DEVELOPMENT OF SHOCK HEATED MOLECULAR BEAM: MODIFICATION OF SHOCK TUBE VALVE

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Abstract. High energy molecular beam source in the range of 1 to 5 eV is one of the most important tools to explore gas-surface interaction involving chemical reaction. It is known that the shock heated molecular beam is capable of overcoming these problems, but the quite low repetition rate less than 1 Hz makes practical application difficult in molecular beam scattering experiment. In our previous report, a small shock tube was developed with 2 mm in inner diameter and 160 mm in length using a solenoid pulse valve. In this study, we install the shock tube in our molecular beam facility and show translational energy of molecular beam increases up to 0.19eV in TOF experiment. Then, we developed a current-loop valve as the sock tube valve to obtain higher translational energy. The maximum lift of 500 μm and the response time of 130 μs were achieved by our current-loop valve. This valve is expected to significantly improve the performance of the shock tube as a molecular beam source.

Keywords: shock tube, molecular beam, current-loop valve, time of flight
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INTRODUCTION

In the molecular beam scattering experiment for exploring gas-surface interaction involving chemical reaction, it is important to produce high energy molecular beam from 1 to 5 eV with high repetition rate. Researchers have developed various kinds of molecular beam sources [1]. A seeded beam, which consists of a light carrier gas and a heavy sample gas, is a typical technique to obtain higher energy beam than a pure beam. An arc-heated beam is a method to heat the gas using thermal plasma generated by an arc discharge. Although these devices have been widely used in molecular beam scattering experiment, they have crucial drawbacks: the beam intensity using the seeded beam technique is much lower than that using a pure nozzle beam. The arc-heated beam generates undesirable electronically excited species that alter the composition of the beam.

On the other hand, it is known that the shock heated molecular beam is capable of overcoming these problems. Skinner and Moyzis reported high energy molecular beam over 1 eV using a shock tube [2]. However, the biggest challenge for this device is to increase the repetition rate. Teshima reported the repetition rate is less than 1 Hz [3] because it takes long time to exhaust the residual gas in the shock tube for next shot. In general, molecular beam scattering experiment requires a repetitive operation to enhance the signal-noise (S/N) ratio of the time-of-flight data. Applying the shock tube to the molecular beam scattering experiment, we must miniaturize the shock tube to reduce the operation interval.

In our previous report, we have developed the diaphragmless small shock tube as molecular beam source [4]. The inner diameter of the tube was 2 mm and the length was 160 mm. The Mach number of 2.8 with the repetition rate of 5 Hz or more was achieved using a solenoid pulse valve. In this study, we install the small shock tube in our molecular beam facility and evaluate the performance. Then, we discuss possibility to improve the performance using a current loop valve.

EXPERIMENTAL SETUP

Schematic of the small shock tube using the solenoid valve is shown in Fig.1. The main valve (Parker Hannifin, General Valve 009-630-900) separates the driver gas from the sample gas in the low pressure tube. The inner diameter of the tube is 2 mm and the length is 160 mm. A supply-valve (Parker Hannifin, General Valve 009-299-900) and an exhaust-valve (Parker Hannifin, General Valve 009-400-900) are attached on the sidewall of the tube to clear residual gas and fill new gas quickly. We used helium as the driver gas and nitrogen as the sample gas. The pressure of driver gas was fixed at 1 MPa and the pressure of sample gas was varied from 0.1 to 100 kPa. The shock wave velocity was measured by three piezoelectric pressure transducers (PCB 132A35). At the end of the tube, there is an orifice with 30μm inner diameter to generate reflected shock wave and to expand the heated gas into the chamber. As mentioned in our previous report, this apparatus is capable of generating the maximum Mach number of 2.8 and the estimated translational energy of 0.4 eV. We installed the shock tube in our molecular beam facility as a beam source and measured the translational energy using the time of flight (TOF) method Figure 2 shows the schematic of the TOF experiment. The pumping system of this facility is composed of a series connection of two turbo molecular pumps (1600L/s and 300L/s) and a liquid nitrogen cold trap. The molecular beam from the shock tube is modulated to the pulsed beam by the two-slit chopper rotating at 100 Hz. The detector of the pulsed molecular beam is the quadrupole mass spectrometer (Extrel, MAX-300). In order to control the pressure ratio between the driver gas (He) and the sample gas (N_2), the pressure of the sample gas was changed by adjusting the sample gas pressure with the regulator of the nitrogen tank. The pressure of the driver gas was set at 1 MPa and repetition rate was at 10 Hz. The schematic diagram of this operation condition is shown in Fig.3.

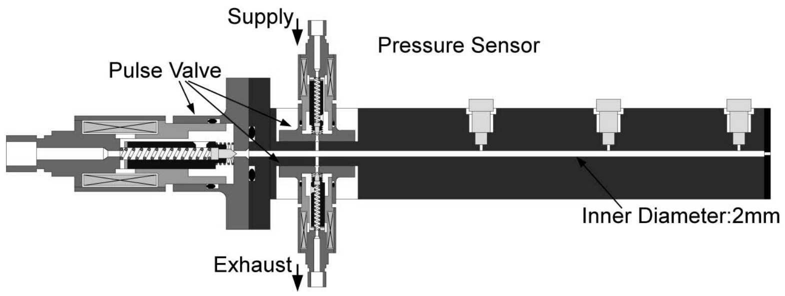


FIGURE 1. Cross-sectional view of the shock tube.

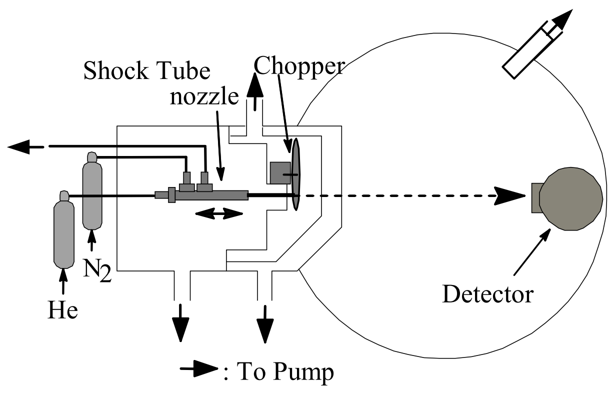


FIGURE 2. Schematic of the Time of flight experiment.

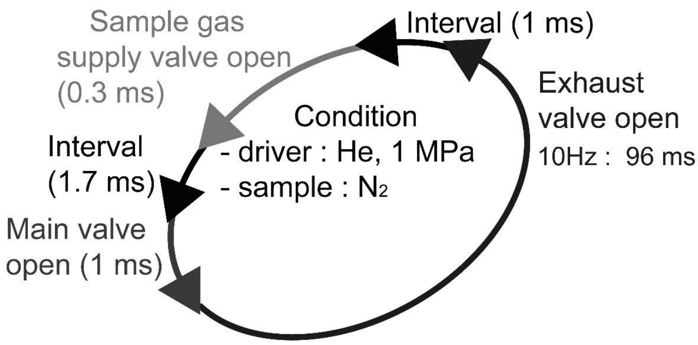


FIGURE 3. Schematic diagram of this operation condition.

MEASUREMENT OF TOF

Figure 4 (a) shows the TOF spectrum when the sample gas pressure upstream of the supply-valve was set at 0.2 MPa. The translational energy of the free jet expansion of nitrogen gas at room temperature was 0.076 eV. Using the shock heated molecular beam, we succeeded to increase the translational energy up to 0.186 eV. Figure 4 (b) shows the relation between the translational energy and the sample gas pressure upstream of the supply-valve. As increasing the sample gas pressure, the translational energy became lower. This is because increase of the sample gas pressure makes pressure ratio low, which leads to low translational energy. These results indicate that we can control the translational energy by the sample gas pressure. However, the S/N ratio was too low to obtain the TOF distribution in practical experimental time. Moreover, the measured translational energy was lower than the estimated energy from the shock speed. One of the reasons of the low translational energy is the thermal boundary layer effect at the orifice of the shock tube [5]. In order to get higher translational energy, the diameter of the orifice must be enlarged to reduce this effect. Another reason is the small valve-opening area of the solenoid valve compared to the tube diameter. The small valve-opening area causes the shortage of the driver gas flow into the shock tube and results in the low shock speed. In this study, we focused on this problem of the valve-opening time and modified the valve as mentioned below.

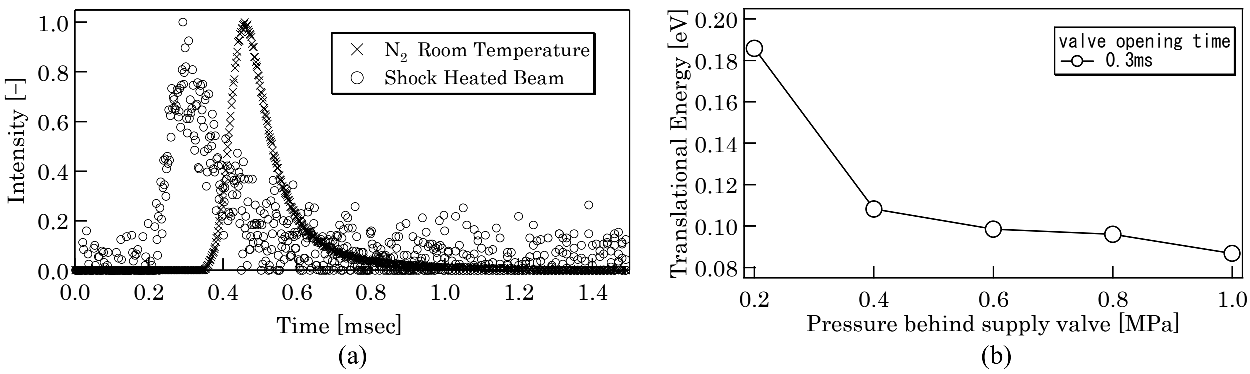
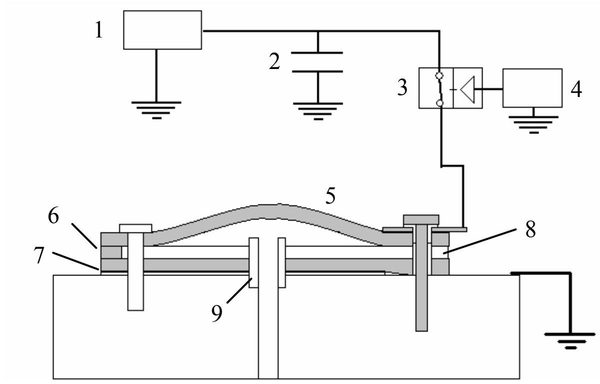


FIGURE 4. (a) TOF spectrum of shock heated beam, (b) Translational energy of shock heated beam.

CURRENT-LOOP VALVE

In order to get the better performance of the shock tube, we decided to replace the solenoid valve used as the main valve with the current-loop valve shown in Fig. 5. This valve was developed by Gentry and Giese [6] for the pulsed molecular beam source. The valve is actuated by high electrical current through a loop formed by two closely spaced metal plates. The magnetic repulsion generated by the opposing currents forces the two metal plates apart and lets the driver gas flow into the shock tube. We used 50 μF capacitor and silicon controlled rectifier (SCR) as the switch. The upside metal plate which seals the hole by bearing down on the fluoro-rubber tube is made from the phosphor bronze sheet with 0.2 mm thick, 3.5 mm wide, and 53 mm long. The inside diameter of the hole is 2 mm that is the same with that of the shock tube. The downside metal plate is made from the copper sheet with 0.2 mm thick, 3.5 mm wide, and 53 mm long. The Teflon sheet with 0.05 mm thick is placed between the two metal plates for electrical insulation. The upside metal plate formed a curvature to seal the fluoro-rubber tube at its stationary position. We applied pulsed current to this test circuit and measured the lift displacement of the metal plate with the high speed camera (Shimadzu, HPV-1). Figure 6 shows a side view of the center of the metal plate at 2130 A current. In order to optimize the various parameters such as applied current and curvature of the upside metal plate for sealing, we changed the current and measured the maximum lift in atmospheric pressure (Fig.7). Here, the curvature is defined as the inverse number of the radius of the upside metal bar. The data is fitted with the quadratic curve because the maximum displacement of the upside metal bar varies as the square of current according to the flexural oscillation theory. The upside metal bar must be lifted more than 500 μm to obtain enough valve-opening area corresponding to the sectional area of the shock tube with 2 mm inner diameter. According to Fig.7, the maximum lift of the upside metal bar reaches to 500 μm when applying about 1500 A current regardless of the curvature. The fact that the displacement is insensitive to the curvature is reasonable because the impulse force powered by current is much larger than the bending force of the upside metal bar. Table 1 shows the response time for the various valves. The response time of the current-loop valve is defined as the time for the metal bar to be lifted by 500 μm when 2130 A current is applied. The current-loop valve we designed achieved shorter response time than the solenoid valve. The response time of the shock tube valve is one of the important factors for the shock heated molecular beam because the response time has significant influence on the shock formation process. The response time of this valve can be further shortened by applying higher voltage to the circuit.



1. High voltage supply 2. Capacitor
3. SCR switch 4. Trigger generator
5. Metal plate 6. Metal spacer
7. Metal plate 8. Teflon spacer
9. Fluoro-rubber tube

FIGURE 5. Test circuit of the current-loop valve.

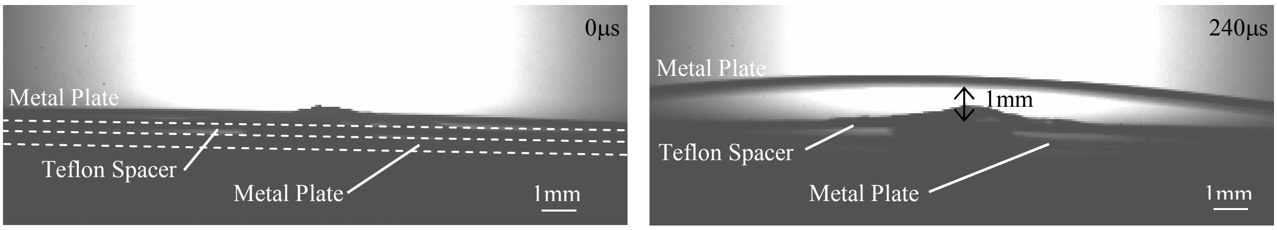


FIGURE 6. A side view of current-loop valve (2130 A current).

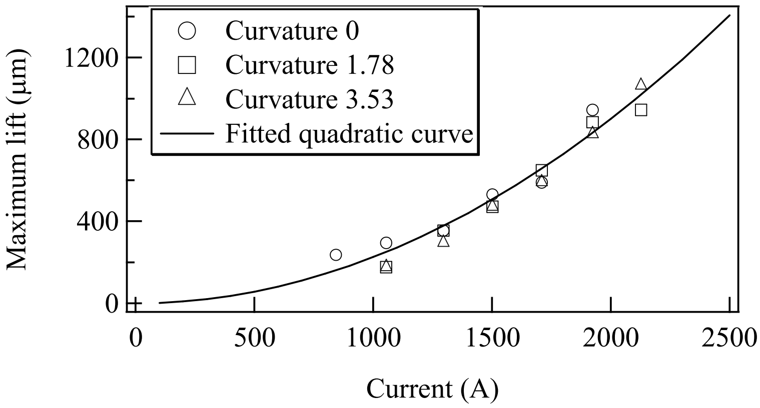


FIGURE 7. Relation between current and maximum lift.

TABLE 1. Response time of shock tube valve.

	Diaphragm	Solenoid valve	Current-loop valve
Response time (μs)	600	200	130

Diaphragm breaking time : measured by D. R. White [7]
Solenoid valve : General valve (009-630-900)

CONCLUDING REMARK

We installed the small shock tube with the solenoid valve in our molecular beam facilities as a beam source. The measured translational energy by TOF experiment was 0.19 eV. This energy was higher than that of the free jet expansion using nitrogen gas at room temperature, but lower than expectation. This is partly because the valve-opening are was smaller than the shock tube diameter.

In order to obtain higher energy molecular beam, we modified the shock tube valve by replacing the solenoid valve with the current-loop valve. The maximum lift of 500 μm and the response time of 130 μs were achieved by our current-loop valve.

We will construct a new shock tube with the current-loop valve and install it in our molecular beam facilities.

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