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Active Shock-Tube-Diaphragm Rupture with Laser Beam Irradiation

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ABSTRACT

We performed shock tube operations with a layer of diaphragm being ruptured by laser beam irradiation. Mylar or Cellophane was examined as the diaphragm material. It has been demonstrated that shock tube can be operated with this new technique. The absorbed energy depends on the material and thickness of the diaphragm and is an important control parameter.

INTRODUCTION

A shock tube is a fundamental experimental tool in researches on shock waves and associated fluid dynamics phenomena. It comprises two sections, a low-pressure channel and a high-pressure channel. They are separated from each other usually with a layer of diaphragm. In its ideal operation, the separation should be instantaneously and completely removed so that a shock wave, the characteristics of which are given from the simple shock tube relations, is generated right away and propagates through the low-pressure channel at a constant speed.

Yet, in real shock tube operation, it takes a finite period for the diaphragm to be ruptured so that the flow passage cross-section past the diaphragm reaches the full channel value.[1,2] If only a fraction of the diaphragm is ruptured or the period for the rupture is too long, a large pressure loss due to flow passage contraction occurs. Even if the pressure loss is tolerable, the shock formation distance is sensitive to the effective diaphragm rupture period. In particular, when we try to generate a weak shock wave, the fill pressure difference between the high and low pressure channels, and then the thrust onto the diaphragm fragments, are not large enough to neglect the necessary period for the passage to fully open.

If the diaphragm is spontaneously ruptured only with a mechanical load due to the pressure difference, the rupture pressure scatters by about 5%. Shock tube experiment needs higher reproducibility. A needle is commonly used to rupture the diaphragm. However, in this case, the needle and attached mechanics disturb the flow and shock wave formation; the rupture period still has a finite value.

In the case of an expansion tube,[3] the shock wave is reflected on the secondary diaphragm, which separates the shock tube from the acceleration tube. If the diaphragm is not ruptured at the moment when the shock wave reflects against the diaphragm, the flow is temporally stagnated; ideal high enthalpy flow cannot be generated.[4]

Yang et al.[5] developed a diaphragm-less shock tube. A layer of rubber membrane was used as the diaphragm. The uncertainty in the shock Mach number of less than 0.25 % was obtained. However, in their shock tube the high and low pressure channels cannot be connected straight. The bent flow passage causes a pressure loss.

An attempt of diaphragm rupture using electromagnetic repulsive forces was done,[6] however this system had some disadvantages: The opening time was not negligible -- at least 700μs -- and electrical disturbances generated by discharge of the storage energy created disturbances on instrumentation.

In this study, active diaphragm rupture with

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large-energy laser beam irradiation is tested, aiming in instantaneous rupture and in active timing control of the rupture. The objective of this study is to examine if shock-tube performance can be improved with this new technique.

EXPERIMENT

Figure 1 shows the experimental setup. For diaphragm rupture, a CO_2 TEA laser (TC-300, General Physics Institute, Moscow, Russia, wave length; 10.6μm, laser energy; 380J, FWHM of the first peak; 50ns.) is used. The beam cross-section is 150mm×150mm square as shown in Fig. 2. The laser has an unstable resonator; an 80mm×80mm square around the center of the beam has a negligible intensity. The beam shot from the CO_2 TEA laser is reflected on the surface of two plane aluminum mirrors and is introduced into a beam-reducer that is composed of a concave and convex conical, diamond-cut mirrors made of aluminum.

As is shown in Fig.3, the sizes of the beam are reduced to almost the half. Then, the laser beam is led into the shock tube. The shock tube has two channels of an 80mm×80mm square cross-section. The diaphragm separates the channel 1 from the channel 2. Mylar and Cellophane are used as diaphragm material. Mylar films of different thickness (5, 9, 25 and 50μm) are tested. The laser energy is also varied to 30, 70, 140 and 190J. The channel 1 (2 m in length) is used as the driver section; the channel 2 (4 m in length) the driven section. The left-hand end of the driver section is open to the atmosphere. Inner wall pressures are measured using piezoelectric pressure transducers (PCB 113A21, rise time; 1μs). The behavior of the diaphragm material after a laser beam irradiation is visualized by shadowgraph method.

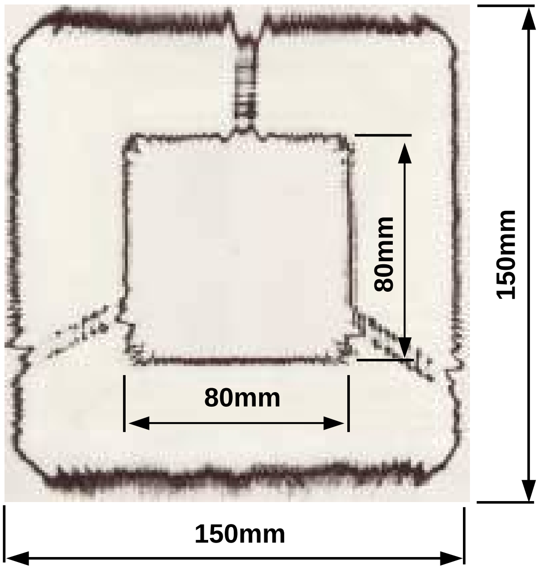


Fig.2 Beam profile recorded on copier paper, location P.

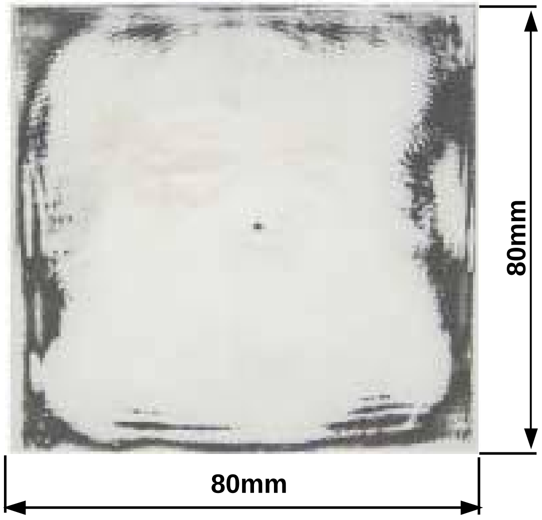


Fig.3 Beam profile after beam reducer at *x*=0mm.

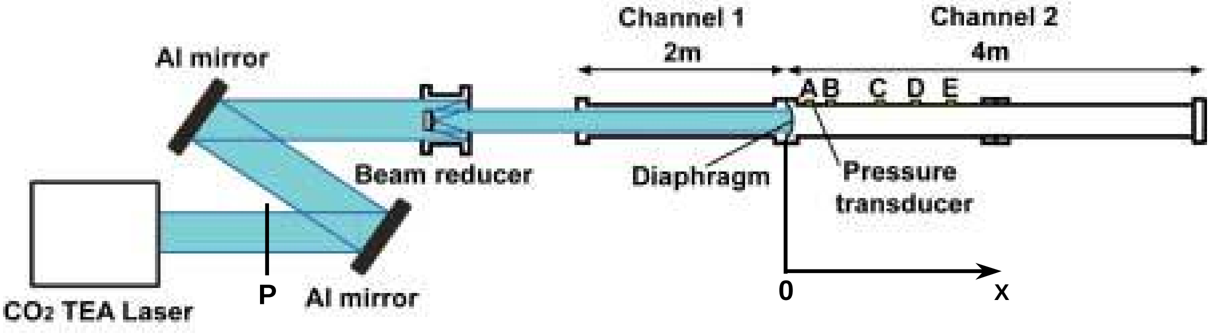


Fig.1 Experimental setup. (A; *x*=110mm, B; *x*= 320mm, C; *x*= 920mm, D; *x*= 1320mm, E; *x*= 1720mm)

RESULTS

Figure 4 shows typical pressure histories measured on the inner wall in the channel 2. The initial pressure in the channel 1 equals the atmospheric value and the pressure difference (ΔP) is set to 30kPa. A layer of Mylar film (thickness: 25μm) is used as the diaphragm. The laser energy incident onto the diaphragm is 300J.

In Fig. 4, large pressure fluctuations are observed at x=110mm. Yet, propagating downstream, the level of the fluctuations gets decreased.

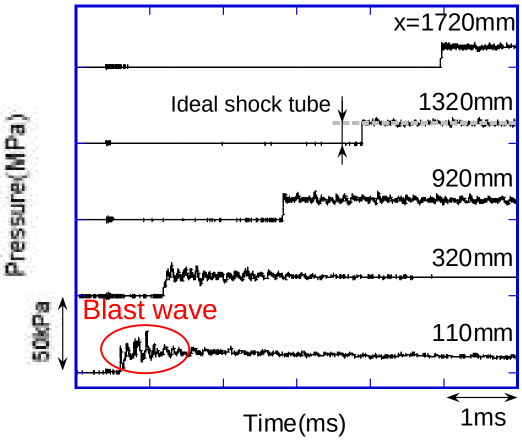
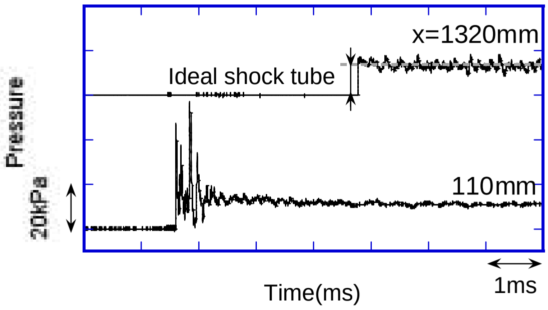


Fig.4 Pressure histories. Mylar: 25μm, ΔP=30kPa, E=300J.

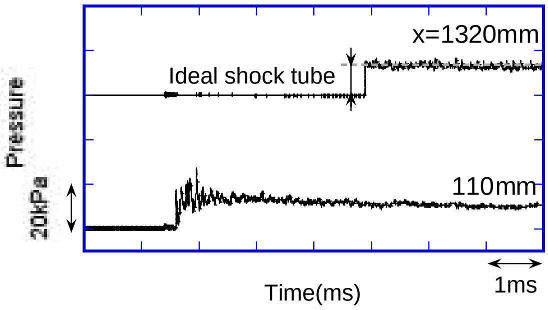
Effect of diaphragm material

With respect to the suitability for the laser-assisted rupture, Mylar (25μm in thickness) and Cellophane (24μm in thickness), both of which are widely used as shock tube diaphragm, are examined. The initial pressure difference, ΔP, is set to 30kPa. The laser energy is 300J.

Pressure histories measured at x=320mm (B) and x=1320mm (D) are shown in Fig.5. Large pressure fluctuations appear with the Cellophane diaphragm. This is the influence of blast wave generated due to ablation of the Cellophane diaphragm. According to the measurement using energy meter, only 25% of an incident beam can pass through a layer of Cellophane diaphragm (24μm), while 50% through a layer of Mylar diaphragm (25μm); The Cellophane diaphragm absorbs larger beam energy than the Mylar film does. Strong blast waves are driven by the ablated material from the Cellophane diaphragm.

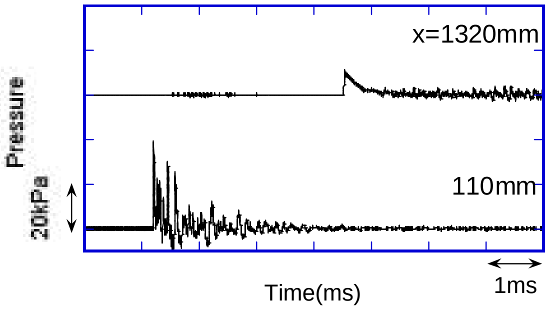


(a) Cellophane: 24μm

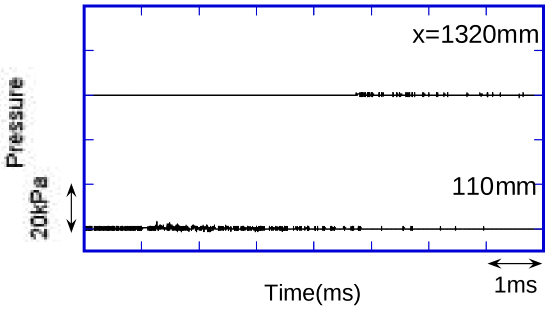


(b) Mylar: 25μm

Fig.5 Pressure histories either with Cellophane or Mylar diaphragm. ΔP=30kPa, E=300J



(a) Cellophane: 24μm



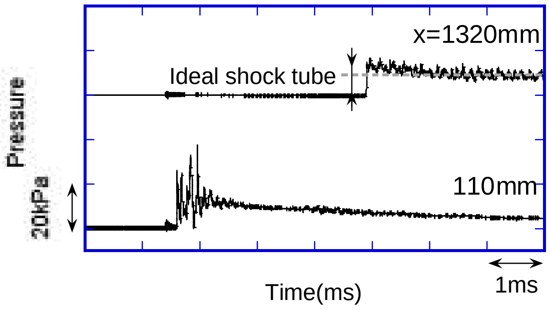
(b) Mylar: 25μm

Fig.6 Pressure histories either with Cellophane or Mylar in case of laser-assisted rupture. ΔP=0kPa, E=300J

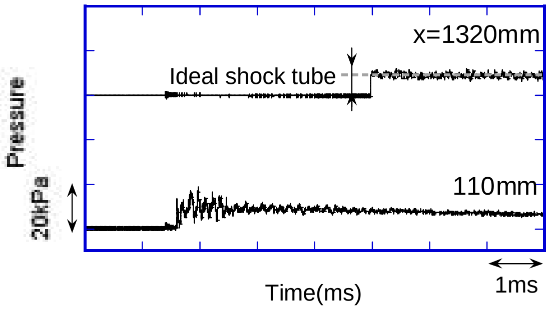
This is also confirmed by the pressure histories in Fig.6, which are measured without a pressure difference between the channel 1 and 2. In the case of the Mylar diaphragm, the pressure fluctuations induced by to the laser beam irradiation are almost negligible.

Effect of number of layers

Here the effects on number of diaphragm layers will be analyzed from the pressure histories. In case of five sheets of Mylar diaphragm of 5μm thickness, larger pressure fluctuations appear at x=110mm than that with a single layer of Mylar diaphragm of 25μm thickness. The most part of beam energy shot on a diaphragm passes through it and the rest of that reflects at the surface. If there are plural layers of diaphragm, the reflected beam is partially trapped in between. Hence, the absorbed energy is increased comparing to that in a single layer of the equal total thickness.

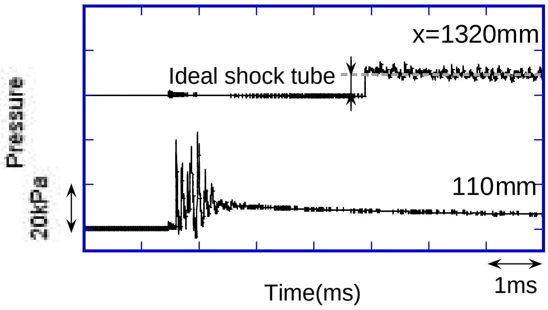


(a) 5μm, five layers.

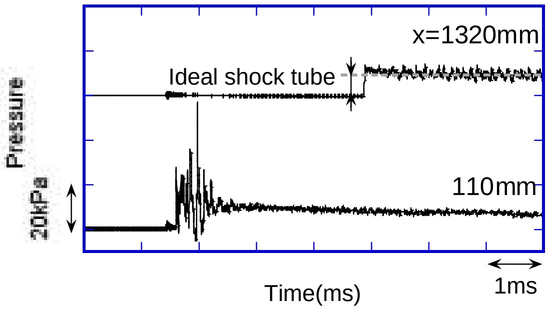


(b) 25μm, single layer.

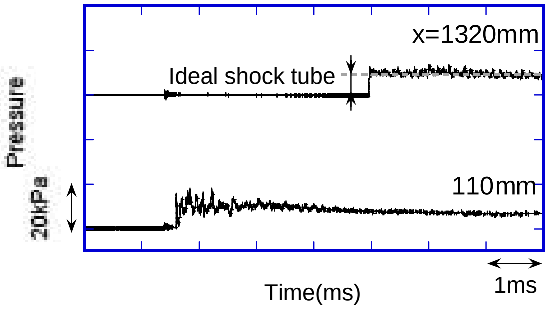
Fig.7 Pressure histories measured with diaphragm of an equal total thickness but different number of layers, Mylar, laser-assisted rupture. ΔP=20kpa, E=300J.



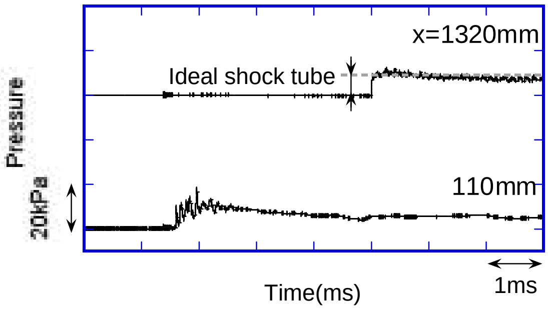
(a) 5μm thick



(b) 9μm thick



(c) 25μm thick



(d) 50μm thick

Fig.8 Pressure histories measured with different thickness of Mylar diaphragm, laser-assisted rupture. ΔP=20kPa. E=300J

Effect of diaphragm thickness

Pressure histories using Mylar diaphragm of different thicknesses are shown in Fig.8. In these experiments, the laser beam energy is set to 300J. These are measured at x=110 and x=1320mm downstream from the diaphragm. Δ*P* is 20kPa. When the diaphragm is thin (5μm and 9μm), large pressure fluctuation is observed.

Figure 9 shows shadowgraphs taken after laser beam is irradiated on to a layer of diaphragm in an open space. Two thicknesses; 5μm and 25μm, are examined. In the case of 5μm, blast wave generated by ablation of diaphragm is observed not only in front of but also behind the diaphragm. Such a blast wave is observed also with the thicker (25μm) diaphragm; yet, the blast wave behind the diaphragm is much weaker. If the diaphragm is thinner, ablation on the rear side becomes significant; a stronger blast wave is generated behind. This tendency is consistent with the pressure histories shown in Fig. 8. With the thinner diaphragm, pressure fluctuation is larger due to this stronger blast wave.

In the case of 50μm thickness, though the fluctuations are small, the ruptured area becomes smaller; the pressure loss past the diaphragm becomes larger. As a result, the overpressure behind the shock wave decreases. When a layer of Mylar diaphragm of 25μm thickness is used, the pressure fluctuation remains relatively small; the over pressure is smaller only by 2% than that of an ideal shock tube.

Among the present diaphragm thicknesses examined, the diaphragm of a thickness of 25μm exhibits the best performance. If the diaphragm is too thin, pressure fluctuations become large. If the diaphragm is too thick, the shock becomes weaker because of the insufficient ruptured area.

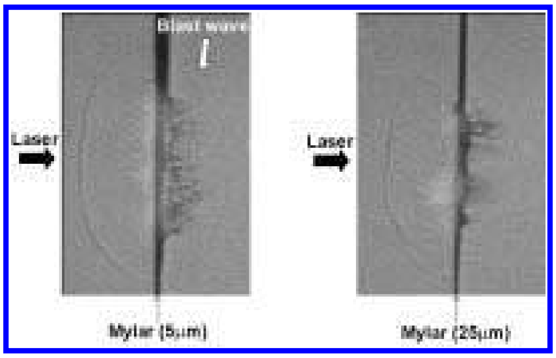
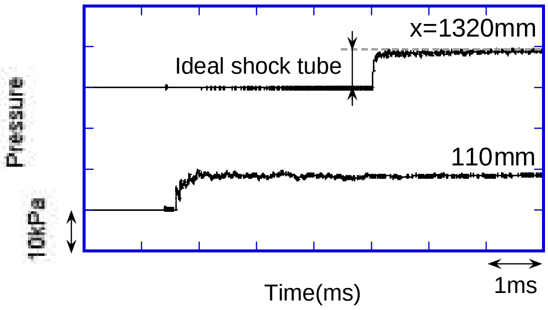


Fig.9 Shadowgraph images when the laser beam is irradiated on Mylar diaphragm, thickness; 5μm and 25μm. Δ*P* =0kPa.

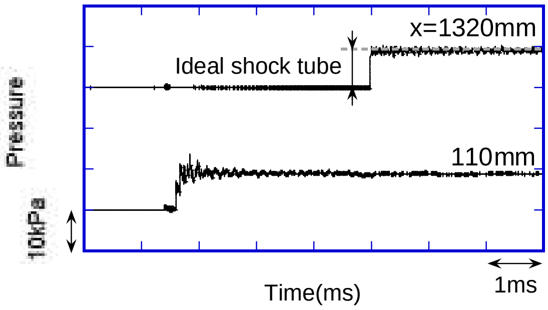
Effect of laser energy

Figures 10 and 11 show pressure histories with different laser energies. A layer of diaphragm, Mylar, 5μm or 9μm in thickness, is used. In the case of 5μm thickness, when the laser energy is 30J, the pressure rise is not sharp even at *x*=1320mm. Though the shock wave can be observed when the laser energy is 140J, pressure fluctuation is large at *x*=110mm compared with that of *E*=70J.

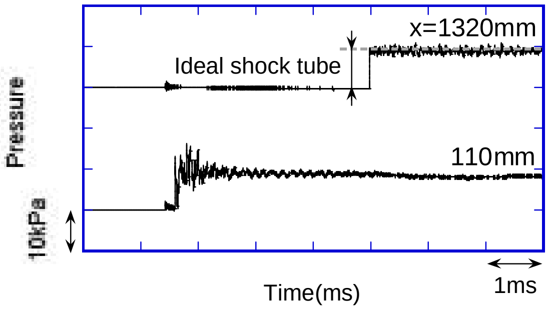
In case of 9μm thickness, the diaphragm is not ruptured completely when the laser energy is 30J and the pressure rise is small. When the energy is 140J, it is so strong that large pressure fluctuation is occurred. Pressure histories of *E*=70J is better than any other cases, but pressure loss is bigger than the case of 5μm thickness.



(a) Mylar: 5μm, *E*=30J

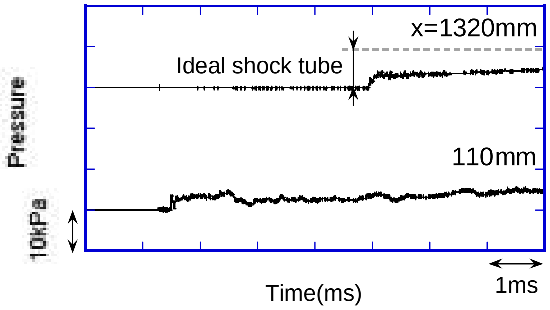


(b) Mylar: 5μm, *E*=70J

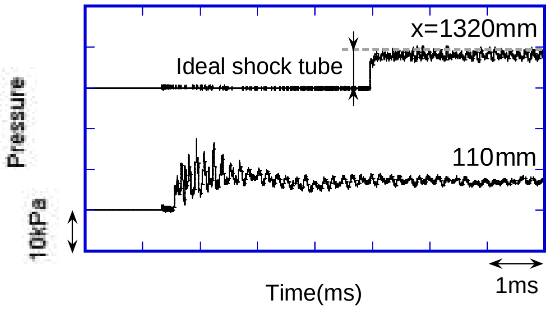


(c) Mylar: 5μm, *E*=140J

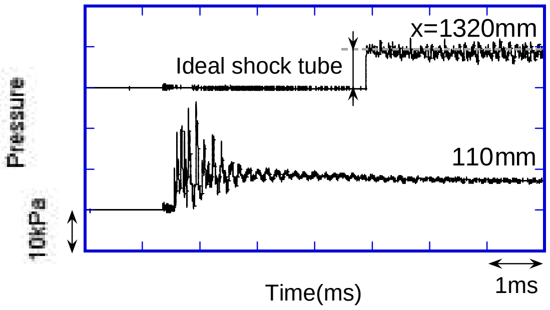
Fig.10 Influence of laser beam energy (30,70 and 140J). Diaphragm material; Mylar (5μm), Δ*P*=20kPa



(a) Mylar: 9μm, *E*=30J



(b) Mylar: 9μm, *E*=70J



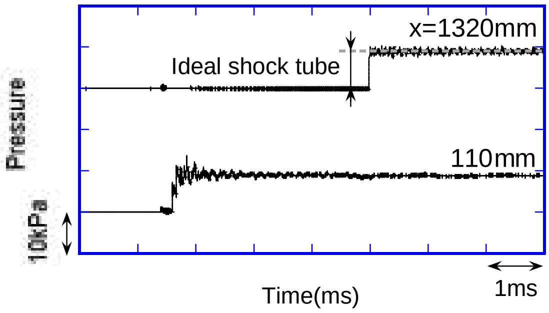
(c) Mylar: 9μm, *E*=140J

Fig.11 Influence of laser beam energy (30,70 and 140J). Diaphragm material; Mylar (9μm), Δ*P*=20kPa

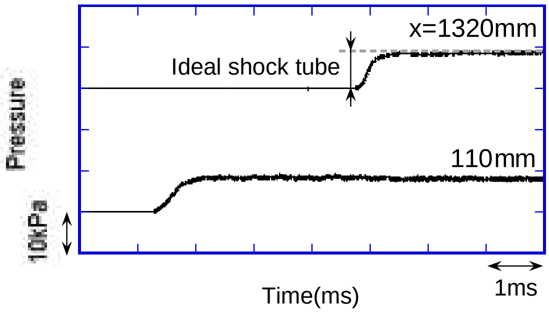
Therefore, optimal combinations of a diaphragm thickness and a laser energy exist for diaphragm rupture with small pressure loss and fluctuation.

Comparison with other rupture methods

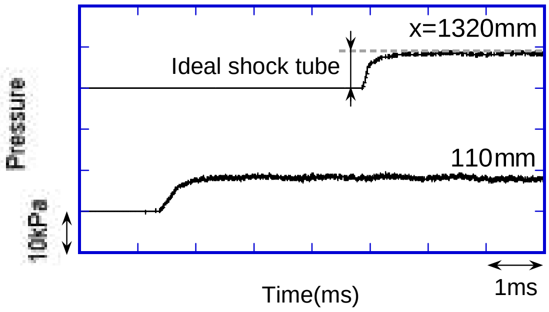
Here, pressure histories of laser-assisted, spontaneous and needle-assisted rupture are compared. Diaphragm used for each rupture is Mylar (5μm), which shows the best pressure history among Mylar (*E*=70J) in the present study. The experimental condition is the same as of 3.3. Figure 12 shows pressure histories obtained with the respective methods. In the case of the spontaneous and needle-assisted rupture, the pressure rise is not sharp even at *x*=1320mm downstream from diaphragm. On the other hand, for the laser-assisted rupture sharp pressure rise is obtained at *x*=1320mm, although small pressure fluctuations are accompanied.



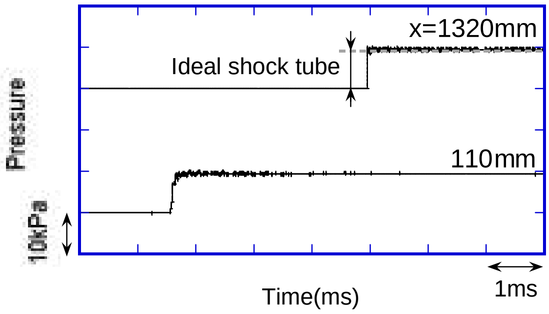
(a) Laser (Mylar: 5μm)



(b) Spontaneous (Mylar: 5μm)



(c) Needle (Mylar: 5μm)



(d) Needle (Cellophane: 24μm)

Fig.12 Pressure histories either with Cellophane or Mylar in case of needle-assisted, passive and laser –assisted rupture. Δ*P*=20kPa.

Overall with the laser-assisted rupture over pressure characteristics similar to that with needle-assisted rupture of Cellophane (see Fig. 12(d)) is obtained. Considering that in the case of the laser-assisted rupture even rupture active temporal control is possible, the presented results will be useful in particular to expansion tube operation.

CONCLUSION

Through the present experiments, it is confirmed that shock tube operation with active diaphragm rupture using an energy laser is possible. Since the amount of energy absorbed in the diaphragm affects the pressure fluctuation, the material, the thickness of the diaphragm and the laser energy are important control parameters. This method is expected to be useful not only in the shock tube operation but also for the active temporal control in the expansion tube operation.

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