

# Mass transport by an induced flow with a laser focusing shock wave

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Mass transport by the shock wave induced flow was investigated for the control in the micro fluidics. The shock wave was generated by laser focusing with a pulsed laser. Using a pulse laser, a non-stationary flow was induced into a micro channel. To obtain a desired flow by designing the periodic frequency of the laser, an interference with the individual wall and shock wave should be studied for the optimization. Moreover, a fluid transportation by diffusion and convection in local area due to the shock-induced flow is aimed to establish an effective flow control. In the high viscous flow, the flow control is very difficult. In this study, the visualization of laser focusing shock wave and flow field measurement by PIV technique are carried out. The particle velocity distribution seeded in the flow was obtained and its velocity relaxation was discussed.

Keywords: Mass transport, Micro-blast wave, Laser focusing, Flow visualization, PIV

## 1. Introductions

Mass transport in micro channel is an important technology in such as bio-engineering, medical analysis, micro electronics, a lot of method have been developed to transfer the carriers or functional fluid to the target. The particular problems should be considered in such devices, e.g. fluid viscosity, surface tension and Van der Waals molecular force may be dominate the flow field. In order to establish the specified flow, several types of fluid transfer technique were applied in the milli- or micro-flow channel, such as high pressure driven flow, oscillating flow, electrophoretic migration, ultrasonic or oscillating stream, etc. Micro shock wave is also a prospective drive source. The non-linear velocity fluctuation is a very interesting stream for local flow control. In this technique, pulsating flow, which is induced by laser focusing can be generated into a desired position by controlling the focus point of the laser. Not only in micro channel, but also in space engineering, laser focusing shock wave has been studied to apply as a pulse thruster. In other case, an application of dry cleaning in silicon wafer process has been attempted to remove the contaminated particles from the reactor. Therefore, it is very important to study the

shock driven flow or driven force acted on the particles.

The objective of this study is to establish the technique that controls the flow in mili or micro channel, which is available in micro technologies. In this study, fluid control using the shock wave

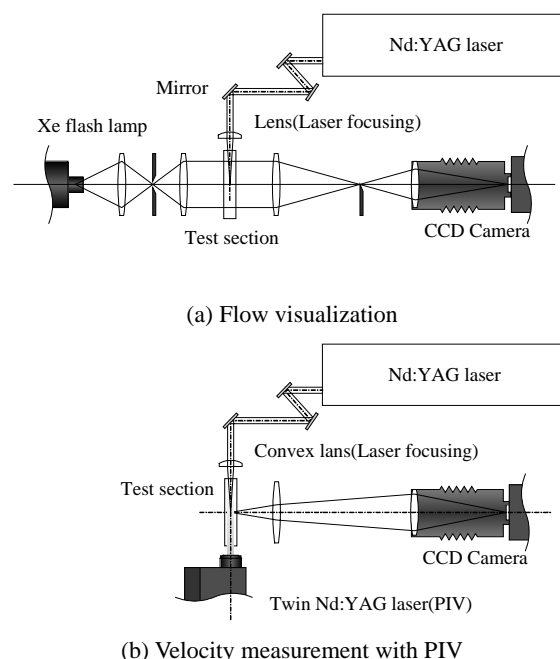


Fig.1 The schematic diagram of experimental setup.

generated by laser focusing was attempted to develop a pulsating flow in micro channel. Using a pulsed laser to generate a shock wave, a non-stationary flow was induced in the channel. To obtain a desired flow by designing the periodic frequency of the laser, an interference with the

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individual wall and shock wave should be studied carefully for the optimization. Moreover, a fluid transportation by diffusion and convection in local area due to the shock-induced flow is aimed to establish an effective flow control. The influence of the viscosity is considerably significant, of course, due to the small scale. So, the introduction of vortices or turbulence is preferable for the flow control, mixing, and molecular reaction. In this study, a flow field behind shock wave was studied with PIV technique.

## 2. Experimental setup

Figure 1 shows the schematic of experimental setup. Figure 1(a) shows a setup for flow visualization and Fig.1(b) shows for the flow field measurement. A single pulsed Nd-YAG laser (Spectra Physics, CRG-130) was used for shock generation, which wavelength is 532nm (second harmonic), output energy is 200mJ/pulse and the pulse duration is about 7ns. A converging lens with 100mm of focal length and 65 mm in diameter is used to focus the laser beam appropriately. Approximately,  $2\text{MJ}/\text{mm}^2$  energy was supplied in the volume with several mm diameters. A shock wave was induced with this laser focusing. Experiment is carried under two different conditions. At first, a shock wave was produced in a free space, and its propagation was observed. The propagating velocity of this spherical shock wave was measured. Secondly, a shock wave is generated between two parallel flat plates, which clearance is 5mm, so a cylindrical shock wave was induced in the test section. The observation area is the same as  $80\text{mm} \times 80\text{mm}$  for both of the cases.

The flow visualization was carried out with a schlieren technique. The light source of visualization is Xenon flash lamp (L7684), which has about 1ms duration time. The propagation of the shock wave was measured by the grab shot which was acquired with this light source and CCD camera (IDT Co'Ltd, Sharp VISION-1400 DE), which resolution is  $1360 \times 1036$  pixels and 8 bits depth in intensity. These timing was decided by the digital delay unit (Stanford Lab., DG535). The shock wave

Mach number was calculated from position of shock front in the images.

The flow velocity behind the shock wave is measured by PIV technique. A double pulsed Nd:YAG laser(Solo-3) was used for the illumination, which wavelength is 532nm(second harmonic) and output energy is 50mJ/pulse. The flow images were acquired with a CCD camera as well as visualization. An incense smoke was used as the tracer particles, which nominal diameter is approximately 0.5 mm. Both imaging optics was same in order to establish the relation between position of shock wave front and induced velocity field. PIV measurement was carried out in the channel. The laser light sheet was introduced in the test section parallel to the two flat plates.

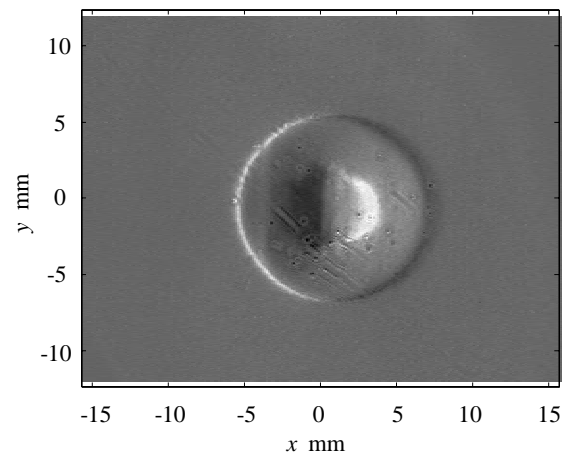


Fig. 2 Schlieren image of a propagating shock wave,  $t=10\ \mu\text{s}$ , cylindrical shock.

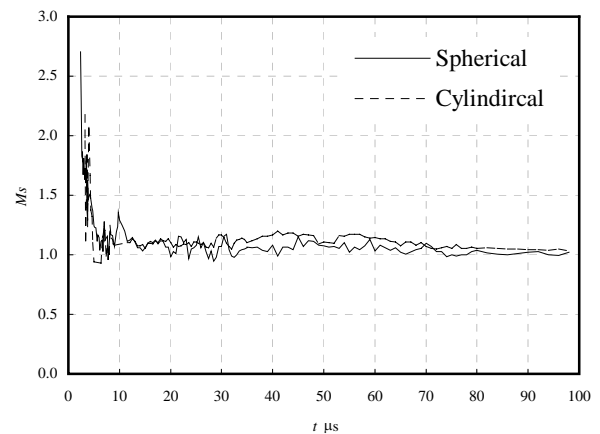


Fig. 3 Shock attenuation with time

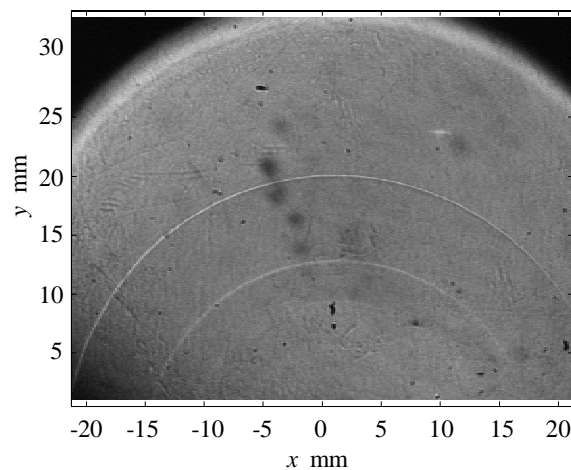


Fig. 4 Schlieren image of propagating shock wave induced laser focusing ( $t=50\ \mu\text{s}$ , cylindrical shock)

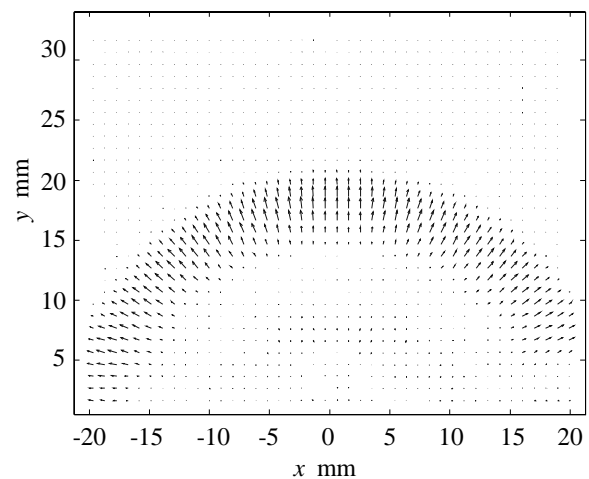


Fig. 5 Velocity field behind shock wave obtained by PIV measurement ( $t=50\ \mu\text{s}$ , cylindrical shock)

### 3. Shock wave propagation

Preliminary experiment is carried under two different conditions. At first, the shock propagations in a free space was measured. The propagating velocity of this spherical shock wave was measured in terms of times. Secondly, a shock wave is generated between two parallel flat plates, which clearance is 5mm, so a cylindrical shock wave was induced in the test section. The observation area is the same as 30 mm x 20 mm for both of the cases. The observation was carried out from immediately after the laser emission until 100 ms. Figure 2 shows flow image of cylindrical shock wave at 10 ms after the laser emission and Fig. 3 shows a shock attenuation of spherical and cylindrical shock wave. As reported in the previous investigations [1-5], the shock speed was attenuated in a short distance. Mach number and radius of shock wave are calculated from visualization images. No remarkable difference of propagation is shown between two conditions.

Following laser emission, plasma area could be found at center of focal point but shock wave front could not be found. Shock wave front could be found clearly at 3 ms after the laser emission. Then, Shock wave radius of axis of laser optic is about 2.5mm and shock wave Mach number is about 2.0. The reason that shock wave front could be seen soon after the laser emission is that the duration time of light source is too

longer against the shock moving speed. Shape of early shock wave front is ellipse along the produced plasma. At 5 ms after, shape of shock wave front becomes just about spherical or cylindrical. So, radius reaches 4.5mm and shock wave Mach number converges approximately 1.1. And then, Strong density gradient is found in the shock wave front. Shock wave radius develops approximately 40mm at 100 ms. It was confirmed that the shock wave generated by laser focusing is relatively weak shock wave

### 4. Flow field measurement

The flow velocity behind the shock wave

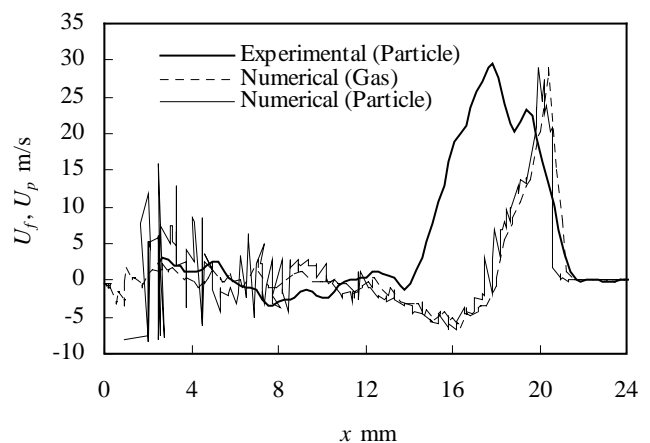


Fig. 6 Flow and particle velocity profile at  $55\ \mu\text{s}$

is measured by PIV technique. Flow field measurement was carried out for the cylindrical shock wave propagation. The measurement was carried out during 25 to 80 ms after the laser emission. Figure 4 shows a shock wave that was visualized by schlieren technique. The focal point of the laser focusing locates out of the image 2 mm below. In this figure, a shock front observed clearly, in addition, the second wave observed behind the shock front. This may be a front of rarefactions wave of blast wave. In fact, as shown in the next figure, the particles are decelerated immediately in this region. Figure 5 is the corresponding velocity field by PIV at 50 ms. As shown in this figure, a velocity field induced by shock wave was clearly measured behind the shock wave. The induced velocity is completely axisymmetric. The particles are accelerated just behind the shock front, then these are decelerated by the rarefaction wave, which is observed in Fig.4.

The shock position and radial particle velocity are shown in Fig. 6. The particle and gas in front of shock wave is rest. The flow velocity induced by the shock wave should be discontinuous, because the mean free path is approximately 60 nm. However, the particle velocity increases linearly just behind the shock wave and it reaches to maximum velocity at about 4mm behind the shock wave, which is approximately 30m/s. And then, the flow velocity decreases rapidly. In this study, actual flow speed behind shock wave or thickness of shock wave front that is proved by quantitative density gradient field or pressure field is not carried out. Considering qualitative density gradient field that is shown by visualization image of shock wave (See Fig.4), thickness of shock wave front is not very thick and it is inferred that actual flow speed gradient behind shock wave front should be discontinuous. Also, considering distance from position of shock wave front to peak of particle speed, particle speed distribution is caused by inertial relaxation of particle. In this study, it was confirmed that smoke could be applied for flow behind shock wave and narrow area, however, the velocity relaxation [6] should be considered in the analysis.

## 5. Conclusions

Fundamental study was carried out to control the flow in small area by using a laser focusing shock wave. A laser focusing shock wave is visualized by schlieren technique and induced velocity is obtained by PIV technique. Obtained velocity field shows a reasonable result that was predicted theoretically. It was found that the induced flow field responded for the shock propagation in a narrow channel. In the PIV measurement, the velocity relaxation should be considered in the flow analysis, on the other hands, from the view-point of particle transfer such as micron size, the momentum relaxation and response against the flow velocity should be taken into consideration in the analysis.

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