

# ソニックブーム伝播に対する大気乱れの影響に関する モデル実験

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## 1. 研究概要

本研究は、レーザーパルスによって発生する弱い衝撃波が伝播する際、周囲の空気乱れ（速度乱れ）によってその圧力波形がどのように変化するか、実験室でのモデル実験により系統的に調べ、そのモデル化のためのデータを得ることを目的とする。

レーザーパルスによってプラスト波が発生する過程をレーザープラズマの挙動を含めて可視化し、先頭の衝撃波が壁で反射した背後の圧力履歴を測定することによって、模擬的なソニックブーム（過剰圧 200 Pa 程度以下）が発生できることが確認された。さらに、スリットから噴出する乱流を通過することにより、過剰圧の最大値が大きく変動すること、圧力の立上り時間が大幅に増加する結果が得られた。

## 2. レーザー誘起衝撃波発生過程

まず、レーザーパルスによって発生するプラズマ、衝撃波の挙動を明らかにすることによって、本研究目的に適した条件を検討した。レーザーパルスの発生源として、名古屋大学にある TEA（Transversely-Excited Atmospheric）炭酸ガスレーザー（エネルギー 10 J、半値幅 140 ns）、Nd:YAG レーザー（エネルギー 1 J、半値幅 9 ns）、Nd:YLF レーザー（エネルギー 20 mJ、半値幅 10 ns）の 3 台を用い、レーザーパルスビームを実験室空間に集光し、半開放空間に衝撃波を発生させる技術を確認した。

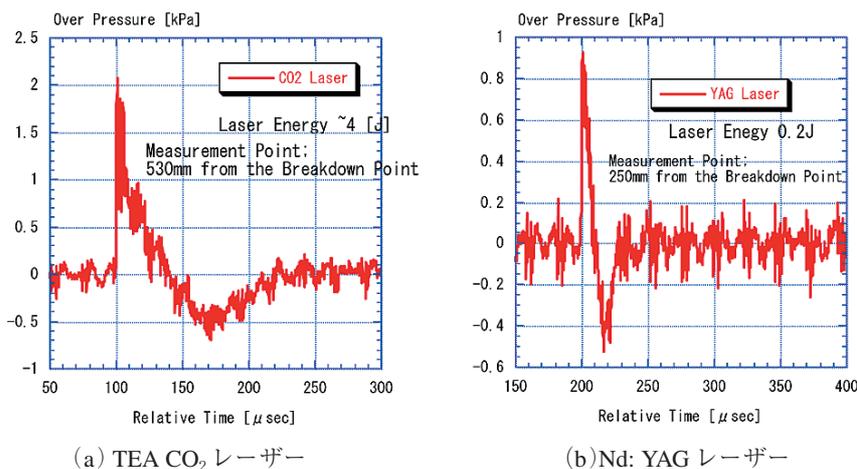


Fig. 2-1 実験で得られた圧力履歴

Fig. 2-1 に TEA CO<sub>2</sub> レーザーおよび Nd:YAG レーザーによって発生した衝撃波による圧力波形を示す。前者の方がパルスエネルギーが大きいため得られる過剰圧は高い。しかし、最初のレーザーパワーピークの半値幅は、前者が 170 ns、後者は 9 ns であり、前者は特に負圧から大気圧に戻るのに要する時間が長い。この結果より、3 の乱流との干渉実験のために

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Nd: YAG レーザーを用いることとした。

実験では、衝撃波は点源が無限の大きさに広がるのではなく、ある有限の体積をもっており、プラズマが膨張・収縮を繰り返す。これが、過剰圧の圧力波形に影響を及ぼす。そこで、衝撃波との関連を調べるため、発生したレーザープラズマの挙動を、高速度フレーミングカメラ（ $10^6$  frame/s, 100 frames ならびに  $10^8$  frame/s, 8 frames）を用いて光学可視化した。詳細については、付録 A1 に譲る。

### 3. レーザーパルス生成衝撃波と噴流との干渉

1 MPa 程度の圧力に空気を充填した貯気槽から、第二貯気槽に開けられたスリットを通して噴流を発生し、速度乱れ場を発生させる装置を開発した。Fig. 3-1 に実験装置の概要を示す。

コンプレッサーからフィルターを介して、容積  $1 \text{ m}^3$  の貯気槽に圧縮空気を充填する。直方体容器である乱流発生装置 (TG) は、一面に幅 2 mm、長さ 200 mm のスリットが設けられており、そこからシート状の噴流が放出される。噴流の強さは、乱流発生装置内の静圧を調整することによって制御される。

Nd : YAG レーザーパルスは、レンズにより大気中に集光され、絶縁破壊を誘起してプラスト波（ほぼ球対称に伝播し背後に膨張領域を伴う衝撃波）を発生させる。衝撃波の圧力は、プラスト波発生位置から  $L_a$  の距離に置かれた高速応答 ( $1 \mu\text{s}$ ) ・高感度の圧電型圧力変換器により測定される。圧力変換器は、直径 200 mm の円盤の中心に置かれ、有効測定時間での周囲からの膨張波の影響を受けないように配慮されている。圧力変換器からの信号は、シグナルコンディショナーを介して、デジタルオシロスコープにより記録される。

乱流発生装置と圧力測定位置までの距離を  $L_b$ 、噴流とプラスト波発生位置までの距離を  $L_c$  として実験を行った。Table 3-1 に実験条件を示す。

Case 1, Case 3 では衝撃波が噴流を通過したのちに圧力変換器に到達するが、Case 2 と Case 4 では、衝撃波が噴流を通過せずに圧力変換器まで到達する。圧力変換器の位置は、Case 1 では噴流中心面から 13 cm であるのに対して、Case 3 では 25 cm と対称位置により近いところに位置する。それぞれの Case に対して、噴流あり、なしの場合それぞれ 10 回ずつ圧力測定を行った。

Fig. 3-2 は Case 1 について噴流あり (右), なし (左) の場合に測定された過剰圧の時間変化の例を示す。噴流がない場合、

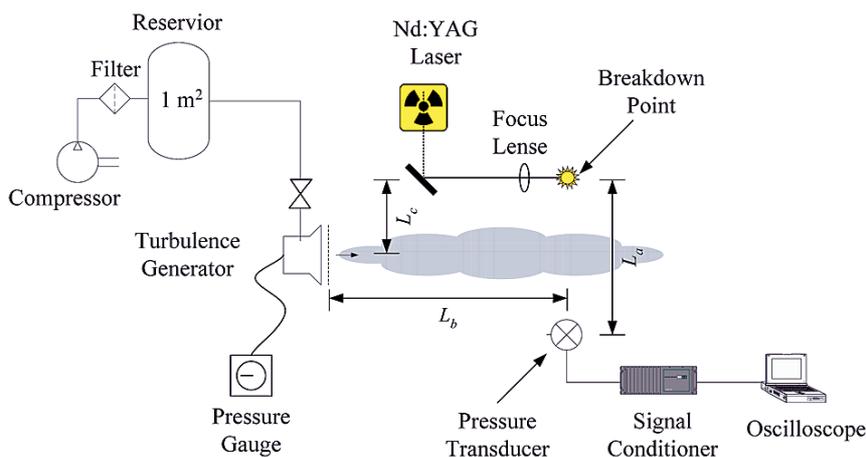


Fig. 3-1 実験装置

Table 3-1 Experimental conditions

	$L_a$ (cm)	$L_b$ (cm)	$L_c$ (cm)	Pressure in TG (kPa)
Case 1	63	83	50	10
Case 2	10	83	50	8
Case 3	60	83	35	7
Case 4	30	83	35	5

圧力の時間変化は非常に再現性が高い。これに対して噴流がある場合には、その最大値、立上り時間ともにばらつきが大きくなる。Fig. 3-3に、各ショットごとの最大過剰圧と立上り時間の変化、Table 3-2に対応する統計評価量を示す。過剰圧を比較すると、平均値は、397.2 Paと398.0 Paとなり有意差はない。しかし標準偏差は、噴流がない場合6.5 Paであるのに対して噴流がある場合には123 Paと約20倍に増加する。すなわち、噴流により過剰圧の最大値は増減両側に大きく変化する。立ち上がり時間の平均値を比べると、噴流なしの場合1.78 $\mu$ sであるのに対して、2.68 $\mu$ sと約1.5倍となる。標準偏差は、それぞれ0.02 $\mu$ sと1.60 $\mu$ sで、80倍大きくなる。

Fig. 3-4に、噴流を通過しない条件における圧力測定例を示す。これらの場合は、噴流あり、なしによる有意な違いは見られない。このことから、Fig. 3-2, 3-3で得られた違いは、噴流の影響によるものであることが確かめられた。

Fig. 3-5, 3-6, Table 3-3に、Case 3の場合の結果を示す。大まかな傾向はCase 1の場合と同様であるが、噴流の相対位置が異なるため、定量的には違いがある。

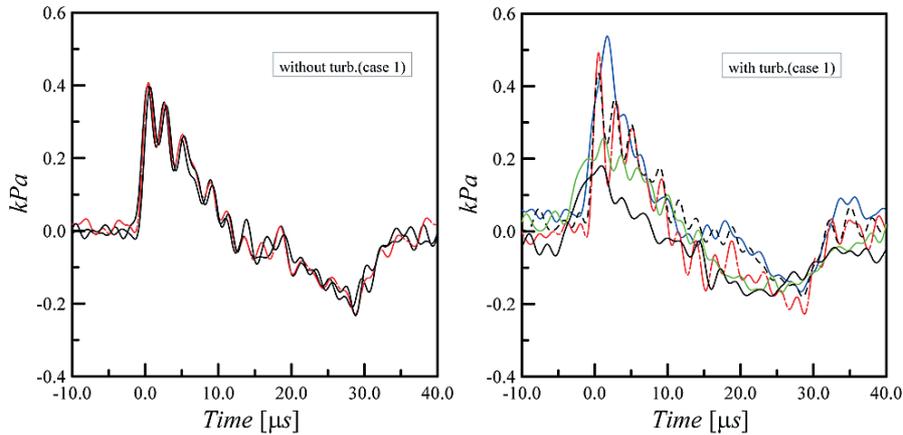
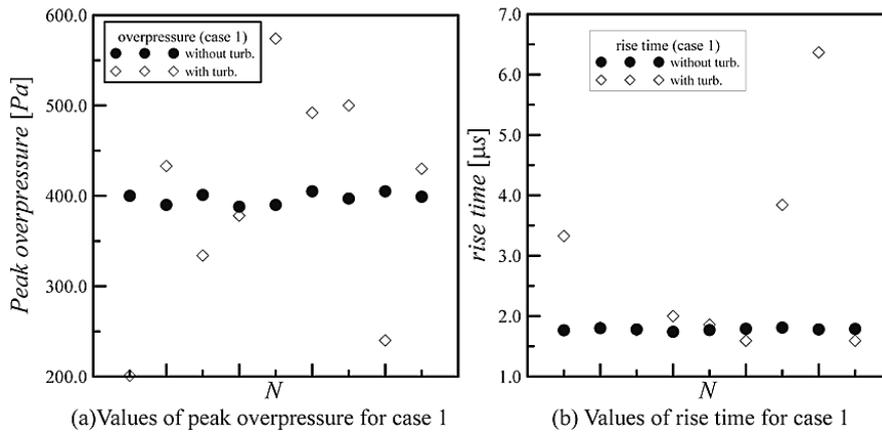


Fig. 3-2 過剰圧測定例 (Case 1), 左; 噴流なし, 右; 噴流あり.



(a) Values of peak overpressure for case 1 (b) Values of rise time for case 1

Fig. 3-3 過剰圧の最大値 (左) および立上り時間 (Case 1).  
横軸は各条件でのショット番号.

Table 3-2 Case 1における統計評価量

Case 1	Without turb.		With turb.	
	Rise time ( $\mu$ s)	Over pressure (Pa)	Rise time ( $\mu$ s)	Over pressure (Pa)
Mean val.	1.7804	397.2	2.684	398
Max.	1.81	405	6.366	574
Min.	1.74	388	1.5917	201
St. deviation	0.0205	6.476	1.5983	122.8

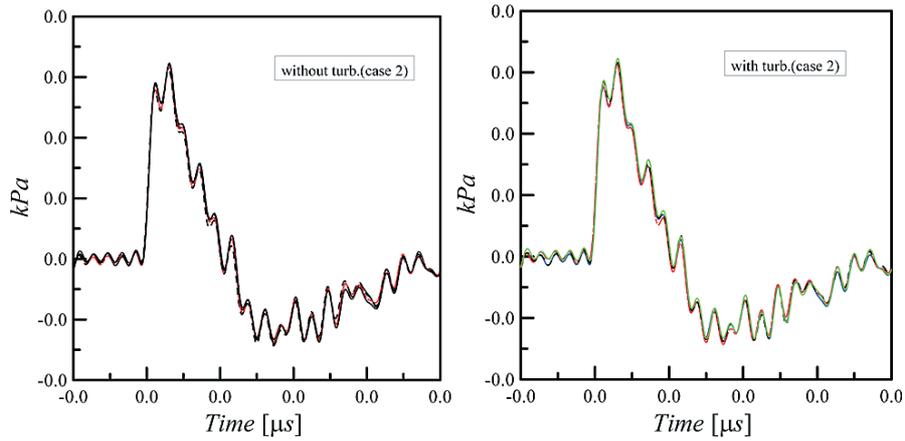


Fig. 3-4 過剰圧測定例（Case 2），左；噴流なし，右；噴流あり。

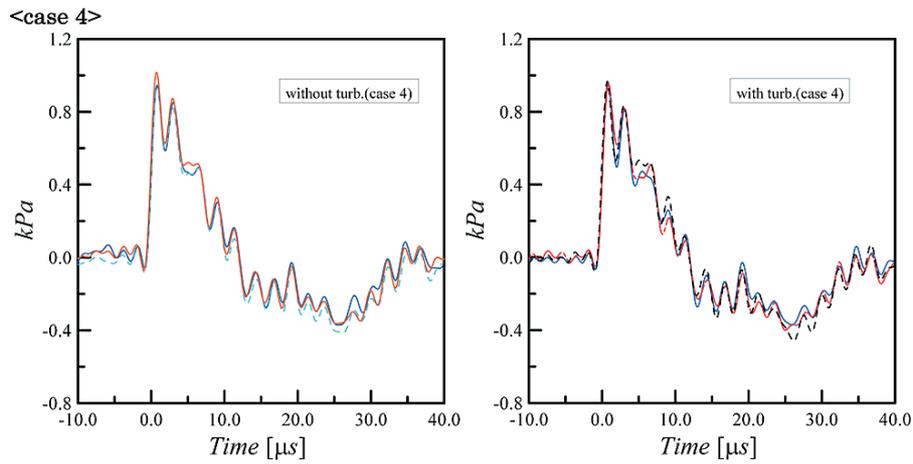


Fig. 3-5 過剰圧測定例（Case 4），左；噴流なし，右；噴流あり。

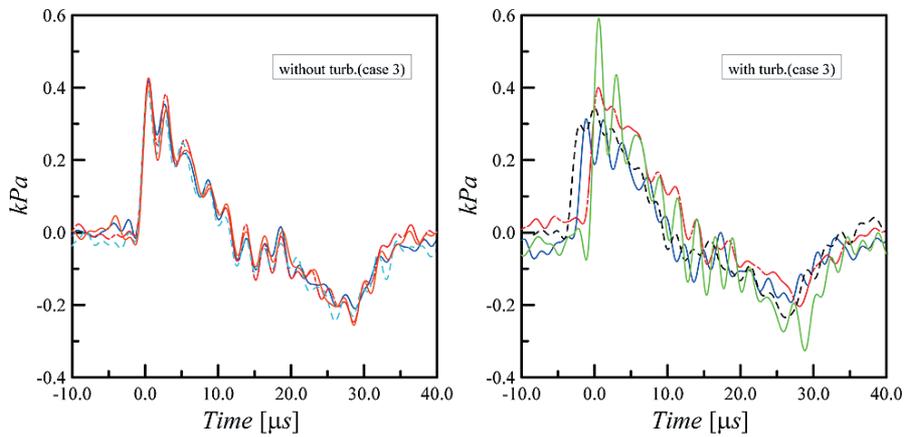


Fig. 3-6 過剰圧測定例（Case 3），左；噴流なし，右；噴流あり。

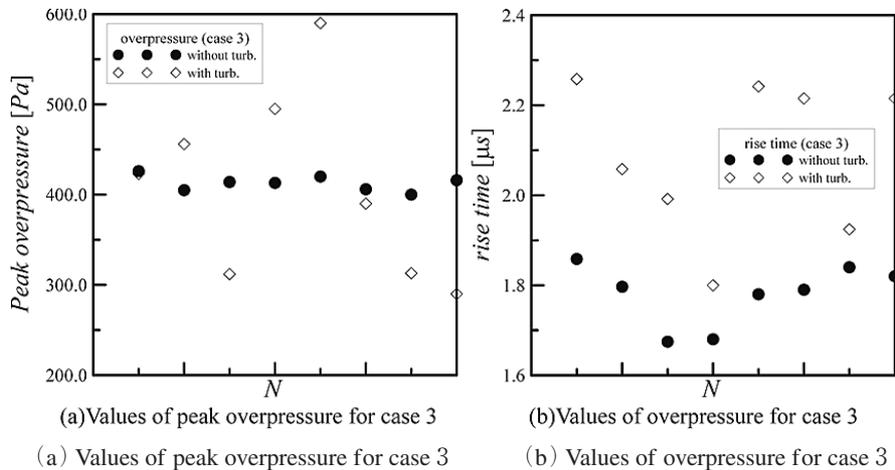


Fig. 3-7 過剰圧の最大値 (左) および立上り時間 (Case 3).  
横軸は各条件でのショット番号.

Table 3-3 Case 3 における統計評価量

Case 3	Without turb.		With turb.	
	Rise time ( $\mu\text{s}$ )	Over pressure (Pa)	Rise time ( $\mu\text{s}$ )	Over pressure (Pa)
Mean val.	1.78	412.5	2.08796	408.6
Max.	1.8583	426	2.2583	590
Min.	1.6746	400	1.7997	290
St. deviation	0.06847	8.519	0.171	104

#### 4. ま と め

本研究では、レーザーパルスを用いてプラズマおよび衝撃波を発生させ、光学可視化によりその挙動を観測した。さらに、シート状の噴流を作用し、最大過剰圧と立上り時間に対する影響を調べた。ここで報告した実験条件の範囲において、噴流を作用することによる最大過剰圧への影響は、平均値についてはわずかであった。しかし、その標準偏差は噴流を作用すると10倍以上に増加した。過剰圧の立上がり時間は、噴流を作用させると平均値が1.2～1.5倍に増加、標準偏差は12～20倍になった。

以上の傾向は、基本的に文献(1)で報告された結果と合致している。文献(1)では放電により衝撃波を発生させたのに対して、本研究ではパルスレーザーを用いているが、再現した現象は本質的に同じものであることが示唆される。このデータを取得するのに用いたNd:YAGレーザーは最高繰返し周波数1 Hzであるが、Nd:YLFレーザーの方は最高10 kHzまで可能であり、今後様々な発展的実験が可能である。

#### 参 考 文 献

- (1) Bart Lipkens and David T. Blackstock, "Model experiment to study sonic boom propagation through turbulence. Part I: General results," J. Acoust. Soc. Am., Vol. 103, No. 1, 1998, pp. 148–158.

## 付録A1：レーザー誘起プラズマ／ 衝撃波の発生／可視化実験装置

### A1.1 Experiment Setup

Experimental system is divided into two systems—plasma generation system and Schlieren visualization system. Fig. A 1-1 shows schematic of the experimental setup for generating laser-plasma in quiescent air at atmospheric pressure and visualizing it. In plasma generation system, a laser pulse was directed along a convex lens to be focused into a small region to enhance gas breakdown, hence to induce plasma. Table 1-1 shows the plasma generation experiment conditions for each laser. The effective laser pulse energy was measured with an energy meter.

Table A 1-1 Conditions of plasma generation system

Laser type	Nd:YAG	Nd:YLF
Wave-length	1064 nm	1047 nm
FWHM	9 ns	15 ns
Pulse energy	140 mJ	25 mJ
Focal length	100 mm	15 mm

Generated plasma was visualized using Schlieren system and was recorded onto an intensified charge couple device high-speed camera, HPV-1. In this study, to control the delay time between the laser pulse and the recording system, a digital delay/pulse generator was used.

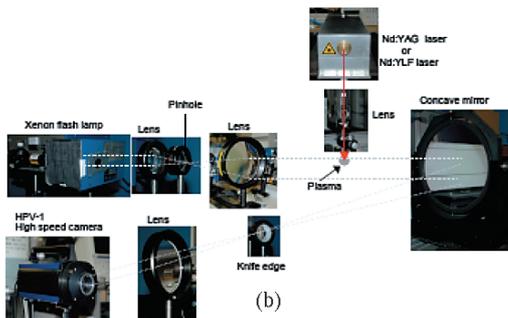
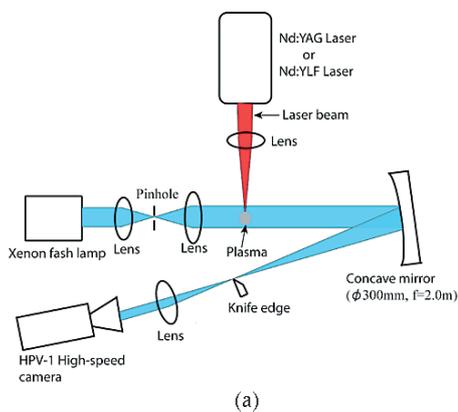


Fig. A 1-1 (a), (b) Schematic illustration of experiment setup for generating Nd: YAG and Nd: YLF laser-plasma at atmospheric pressure

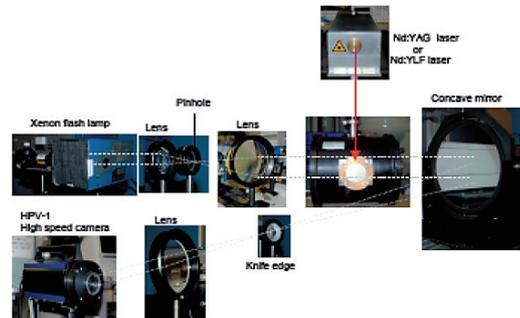


Fig. A 1-2 Schematic illustration of experiment setup for generating Nd: YLF laser plasma at lower ambient pressure

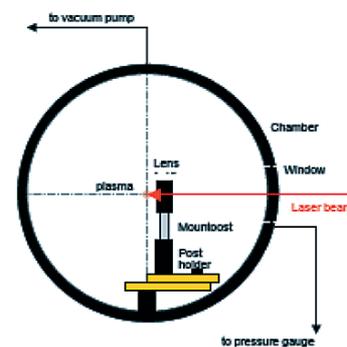


Fig. A 1-3 Schematic illustration of positioning focus lens inside the chamber

## A1.2 Plasma Generation System

### A1.2.1 Laser

#### (1) Nd: YAG laser

Table 1-2 shows general specification of Q-switched Nd: YAG laser (Quanta System ).



Fig.A 1-4 Nd: YAG laser

Table A 1-2 Specification of Nd: YAG laser

Model	SYL 203
Medium	Nd:YAG
Wavelength	1064 nm
Energy	2 J/pulse
FWHM	9 ns

#### (2) Nd: YLF laser

Table 1-3 shows general specification of Nd: YLF laser (EdgeWave, Germany).



Fig. A 1-5 Nd: YLF laser

Table A 1-3 Specification of Nd: YLF laser

Model	IS 8 I-E
Medium	Nd:YLF
Wavelength	1047 nm
Energy	25 mJ/pulse
FWHM	15 ns

## A1.3 Schlieren Visualization System

### A1.3.1 Setup

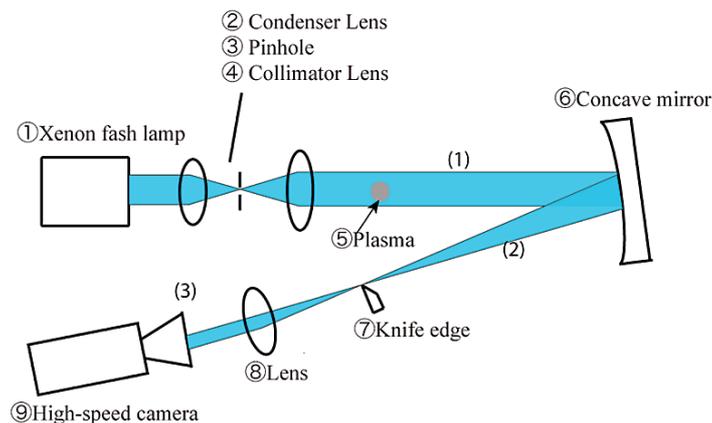


Fig. A 1-6 Configuration of visualization system

Schlieren visualization system is used to visualize the gradual development of the generated laser-plasma over time. Basically, the system includes (1) light source parallelization process, (2) parallel luminous flux focus process, and (3) recording process using high-speed camera. A xenon flash lamp served as the light source, connected to inductor box to luminescence light longer enough for recording purpose.

### A1.3.2 High-speed Camera

#### HPV-1 High-speed Camera

Through a Schlieren visualization system, a high-speed framing camera is being used to record the time evolution of the laser-induced plasma. Images can sequentially be taken every  $4 \mu\text{s}$  for 100 images, so that  $400 \mu\text{s}$  of duration during plasma evolution is recordable. Table 3-4 shows general specification of the camera.



Fig. A 1-7 HPV-1 High-speed camera

Table A 1-4 Specification of HPV-1

Model	HPV-1 (Shimazu Co.)
Resolution	$312 \times 260$ pixels
Frame rate	$4 \mu\text{s}/\text{frame}$
Record frames	100 images

## 付録 A 2 : レーザー誘起プラズマの挙動

### A2.1 Nd: YAG laser-induced plasma behavior

The study of the Nd: YAG laser-induced plasma behavior in ambient air at atmospheric pressure and the mechanism of its instability will cover the phases in order:

- (i) Blast wave generation and propagation.
- (ii) Jet and toroidal structure formation.

#### A2.1.1 Blast wave generation and propagation

Fig. A 2-1 shows an example of the visualized time evolution of a plasma and blast wave in the early stages of development. As the laser pulse that is incident from the left side has terminated, the small focal region which is directly heated during the laser pulse irradiation hereafter is referred as plasma and was observed in the first frame at  $t = 24 \mu\text{s}$  and thereafter. At atmospheric pressure, the initial plasma is almost ellipsoidal in shape with the major axis oriented along the laser beam. As can be observed, a blast wave begins to travel out from the heated region after the plasma front and the blast front propagate together.

The blast wave surface expansion can be quantified in terms of horizontal and vertical radii of the ellipse. The horizontal radius  $r_h$  corresponds to the one parallel to the laser beam axis or x-axis; the vertical radius  $r_v$  corresponds to the one perpendicular to the axis. Fig. A 2-2 shows the relationship between measured shock wave radius  $r_h$  and  $r_v$ , and its expansion velocities, horizontal velocity  $v_h$  and vertical velocity  $v_v$ , and  $t$ , the time from the start of expansion in the early stages, from  $t = 24 \mu\text{s}$  up to  $t = 44 \mu\text{s}$ . Initially, the blast is ellipsoidal in shape due to the asymmetric plasma region. However, the blast wave becomes almost spherical by  $t = 44 \mu\text{s}$ . This is demonstrated both in Fig. A 2-1 and Fig. A 2-2. The shock front tends to become spherical in shape with increasing distance from the origin independently of any finite source shape.

Expansion velocities  $v_h$  and  $v_v$  in the figure are calculated from temporal variation of  $r_h$  and  $r_v$ , respectively. The velocity during the blast wave expansion gradually decreases, hence the Shock Mach number decreases in intensity.

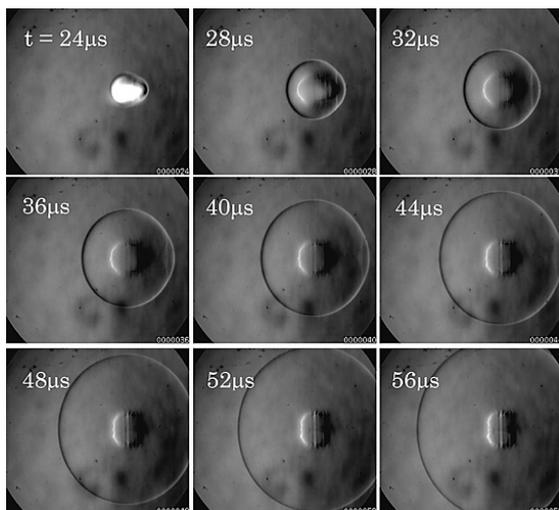


Fig. A 2-1 Framing Schlieren images on variation radii of expanding shock wave at the early stage

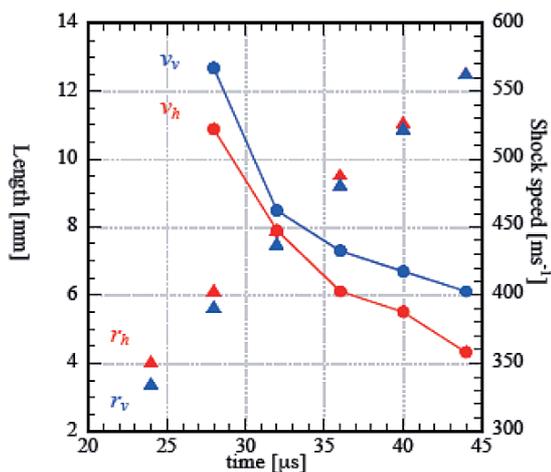


Fig. A 2-2 Temporal variation of radii and expansion velocity of expanding shock wave

#### A2.1.2 Jet and toroidal structure formations

Fig. A 2-3 shows typical Schlieren images express time evolution of the laser-induced flow. Time passed after Nd: YAG laser pulse irradiation is designated by  $t$ , and the first frame at  $t = 24 \mu\text{s}$  the laser pulse has already terminated. The laser pulse is incident from left. As have been mentioned before, the small focal region which is directly heated during the laser initiation hereafter will be referred to as a plasma and was observed in the first frame at  $t = 24 \mu\text{s}$  and onwards, and initially, the plasma is almost ellipsoidal in shape with the major axis oriented along the laser beam. As time elapsed, plasma kernel keeps expanding vertically, but compresses horizontally towards its centre

at early stages before propagating up the laser incidence axis towards the focal lens, as can be observed in Fig. 2-3 qualitatively and be confirmed in Fig. 2-4 quantitatively.

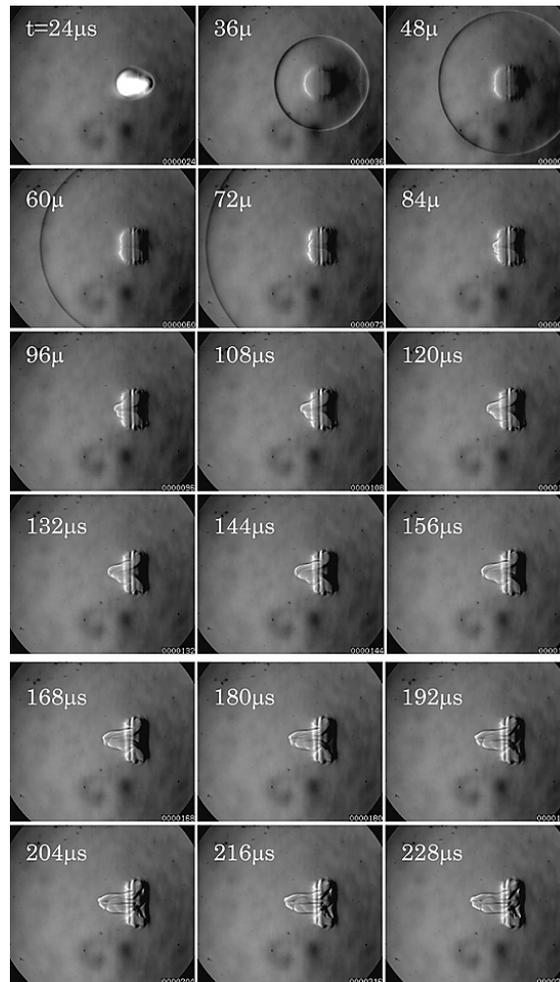


Fig. A 2-3 Framing Schlieren images on laser-induced plasma in quiescent air,

At  $t, \mu\text{s} - \mu\text{s}$  the plasma is almost spherical in shape. At  $t = 60 \mu\text{s}$  and onward, the structure of the laser-plasma in ambient air at atmospheric pressure are characterized by the appearance of a toroidal structure feature and its subsequent spreading. At about the same time, a jetting emerges from the right part of the plasma and propagates towards the laser source, as been shown in Fig. 2-6. This jetting has been observed in other works.

The shock wave caused by the rapid energy deposition quickly travels outwards into surrounding gas produces a pressure gradient directed away from the center. At the plasma center, an overexpanded region of lower pressure is formed, relative to the ambient gas, into which two opposing gas flows penetrate—coming from the surrounding region along the axis of the laser pulse. These counterpropagating, colliding gas flows create a pair of symmetric vorticity, which then act in harmony to move the hot gas remnants radially outwards and into a toroidal shape. The vortex generation (toroidal shape propagating radially) is clearly observed at  $t = 72 \mu\text{s} \sim t = 228 \mu\text{s}$ . The vortical motions deform the ellipsoid of the plasma to its major axis is displaced vertically (Fig. A 2-5) and at the same time it is clearly observed that the plasma jetting extruding toward laser source give rise to a front lobe.

The formation of the front lobe is caused by either the possibility of ionized gas facing the incoming laser beam to absorb more laser energy, thus the boundary of highly heated plasma could propagate back toward the laser source, or to the propagation of a shock wave generated from the initial expansion of plasma with an axial component toward the laser source, as have been explained above.

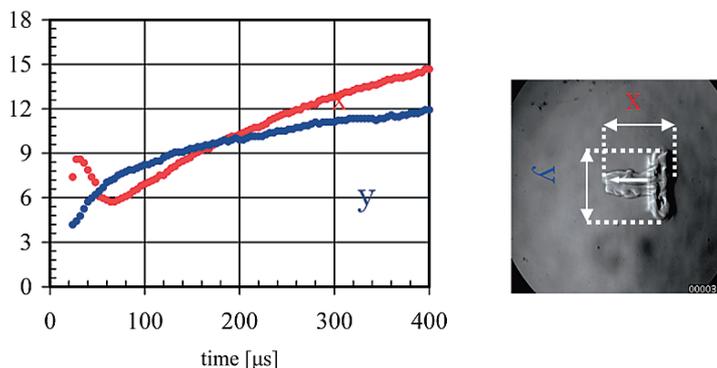


Fig. A 2-4 Relationship between horizontal and vertical length of expanding plasma and time

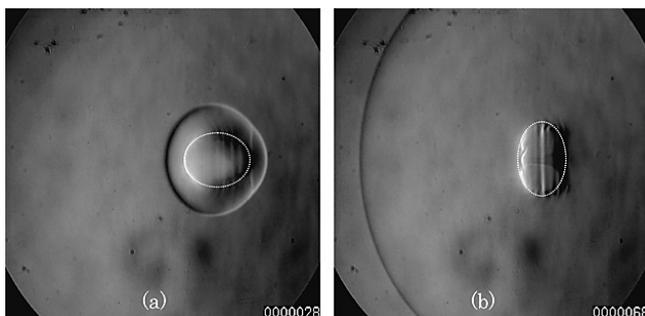


Fig. A 2-5 Major axis of ellipsoid displaces from (a) horizontal axis to (b) vertical axis

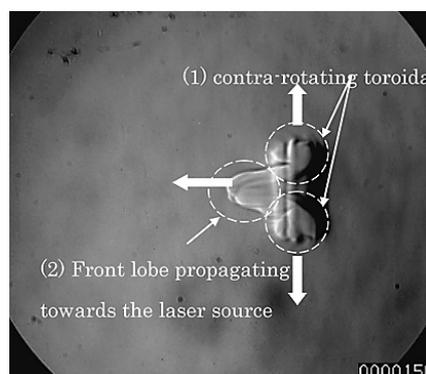


Fig. A 2-6 Two significant segments, toroidal shape and front lobe, appear during plasma deformation

**A2.2 Similarity between Nd: YLF and Nd:YAG laser-induced plasma**

Nd: YLF laser-induced plasma experiment has been conducted using the same experimental setup as the Nd:YAG laser-plasma experiment. The conditions for both experiments are shown in Table A 2-1 below.

Table A 2-1 Experiment conditions for Nd:YAG and Nd:YLF laser

Laser type	Nd:YAG	Nd:YLF
Wave-length $\lambda$	1064 nm	1047 nm
FWHM	9 ns	15 ns
Pulse energy $E$	140 mJ	25 mJ
Focal length $f$	100 mm	15 mm
Ambient pressure $P_o$	100 kPa	100 kPa

**A2.2.1 Qualitative analysis**

In both cases, the appearance of the waves and development of the vortex are qualitatively the same. There are three similarity of characteristics demonstrated in both Nd:YAG and Nd:YLF laser-induced plasma at atmospheric ambient pressure. The significant similarities are:

- (1) Initial plasma is ellipsoidal in shape. Hence, initial blast wave is ellipsoid-shape but tends to develop to become nearly spherical in shape as it expands outwards.
- (2) The plasma deforms from initially ellipsoidal shape to its major axis is displaced vertically due to the counter-rotating vortical motions of torus-like structures.
- (3) Appearance of two distinct segments; the torus-like shape structure propagating radially and the front lobe propagating toward the laser source.

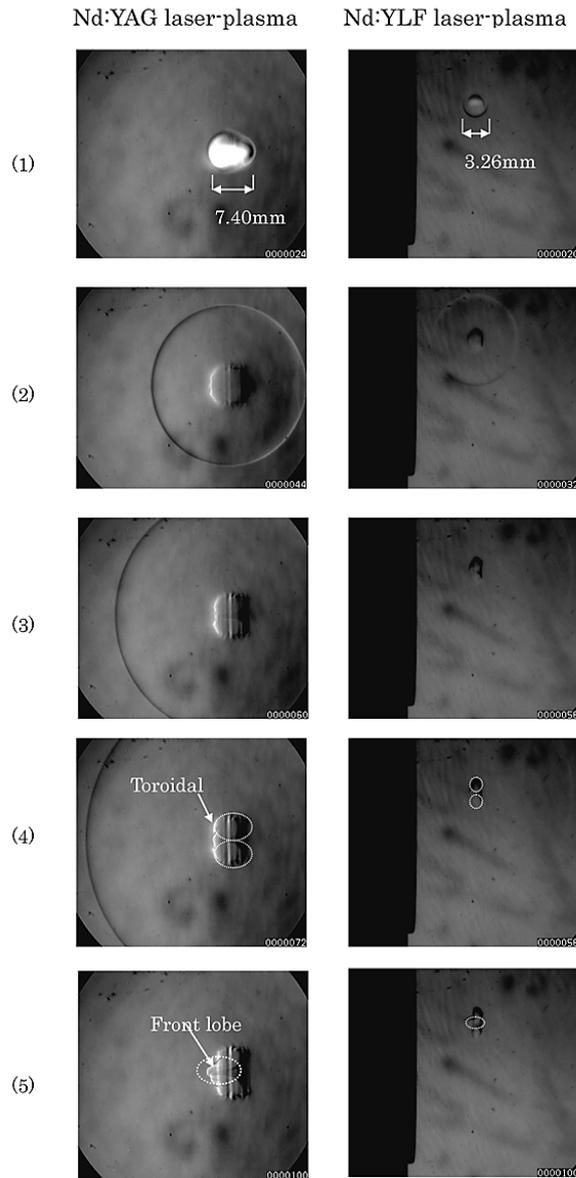


Fig. 4-7 Qualitative comparison between Nd: YAG and Nd: YLF laser-induced plasma at atmospheric pressure

### A2.2.2 Quantitative analysis

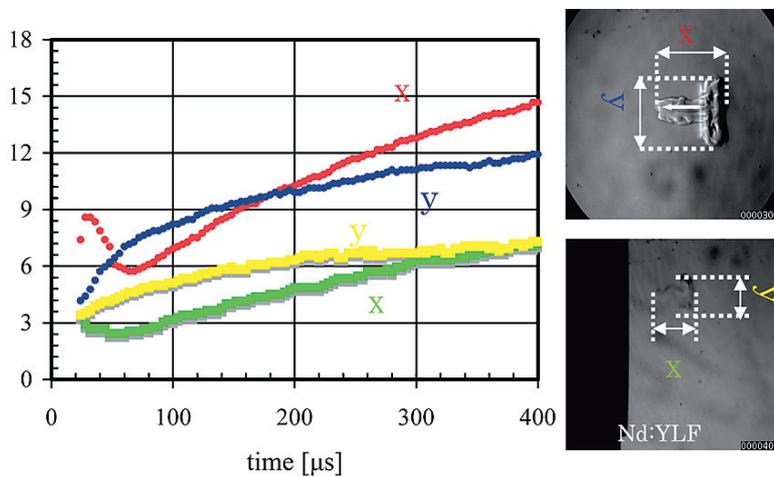


Fig. A 2-8 Relationship between horizontal and vertical length of expanding plasma and time

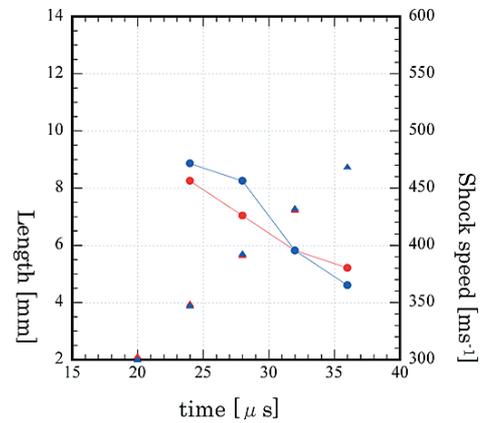


Fig. A 2-9 Temporal variation of radii and expansion velocity of expanding shock wave

### A2.3 Pressure effect on the plasma behavior

Fig. A 2-10 shows Schlieren images; results of experiment conducted under four conditions of ambient pressure;  $P_0 = 100\text{kPa}$ ,  $80\text{kPa}$ ,  $60\text{kPa}$ , and  $40\text{kPa}$ . All the images are synchronized with each other.

As shown in the figure, at  $t = 20 \mu\text{s}$ , initial spherical shape of plasma is generated only at  $P_0 = 60\text{kPa}$  and  $P_0 = 40\text{kPa}$  with diameter  $d = 3.72 \text{ mm}$  and,  $d = 3.48 \text{ mm}$  respectively, while at  $P_0 = 100\text{kPa}$  and  $P_0 = 80\text{kPa}$ , the plasma is almost ellipsoidal shape with major axis oriented along the laser source. The lower the ambient pressure, plasma decreases in initial size. When the initial pressure is reduced, the energy absorbed by the plasma kernel will be less than that absorbed at the atmospheric pressure and the size of initial plasma is expected to decrease.

Plasma that is induced under atmospheric pressure demonstrates two significant segments; a toroidal shape propagating radially and a front lobe propagating toward the laser source (see Fig. 2-6). However, the lower the ambient pressure, the extrusion of the front lobe no longer could be observed; for example, at  $t = 160 \mu\text{s}$ , a motion of a lobe extruding toward the laser source (left) could be clearly observed for  $P_0 = 100\text{kPa}$  and  $P_0 = 80\text{kPa}$  compared with for the lower pressure where completely no observation of lobe extrusion recorded for  $P_0 = 40\text{kPa}$ .

Small-scale perturbations appearing on the plasma interface are enhanced at high ambient pressure. However, the lower the ambient pressure, the large-scale disturbances were enhanced. The right part of plasma at  $t = 400 \mu\text{s}$  is an almost red-blood-cell-shape (from side view)  $P_0 = 40\text{kPa}$  for, whereas the perturbations grow up as the ambient pressures increase, and much small-scale perturbations were enhanced for  $P_0 = 100\text{kPa}$ . Such small-scale large-scale flow patterns are also reported in Sasoh *et.al*; they assumed the possible process to explain the relationship between ambient pressure and perturbation patterns is Rayleigh-Taylor instability. In Rayleigh-Taylor instability, rate of the perturbation grows with  $e^{t\sqrt{gkA}}$ , where  $g$ ,  $k$ , and  $A$  designate acceleration measured on the interface, dominant wave number of perturbation, and Atwood number, respectively. Since the ambient pressure  $P_0$  and  $k$  have a linear relation, increasing in  $k$  and hence  $P_0$  will increase the perturbation rate. Table A 2-2 concludes the ambient pressure effect on the plasma behavior.

Table A 2-2 Ambient pressure effect on plasma flow evolution

Ambient pressure	100 kPa	80 kPa	60 kPa	40 kPa
Plasma shape	Ellipsoid ( $d_h = 3.12 \text{ mm}$ , $d_v = 3.00 \text{ mm}$ )	Ellipsoid ( $d_h = 3.00 \text{ mm}$ , $d_v = 2.88 \text{ mm}$ )	Sphere ( $d = 3.72 \text{ mm}$ )	Sphere ( $d = 3.48 \text{ mm}$ )
Front lobe extrusion ( $t = 20 \mu\text{s} \sim t = 400 \mu\text{s}$ )	○	○	△	×
Growth rate of perturbations	 decreasing with $P_0$			

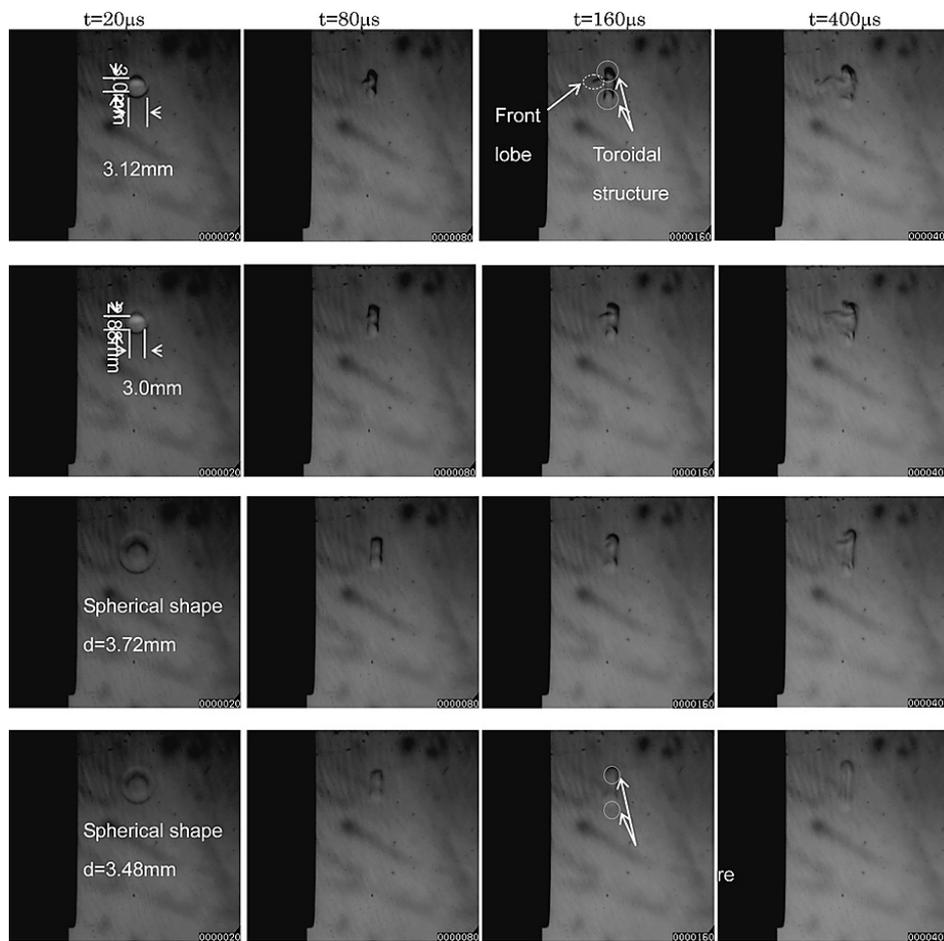


Fig. A 2-10 Framing Schlieren images, ambient air (a)  $P_0 = 100\text{ kPa}$ ,  $d = 15\text{ mm}$ , (b)  $80\text{ kPa}$ ,  $15\text{ mm}$ , (c)  $60\text{ kPa}$ ,  $15\text{ mm}$ , (d)  $40\text{ kPa}$ ,  $15\text{ mm}$