Hydrodynamic shock tube for quick transportation of spray with large flow rate

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Abstract This paper reports an experimental study of generating water spray with large flow rate by means of hydrodynamic shock tubes. A water column was put in the low-pressure section of the shock tube and high-pressure helium gas was added into the high-pressure section. When the diaphragm separating the gas and the water was ruptured by the high-pressure gas, the water column was driven downwards to discharge from the tube exit to form a jet/spray. Two kinds of rupture methods, namely quasi-static and dynamic processes, were tested. Flow visualizations confirmed that the gas/liquid contact surface and the generated jet/spray were quite unstable.

1 Introduction
The concept of hydrodynamic shock tube was first given by Glass and Heuckroth (1963). A hydrodynamic shock tube (HST) is when a high-pressure gas acts as the driver and a liquid is the driven fluid, or vice versa. When the diaphragm between the gas and the liquid ruptures, a shock wave is generated in one phase and it will transmit into the other phase. Thus, the application of the shock tube technique can be extended to many areas. Since the work of Glass and Heuckroth (1963), Kawada et al. (1973) studied shock wave convergence in the HST and Van der Grinten et al. (1985) also conducted research work on shock wave propagation in porous medium using HST. Kedrinskii (1992) concluded four kinds of HST, including the type of HST developed by himself using wire exploding to produce underwater shock waves.

This paper reports a new application of HST, that is, shock tubes are applied to drive water jets into air. Actually, it is the original type of HST of Glass and Heuckroth (1963), except the end wall of the low-pressure section is open to the atmosphere. From the open end, the liquid flows out. The liquid in the tube experiences acceleration, breakup, droplet coalescence, and other two-phase transportation processes. The theoretical model of the acceleration of a liquid cylinder by a high-pressure gas was given by Politzer and King (1971), but they did not consider the instability on the gas/liquid interface. The transportation of solid particles by shock waves using a shock tube has been studied by Bellhouse et al. (1997).

Although research on shock interaction with droplets is not a new topic [see Simpkins and Bales (1972), Yoshida and Takayama (1990)], very little research has been done on the transportation of liquid/spray with large flow rate by shock waves or compressible gases. The current work has a direct application to an impulse fire extinguishing system (Steur and Lerdahl 1998; SAKURA 1998).

2 Experimental
Figure 1 shows schematics of two vertical hydrodynamic shock tubes for generating water jets. In Fig. 1a, the HST is composed of only two parts, that is, a high-pressure section filled with helium gas and a low-pressure section filled with water. Each section has a 34-mm inner diameter, a 44-mm outer diameter, and is 250 mm long. The water and the gas are separated by a diaphragm of 16-μm Mylar film. High-pressure helium gas is gradually added into the lower section until the diaphragm ruptures. Then the high-pressure gas drives the water flowing out of the tube. Before the rupture of the diaphragm, the pressurization to the diaphragm is a quasi-static process. In contrast, the pressurization to the diaphragm in the HST of Fig. 1b is dynamic. The HST is composed of three parts, (1) a high-pressure section filled with helium gas; (2) a low-pressure section of air at atmospheric pressure; (3) the water section. Each section also has a 34-mm inner diameter, a 44-mm outer diameter, and is 250 mm long. So the total length of the HST is 750 mm. The combination of helium gas/air is commonly used in shock tube technique to obtain a shock wave with a higher Mach number. A 16-μm Mylar film acts as the separating diaphragm between the helium gas and the air. The water column in the top section is held by a 15-μm aluminum diaphragm. When the Mylar film ruptures, a shock wave moves in the air in the middle section and later impacts on the aluminum diaphragm. The rupture pressures of the Mylar film in this experiment were about 0.25 MPa, which generated an air

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shock of Mach number 1.31. This shock wave cannot immediately rupture the aluminum diaphragm which is holding a heavy fluid, so that upon the shock impact, the rupture process is delayed for several milliseconds (Shi and Wang 2001). After that, the liquid is pushed out of the tube and a jet is formed. The jet velocities at the exit of the tubes of Fig. 1 were measured to be all about 5 m/s (Shi et al. 2001). The jet flow and the two-phase flow in the HST were visualized using a stroboscopic light (PS-240 & PL240, flash time 25 μs, Sugahara Laboratory, Japan). The triggering device was a 0.3-mm diameter copper wire that was taped on the open end-section of the HST. When the liquid column moved upward crossing the copper wire, a sudden voltage increase in the circuit triggered the flash. A photograph of the two sections HST is shown in Fig. 2, where the facility is in horizontal.

![Fig. 1a, b. Schematic of the vertical hydrodynamic shock tubes for quick transportation of large flow rate of jet/spray. a Two-section-type HST; b three-section-type HST. The sections of the helium gas and air comprises a shock tube. This combination is commonly used in shock tube technique](image)

3 Results

Figures 3 and 4 show the generation processes of water jet/spray from the HST of Fig. 1. In Fig. 3a, the water jet just appears at the tube exit, pushed by the high-pressure helium gas (see the bubbles at the bottom of the photograph). In Fig. 3b, the diameter of the jet is increased due to the air drag. This can be understood by considering that the fluid particles stagnate on the front surface, so that the pressure difference induced by stagnation pressure forces the liquid cylinder to expand radially. In Fig. 3c and d, the liquid spalling from the left part of the jet looks like the Kelvin-Helmholtz instability, but it is thought to be caused by the disturbance of the taping paper at the tube exit.

Figure 3e and f shows the jet sequences before and after the helium gas emanates from the tube exit. The leaking of the high-pressure gas causes a rapid liquid atomization and the radial expansion of spray (Fig. 3f). Meanwhile, the flow in the tube becomes a type of fog two-phase flow. It is seen from Fig. 3a–d that the upward-moving gas/liquid

![Fig. 2. Photograph of a horizontal two-sections-type hydrodynamic shock tube. It can be put vertically as in Fig. 1. On the left is a valve for adjusting the pressure in the high-pressure section. A digital pressure gauge (maximum range 5 MPa) is between the valve and the tube, which is for monitoring the pressure in the high-pressure section](image)

![Fig. 3a-f. Flow sequences at different stages in the device of Fig. 1a. At the bottom of plate a, the bubble, which consists of some smaller bubbles, is formed after the diaphragm rupture. The bubble changes its shape as it moves upwards; see b and c](image)