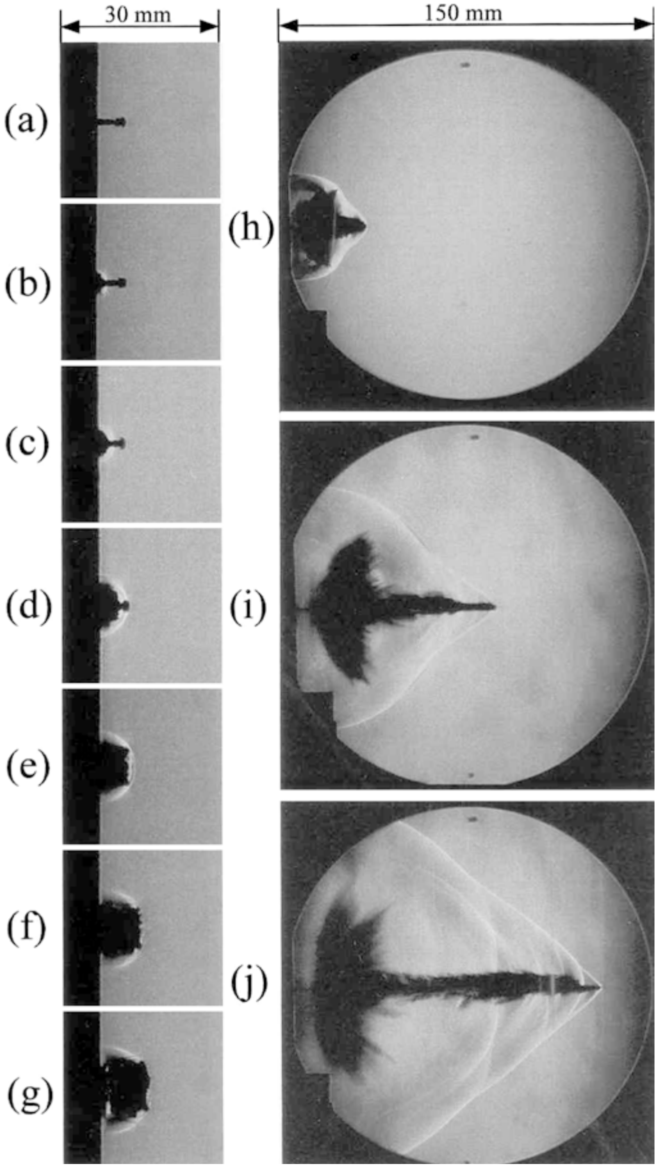


Fig. 13. Schlieren photographs of supersonic water jets from a 1-mm-diameter nozzle. IE method

cause complicated wave structure (Fig. 14i), but the wave shape of the jet boundary also causes many Mach waves (Fig. 14j). The process of a supersonic liquid jet overtaking shock waves was first stated by Shi and Takayama (1999) in their holographic observation of hypersonic liquid fuel jets. The present schlieren photography confirms the previous explanation. The aerodynamics of a supersonic projectile overtaking a gun muzzle blast wave can be seen in the work of Jiang et al. (1998).

4

Conclusions

A small high-speed liquid jet apparatus was designed to demonstrate various factors in the generation of supersonic water jets. It was found that the CU method is very effective in the disintegration and atomization of the liquid jet, but its role in jet acceleration depends on the impact momentum of the projectile, the nozzle diameter and the liquid volume. Combined shadowgraphy and schlieren photography revealed that the jet bifurcation often accompanies the IE method, and the bifurcation is caused by the interrupted acceleration of the liquid in the nozzle as well as the discontinuity of the jet. The jet in the CU method brings about a complicated shock wave system. It is observed that the disruption of the jet head and the discontinuity of the jet can cause some new shock structures. In the relationships between the jet velocity and downstream distance, the IE method shows an advantage in keeping the jet velocity stable, since only the jet velocity of a 0.5-mm nozzle is decreased significantly, whereas the CU method shows that both 0.5- and 1-mm nozzles reduce the jets velocities significantly.

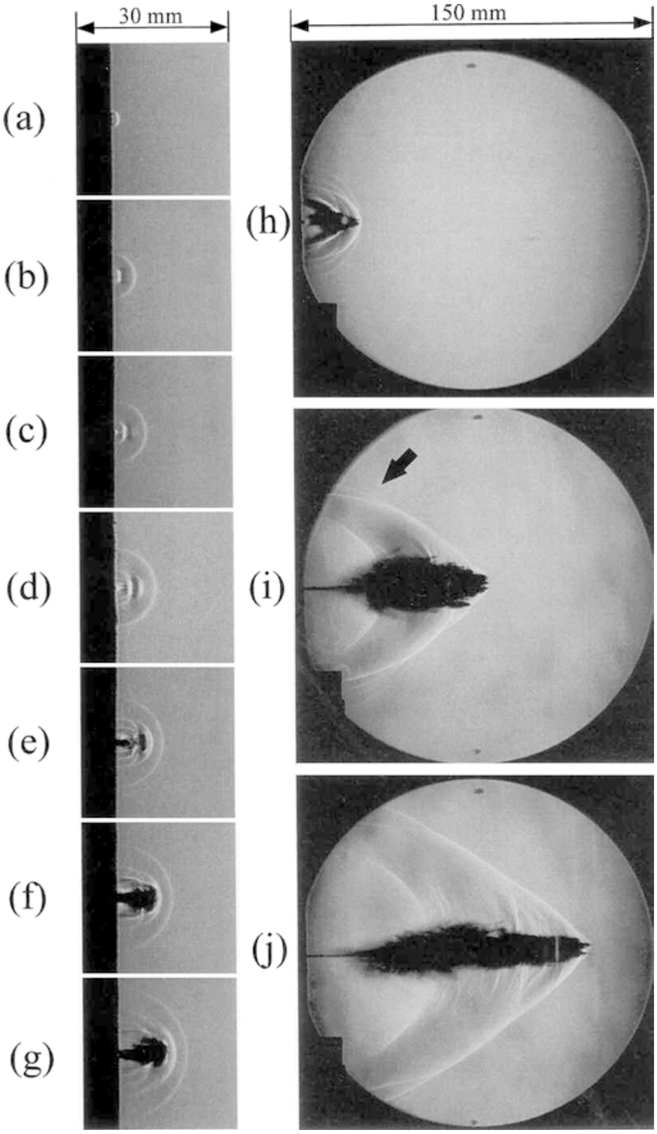


Fig. 14. Schlieren photographs of supersonic water jets from a 1-mm-diameter nozzle. CU method

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