Impact of a shock wave on a structure on explosion at altitude

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Impact of a shock wave on a structure. Explosion at altitude levels

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Abstract

The number of explosive attacks on civilian buildings has in recent years relatively increased and the pattern of the damages inflicted on structures when the explosion takes place at altitude remains quite difficult to predict. The primary aim of the work reported here is to enhance the understanding of how blast waves from an explosion at altitude interact with the ground and with a structure. The experimental investigation is achieved by means of small-scale experiments using a propane-oxygen stoichiometric mixture as explosive. This approach is original because it aims at modelling high explosive detonation by gaseous charge explosion using an equivalent TNT. Several adimensional laws are expressed and validated by experiments. These relationships allow to determine the propagation of a blast wave and its interaction on a structure by the function of the position of the explosive charge when the explosion happens at altitude. Then by the knowledge of the blast loading, using Hopkinson's scaling law and the equivalent TNT, we can predict at real scale the interaction of blast waves with the ground and the structure. Simulations are achieved with the Autodyn code, and a good correlation with experimental results is obtained.

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1. Introduction

Because of several accidental or intentional events related to different structures all over the world, engineers are paying now more attention for the architecture of public buildings to provide life safety in the face of explosions. Although several studies were dedicated in last years to the detailed numerical analysis of blast wave damage to buildings, only few works are available for the prediction of the propagation of blast waves when the explosion takes place at altitude (Brossard et al., 1993). An original experimental work which aims to simulate the propagation and the interaction of shock wave with a structure resulting from explosion of TNT charge at altitude levels is conducted. The energy equivalency between gaseous charge and TNT charge allows to realise such experiments at laboratory scale.

The purpose of this paper is to present the experimental results obtained from small scale experiments taking into account the detonation process of the gaseous charge over a large plane surface or over a rigid structure. The incident blast wave is also modified by interaction with the rigid surface. Two important parameters of the study are the reduced radial distance λ and the angle α of the incident shock. All the results are correlated by means of least-square polynomials and concern the overpressure of the reflected shock front, the positive phase duration, the positive impulse. The type of wave reflection and the Mach stem formation are characterised. Then, it is possible to transpose our results at real scale, by use of Hopkinson scaling laws.

2. Description of the experimental setup

The experimental investigation is achieved by means of small-scale experiments. The reflection phenomena is simply represented in Fig.1. About incident shock angle $\alpha \sim 40°$, the shock front is then propagating over a surface as a Mach Stem (MS) process algebrically described by Reinhardt (Kinney,

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1985, p.126). The shock wave is the consequence of the detonation of a spherical gaseous charge of stoichiometric propane-oxygen mixture which is confined in a balloon (radius $0.03 \leq R_0 \leq 0.07$ m) over a large plane surface (length 1.80 m, width 1.20 m). The balloon is fixed on a runner's portico fixed on the large plane surface as it is shown on the figure 2. The detonation is ignited by an exploding wire located at the center of the spherical explosive charge at some elevation HOB (Height of Burst) over the ground. This exploding wire (length 0.01 m and diameter $1.2 \cdot 10^{-4}$ m) made of copper and zinc delivers an electrical pulse with a charge voltage equal to 7000 Volts. The capacitance of the ignition system is 8.14 μF. The piezoelectric pressure gauges A_i (Kistler 603B) are distributed on the plane surface with a distance r_i from the projection H on the ground of the center of explosion or on the faces of a structure placed under the balloon. The minimum and maximum values of r_i are respectively 0.02 and 0.85 m. The angle α of the incident shock IS varies from 0° on the axis of symetry (OH) to 80° on the farther pressure gauge at the minimum height of burst. Then it is also possible to study the blast wave propagation on a structure when the explosion takes place at altitude that is to say over the structure. The observation of the shock wave parameters is made in the reduced distances λ ranging from 0.66 to 4.25 m.MJ$^{-1/3}$. The reduced distance λ is defined by the ratio of the distance R from the explosion center to the gauge over the cubed root of the chemical energy released by the gaseous charge. In fact, the measures are collected from different experimental set-ups, that we will describe later. From the numerized pressure records given by pressure gauges, the signal is characterized by the arrival time t_a, the positive overpressure ΔP^+, the reduced positive phase duration and impulse $\frac{t^+}{E^{1/3}}$ and $\frac{I^+}{E^{1/3}}$, where E (MJ) is the chemical energy contained in the spherical gaseous charges (radius R_0) All these results are then correlated as function of the parameter λ.

3. Computational model

We use Autodyn software in this study. Autodyn is a three-dimensional finite volume, finite difference and finite element based hydrocode that has been developed over many years to allow the efficient solution of a wide range of impact penetration and blast problems. Autodyn permits to model the detonation of a solid charge. Consequently, in order to achieve the numerical simulations of the conducted experiments described above, the energy release E resulting from the detonation of the propane-oxygen mixture is expressed in terms of TNT equivalent energy.

An energy equivalency coefficient 2.3 has been determined (S. Trélat et al., 2006) then it is also possible to simulate the explosion of a gaseous mixture by a TNT charge. Indeed, the equivalent released mass of TNT produces the same pressure levels than the gaseous explosive charge. For example, a 0.06 m radius hemisphere which confines the mixture within the stoichiometric composition has a TNT equivalent mass approximatively equal to 1.3 g.

The materials used in the study are AIR and TNT. We can find their characteristics in the Autodyn library (Autodyn, 2005) A two-dimensional or three-dimensional Euler FCT (higher order Euler processor) subgrid is used for the air. The lateral faces of the undergound level are supposed to have rigid surfaces and air flow is allowed in the rest of the boundaries. Numerical analyses are undertaken in two stages: firstly, the initiation of the explosion and the propagation of the blast wave in the surrounded air are simulated ; as it can be considered that the problem has spherical symmetry until the blast wave impacts a rigid surface, this first problem can be treated as one-dimensionally. For example, the initial detonation and expansion of the sphere of 1.3 g of TNT is modeled in a one-dimensional, spherically symmetric model of 5.7 mm radius with a JWL (Jones-Wilkins-Lee) equation of state for TNT and an ideal gas equation of state for the air. The one-dimensional expansion analysis continues until just before the impact of the blast wave on the rigid surface (of the ground or of the structure). Afterwards, due to the oblique wave reflection, the flow becomes multi-dimensional. Therefore, in order to maintain a continuous process, we save the solution of the one-dimensional model. The second stage of the modeling procedure is called the "remap" operation, which consists in transposing the final states of the cells of the one-dimensional model to the new, two-dimensional (without obstacle) or three-dimensional model (with the structure). This remap operation permits to reduce drastically the computational cost of the analysis. The size of one-dimensional cells is $6 \cdot 10^{-5}$ m, the size of two-dimensional elements is $2 \cdot 10^{-3} \times 2 \cdot 10^{-3}$ m^2 and the size of three-dimensional brick elements is $5 \cdot 10^{-3} \times 5 \cdot 10^{-3} \times 5 \cdot 10^{-3}$ m^3.

4. Results

4.1. Explosion at altitude over the ground
The Mach stem phenomenon

When an explosion occurs at a height HOB above the ground (fig. 3), the incident spherical shock is initially reflected as a RS (Regular Reflected Shock. As the blast wave propagates, the angle of incidence α between the incident shock (IS) and the ground increases, and there is a transition to MS (Mach Stem reflection).

At this point, we should consider how the angle of transition α_m can be determined. On a single height-of-burst experiment, the overpressure is measured at a series of distances r_i from ground zero, using gauges mounted in plates at ground level as illustrated in figure 3. The peak overpressure, and so the Mach number of incident shock is then deduced from the recorded pressure-time signal by applying Hugoniot relationships. Knowing this Mach number, it is then possible to determine the angle of incidence at transition by using the curve from Kinney (1962) representing the Mach number of the incident shock as function of the angle of incident shock. Finally, thanks to the height versus distance curve (Kinney, 1985) obtained approximately from observations on spherical charges, we are able to establish the time trajectory of the triple point.

Observation of the Mach stem phenomenon

Here is presented an example illustrating the theory described above. On a single height-of-burst experiment (HOB = 16 cm, $E = 13.75$ kJ) represented on the figure 4., we have determined the incident shock angle of transition $\alpha_m = 39.94°$ which is given by the intersection between the Kinney's curve and our experiments results (Fig. 5). At this incident shock angle α_m, the shock front is then propagating as a Mach Stem. Then, by using the height versus distance curve (Kinney, 1985) obtained approximately from observations on spherical charges, we are able to establish the time trajectory of the triple point (called slip line). In this paper, we want to observe experimentally this phenomenon. We also choose a distance r_t where the region under the Mach stem is not so small: $r_t = 43.5$ cm. At this distance r_t = 43.5 cm, we determine the Mach stem height h_t (the height of the triple point) which is estimated here to 5.5 cm. As a consequence, in order to observe this phenomenon, we have placed gauges in the region around the triple point: one gauge at ground level (0 cm), and four gauges in 'lollipop' mounts at some distance (4-5.5-11-16 cm) above the ground (cf Fig. 3 and 4). The gauge located at a distance of 5.5 cm above the ground corresponds to the triple point, as a consequence, the gauges (0 cm) and (4cm) are located in the Mach stem region, and the gauges (11 cm) and (16 cm) are located in the region where the reflected shock and the incident shock are propagating. Figures 6 and 7 show the pressure signal records measured at these distances above the ground, in the Mach stem region. We notice that the signals have different profiles as function of the region where the gauge is located: the three gauges located in the Mach stem region have similar form (Fig. 6), idem for the two gauges located in the other region (Fig. 7). So the Mach stem phenomenon has an influence on the form of the pressure signal: the second peaks in the decrease phase of the pressure signals measured in the region above the triple point (Fig. 7) can be justified by the presence of the reflected shock. This experiment has been simulated with Autodyn ; figure 8 shows the propagation of the blast wave in the region around the triple point. This figure clearly evidences the Mach Stem phenomenon: the three shock waves (Mach Stem, Incident and Reflected Shocks) are crossing at a single point: the triple point, located at a distance of 5.5 cm above the ground.

Least square polynomials

Two typical pressure records at two different values of the incident shock angle α_i, but with the same radial reduced distance λ (m.MJ$^{-1/3}$) are presented in figure 9. These pressure signals are obtained from the detonation of a spherical gaseous charge (energy E) at an altitude HOB over the ground. From this graphic, we can observe the effects of the incident shock on the positive overpressure measured at different locations: normal reflection with $\alpha = 9.5°$, $r_i = 0.21$ m, $E = 5.8$ kJ and after the transition point with $\alpha = 56°$, $r_i = 0.29$ m, $E = 13.75$ kJ. The peak overpressure decreases as the incident shock angle α increases. Also our purpose is here to investigate the blast loading using the parameters α and λ. The overpressure histories of the blast loading are characterized by means of parameters illustrated in a typical signal (Fig. 9) as function of the reduced radial distance λ in the range of 0.66 to 4.03 m.MJ$^{-1/3}$ and different values of α from 0 to 80°.

These characteristics of pressure wave (positive peak overpressure $\frac{\Delta P^+}{P_0}$, positive phase duration $\frac{t^+}{E^{1/3}}$, arrival time t_a) are represented as a function of the reduced radial distance λ on figures 10, 11 and 12. The positive peak overpressures $\frac{\Delta P^+}{P_0}$ are correlated as function of λ by means of least-squares polynomials subordinated to the angle of incident shock, whereas the experimental results of positive duration $\frac{t^+}{E^{1/3}}$ seem to be not sensitive to α.

- With $\alpha\ (^\circ) \leq 48.2$ and $0.66 < \lambda\ (\mathrm{m.MJ}^{-1/3}) \leq 4.03$:

$$\ln\left(\frac{\Delta P^+}{P_0}\right) = 1.35 - 2.89\,(\ln\lambda) + 0.44\,(\ln\lambda)^2 \quad (eq(1))$$

- With $48.2 < \alpha\ (^\circ) \leq 80^\circ$ and $0.66 < \lambda\ (\mathrm{m.MJ}^{-1/3}) \leq 4.03$:

$$\ln\left(\frac{\Delta P^+}{P_0}\right) = 1.49 - 2.78\,(\ln\lambda) + 0.55\,(\ln\lambda)^2 \quad (eq(2))$$

- $\forall\alpha$ and $0.66 < \lambda\ (\mathrm{m.MJ}^{-1/3}) \leq 4.03$:

$$\ln\left(\frac{t^+}{E^{1/3}}\right) = -0.24 + 0.91\,(\ln\lambda) - 0.22\,(\ln\lambda)^2\ (eq(3))$$

$$t_a = -1,42.10^{-4} + 3,90.10^{-4}\lambda + 2,44.10^{-5}\lambda^2\ (eq(4))$$

We have also reported on this curves other similar results from Brossard et al. (1993), so that we can compare them with our results. In its paper, Brossard's purpose is to supply several useful curves as a function of the parameters (λ and α) in the range $0.53 \leq \lambda\ (\mathrm{m.MJ}^{-1/3}) \leq 12$: these results concern the detonation of gaseous charges and take into account both the positive and the negative phases of the pressure signal of the reflected wave on a large plane surface. This pressure signal characterises the dynamic load imposed by the blast wave. The pressure wave is generated by a hemispherical charge (radius $0.02 \leq R_0 \leq 0.07$ m) of stoichiometric propane-oxygen mixture confined in a soap bubble as in our experimental setup. The results of Brossard are clearly in good agreement with our results. On Fig. 10, 11, 12, the Autodyn small scale points result from Autodyn simulation conducted at the same scale than our experiments. We observe that the tendencies for both experimental and numerical results are coherent.

4.2. Explosion at altitude over a structure

The experimental setup enables to observe the shock wave propagation in a flow field which is obstructed by a parallelepipedic structure (length 0.40 m, width 0.18 m and height 0.14 m, fig. 13) and a cylindrical structure (diameter 0.36 m and height 0.36 m, fig. 14). Two gauges (1 and 2) are located on the top face of the structure ; the pressure measured by these gauges is also a reflected pressure. As a consequence, we have reported the results obtained with these gauges on the figure 15 in order to compare with our least-squares polynomials (eq(1)-eq(2)) established before. And we observe that these data obtained from the explosion located over both the structures are very-well correlated with our polynomials. For example, the two points measured on the top face of the parallelepiped with the reduced distances $\lambda = 1.64$ and 1.72 $\mathrm{m.MJ}^{-1/3}$ (E = 1.72 kJ, HOB = 10 cm) correspond respectively to an angle of incident shock $\alpha = 59.5^\circ$ and $\alpha = 61^\circ$; these two points are placed on the polynomial eq(2) for $48.2 < \alpha\ (^\circ) \leq 80^\circ$, which is satisfactory. The pressure signals presented on figures 16 and 17 are obtained from the detonation of a spherical gaseous charge (energy E) at an altitude HOB over the structure. The gauges 3, 4 and 5 are located on the lateral face of the structure, which is not directly exposed to the explosion. The overpressures seem to be very much lower than the reflected pressures on the top face ; the second peak which is observed correspond to the reflection on the table.

5. Validation of the approach at large scale

The aim of this paragraph is to compare the results obtained at real scale with Autodyn with the experimental and numerical results given at small scale, by means of the Hopkinson scaling law.

We work here on the case of the detonation of a spherical stoechiometric propane oxygen charge, which radius is 6 cm: the explosion takes place at an altitude of 10 cm above the ground.

Such a charge corresponds to a TNT equivalent mass m of a few grams (Trélat and al, 2005). If a gauge is placed at a distance r from the center of explosion (energy E and mass m), this one will support a blast wave of amplitude ΔP^+ during a time duration t^+ (impulsion I^+). The Hopkinson scaling law states that a second gauge placed at a distance kr from the explosion (energy k^3E and mass k^3m) will support a blast wave of same amplitude during a time duration kt^+ (impulsion kI^+). The scale coefficient is k. The Hopkinson law states that if the detonation of a TNT mass m (a few grams) generates a blast wave of amplitude ΔP^+ during a time duration t^+ at a distance of 10 cm from the center of the explosion, so the detonation of a TNT mass km (a few tones) will generate a blast wave of amplitude ΔP^+ during a time duration kt^+ at a distance of $10.k$ cm from the center of the explosion.

The results of positive overpressure and time duration obtained with Autodyn at full scale and at small scale (i.e the same scale as in experiences) are reported on the figure 18, the experimental laws deduced from the experiments are also reported on the graphics. A good concordance is observed between the experimental and numerical results of overpressure at small scale and at full scale. However, concerning the time duration, the Autodyn results calculated at full scale are higher than the results calculated at small scale of about 15 %.

6. Conclusion

In this work, the nature of reflection shock wave (regular, Mach) on the ground or on a structure consecutive to an explosion is investigated. Several adimensionnal laws are expressed as function of reduced radial distance and the angle of incident shock. These relationships, validated at small scale, allow to determine the propagation of a blast wave and its interaction on a structure as function of the position of the explosive charge when the explosion is located at altitude, over the ground or over two types of structures (a parallelepipedic and a cylindrical structure). The results obtained from a gaseous charge explosion can be expressed in terms of TNT charge by means of the energy equivalency. These experimental studies realised at small scale allow to validate the Autodyn numerical simulation conducted with TNT charges. The more important overpressure on a structure resulting from an explosion at altitude level is obtained along the slip line (i.e. triple point trajectory). It means that the Mach Stem formation represents a more dangerous loading for the structure than the regular reflection configuration. Finally, by applying Hopkinson scaling law, we are able to predict at full scale the Mach Stem configuration and the maximum loading on a structure which can be produced by an explosion at altitude levels...

Acknowledgments

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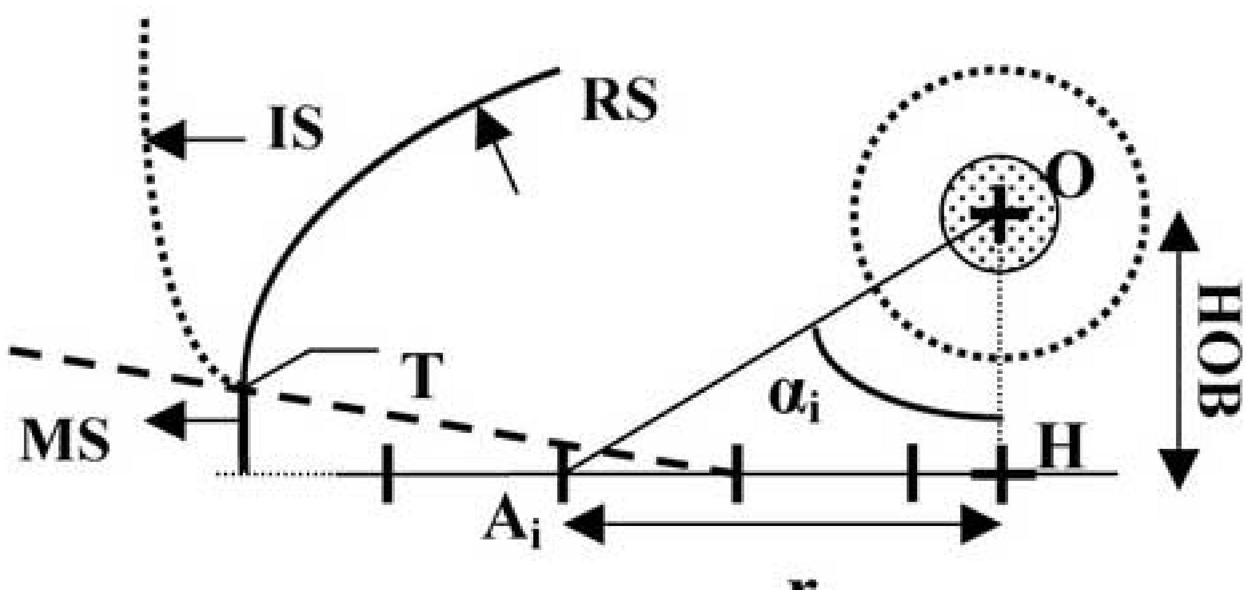
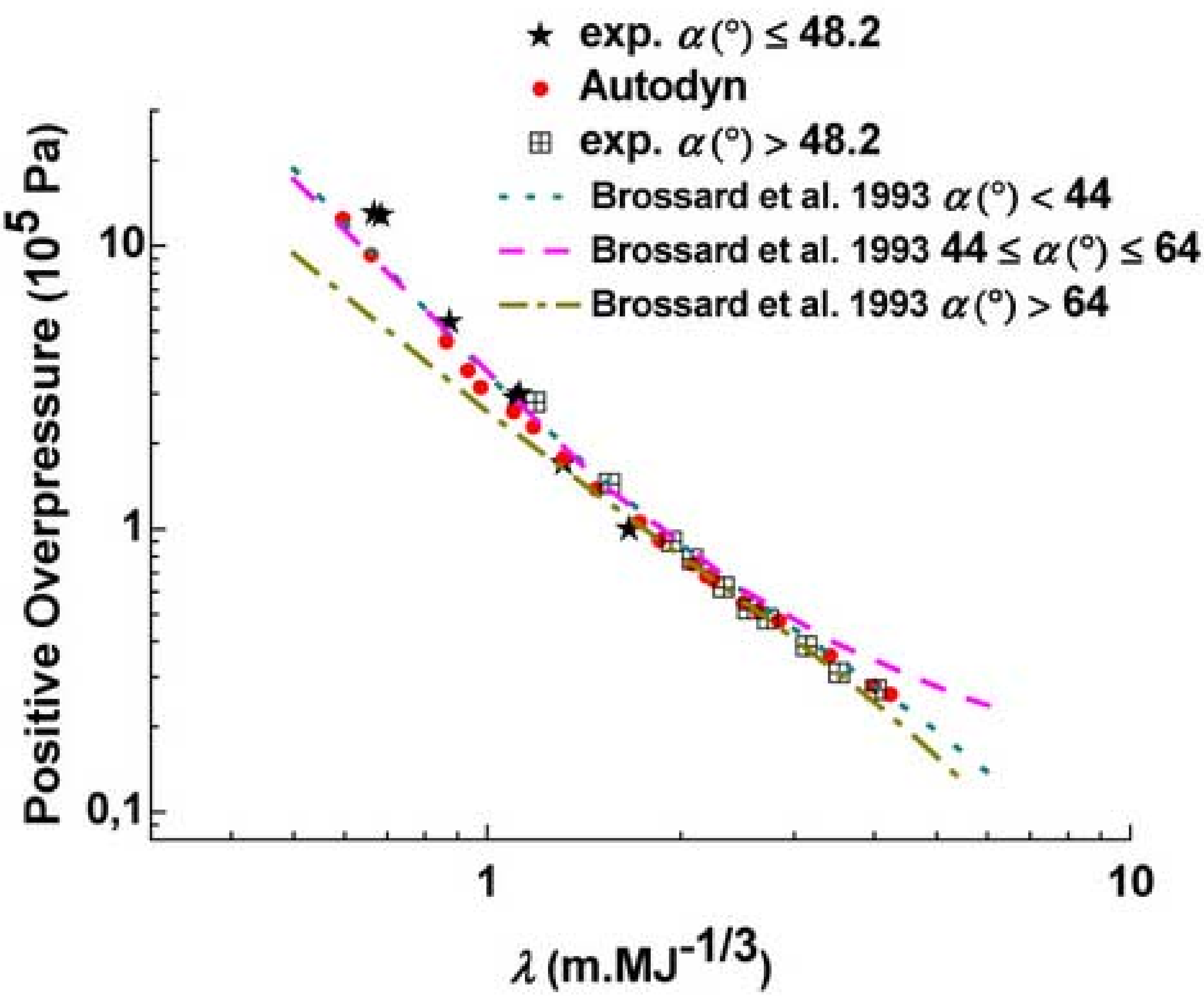
List of Figures

sochet-et-al._figure1




exp. α(°) ≤ 48.2
Autodyn
exp. α(°) > 48.2
Brossard et al. 1993 α(°) < 44
Brossard et al. 1993 44 ≤ α(°) ≤ 64
Brossard et al. 1993 α(°) > 64
Positive Overpressure (10^5 Pa)
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λ (m.MJ^-1/3)

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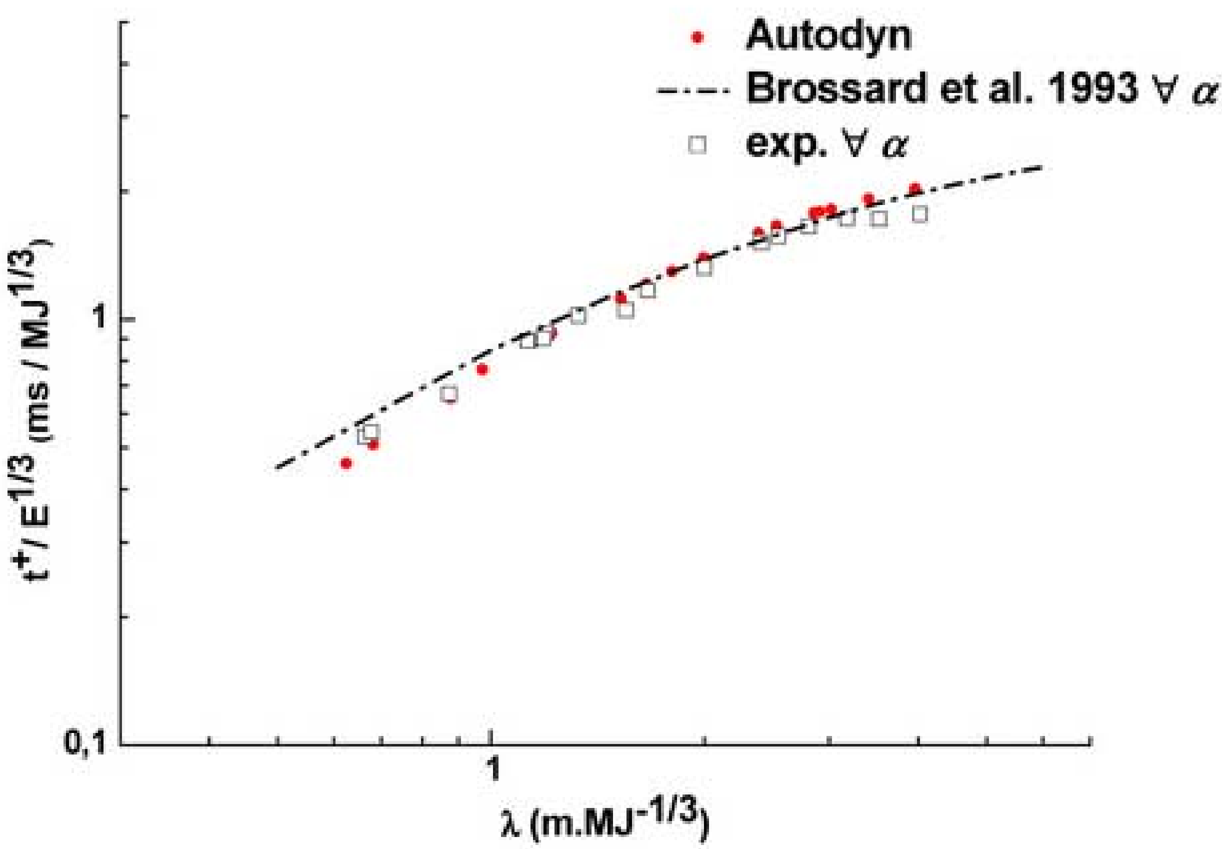

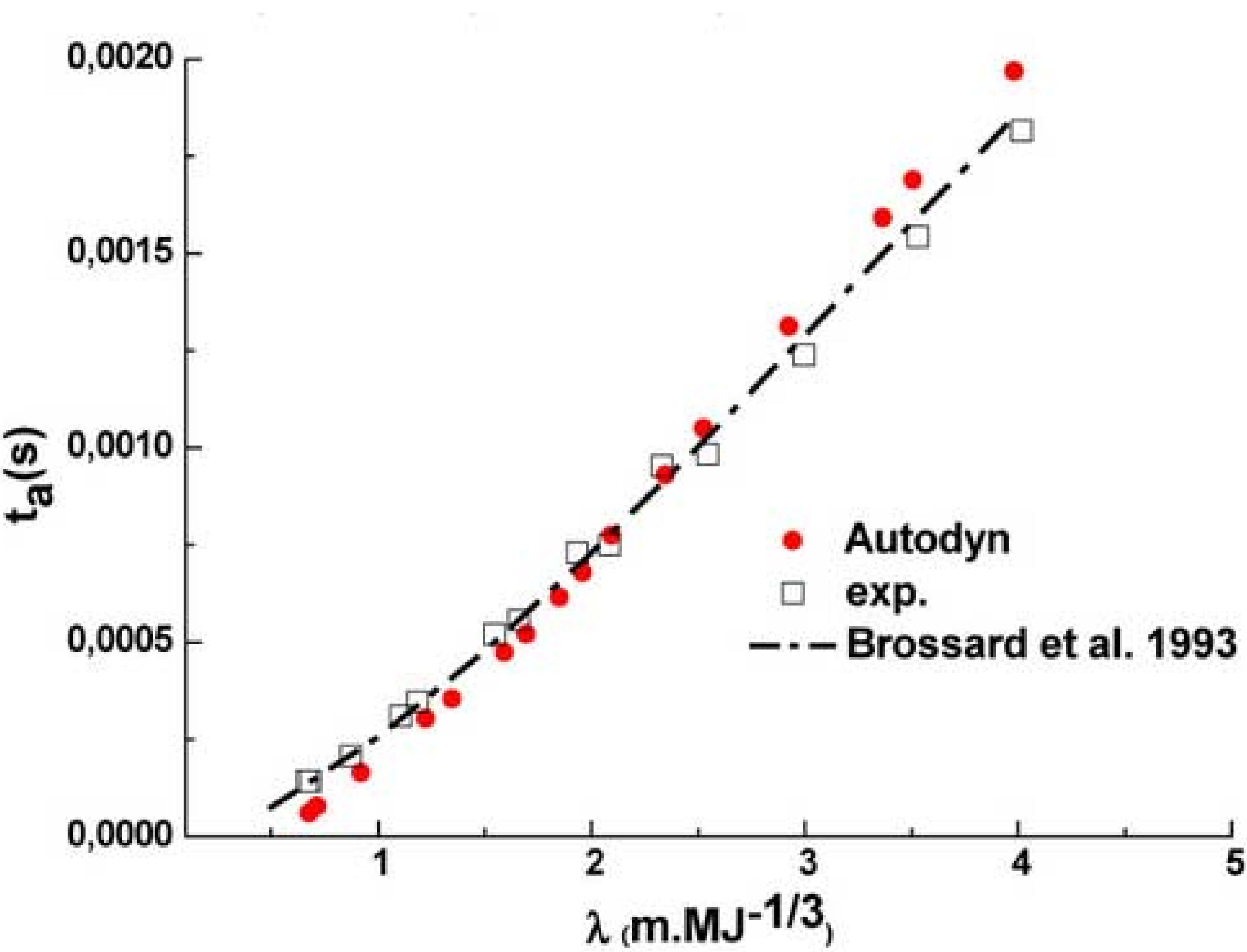
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λ (m.MJ-1/3)
Autodyn
exp.
Brossard et al. 1993

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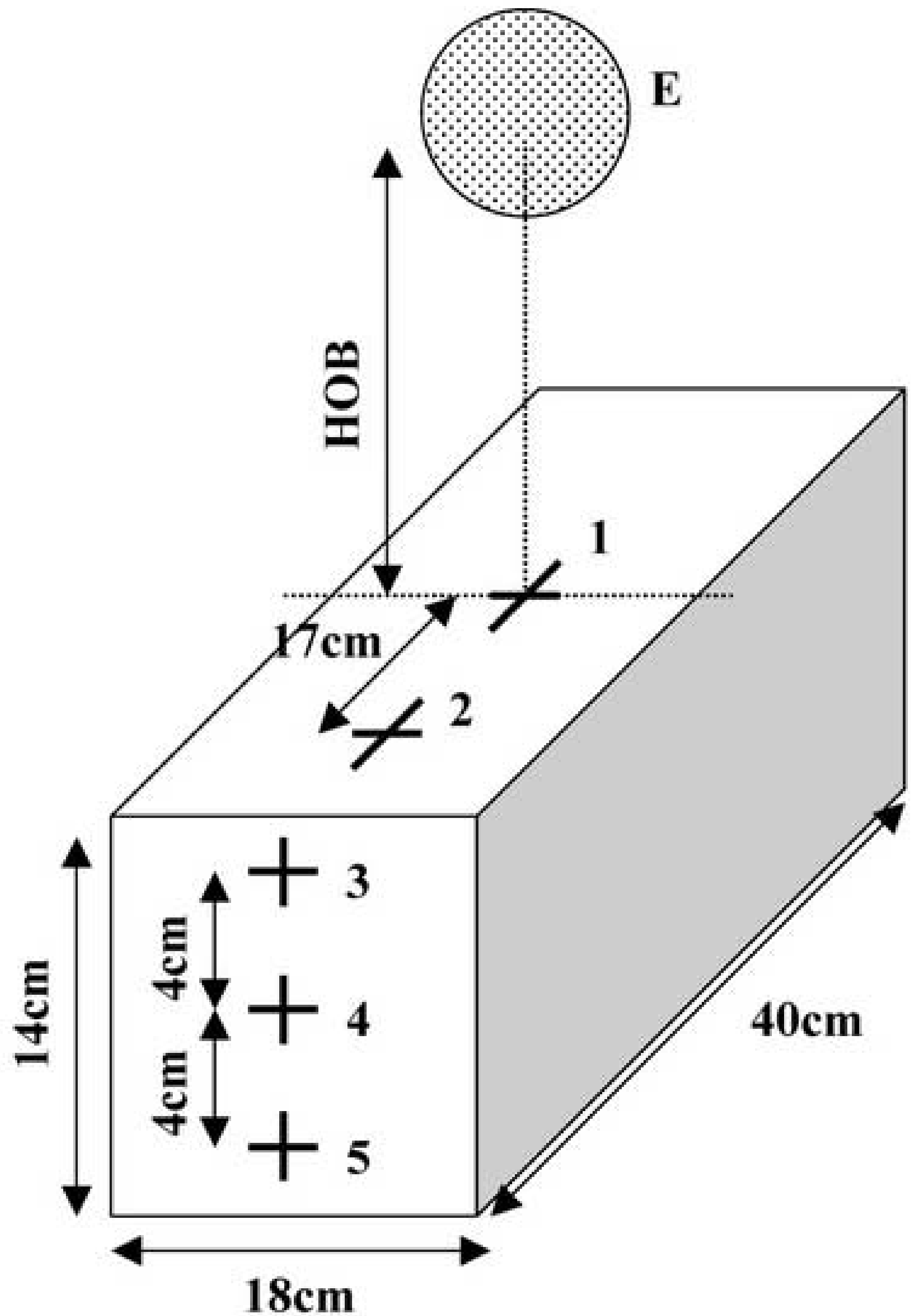

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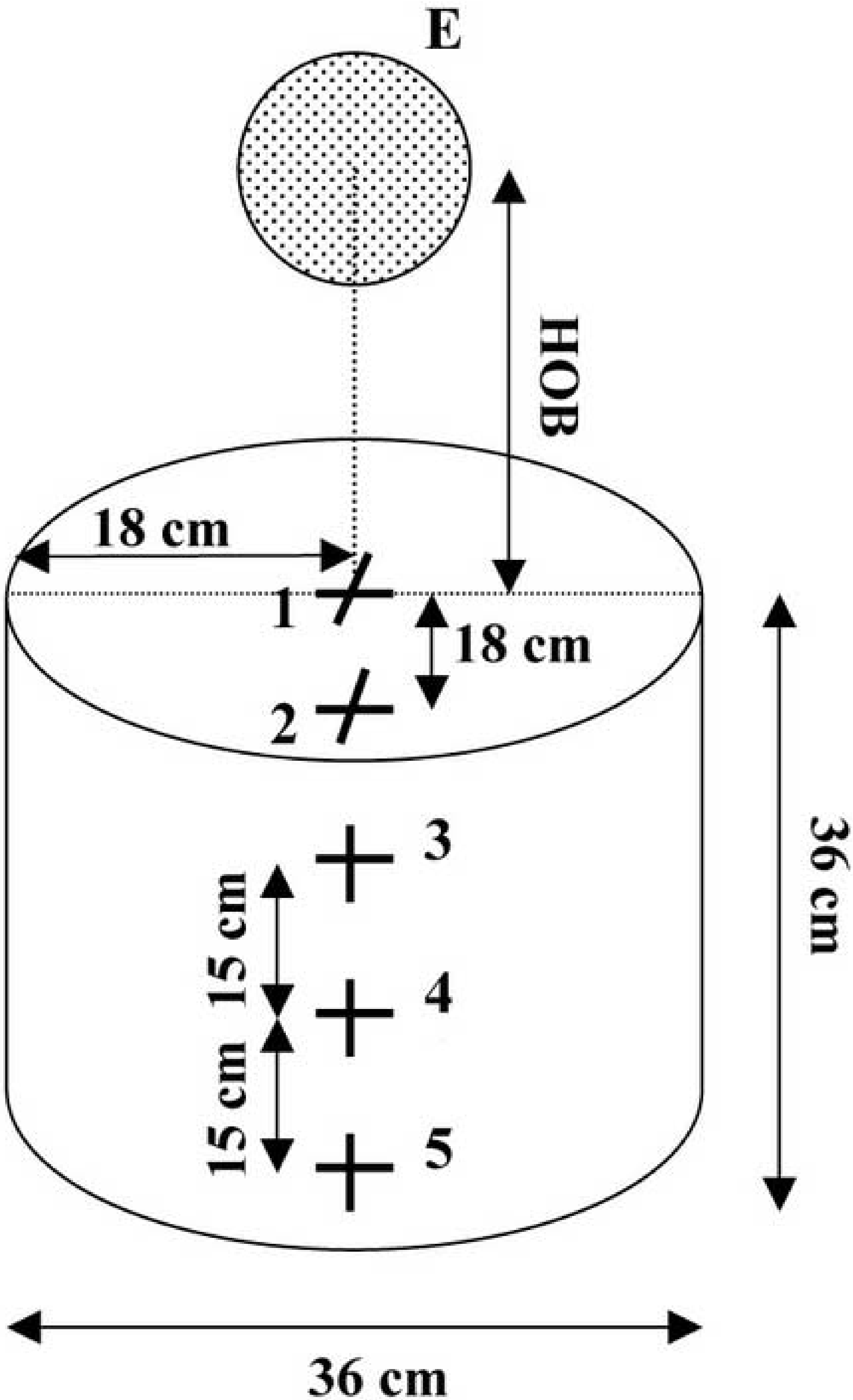

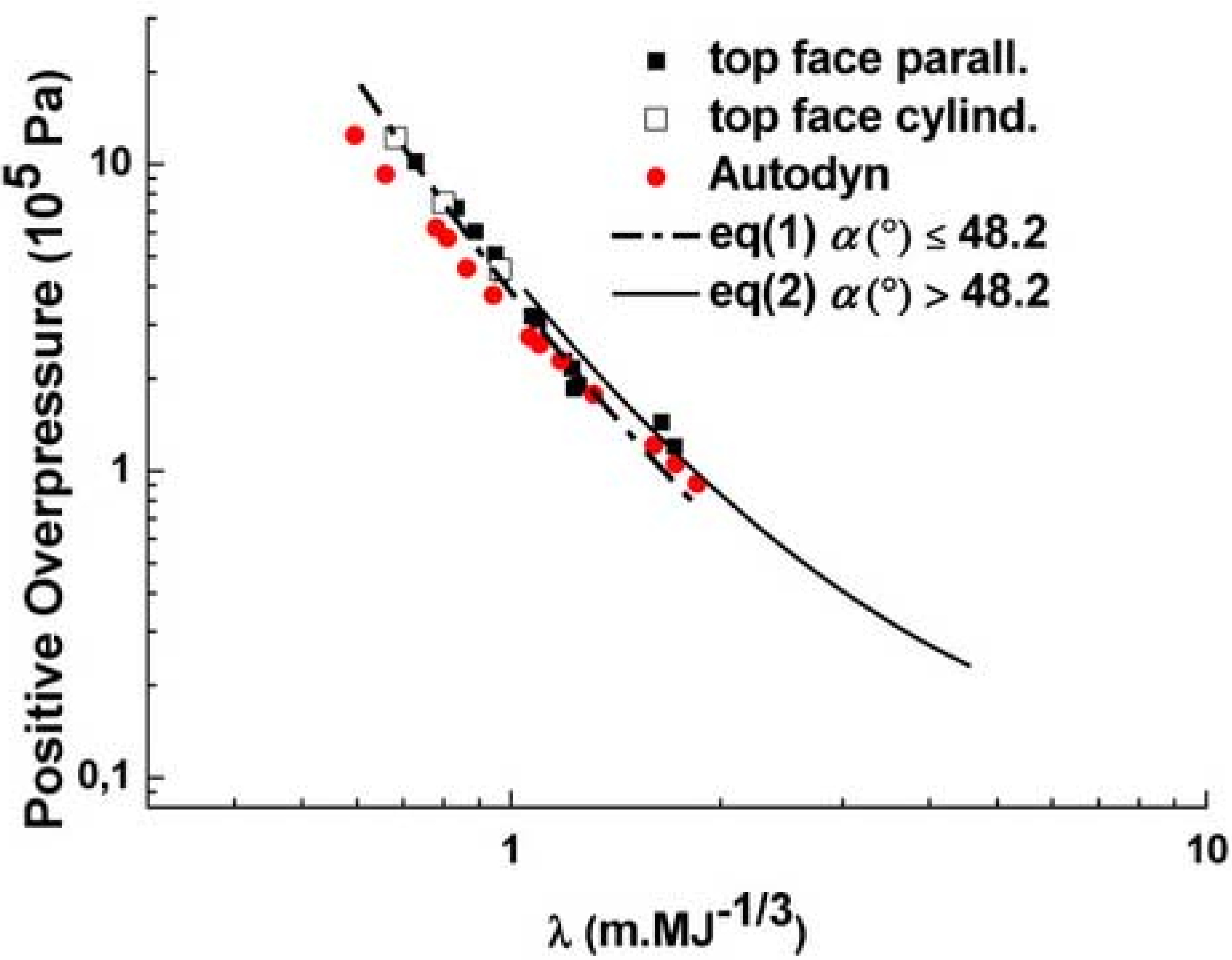
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Autodyn
eq(1) α(°) ≤ 48.2
eq(2) α(°) > 48.2
Positive Overpressure (10^5 Pa)
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10
λ (m.MJ^-1/3)

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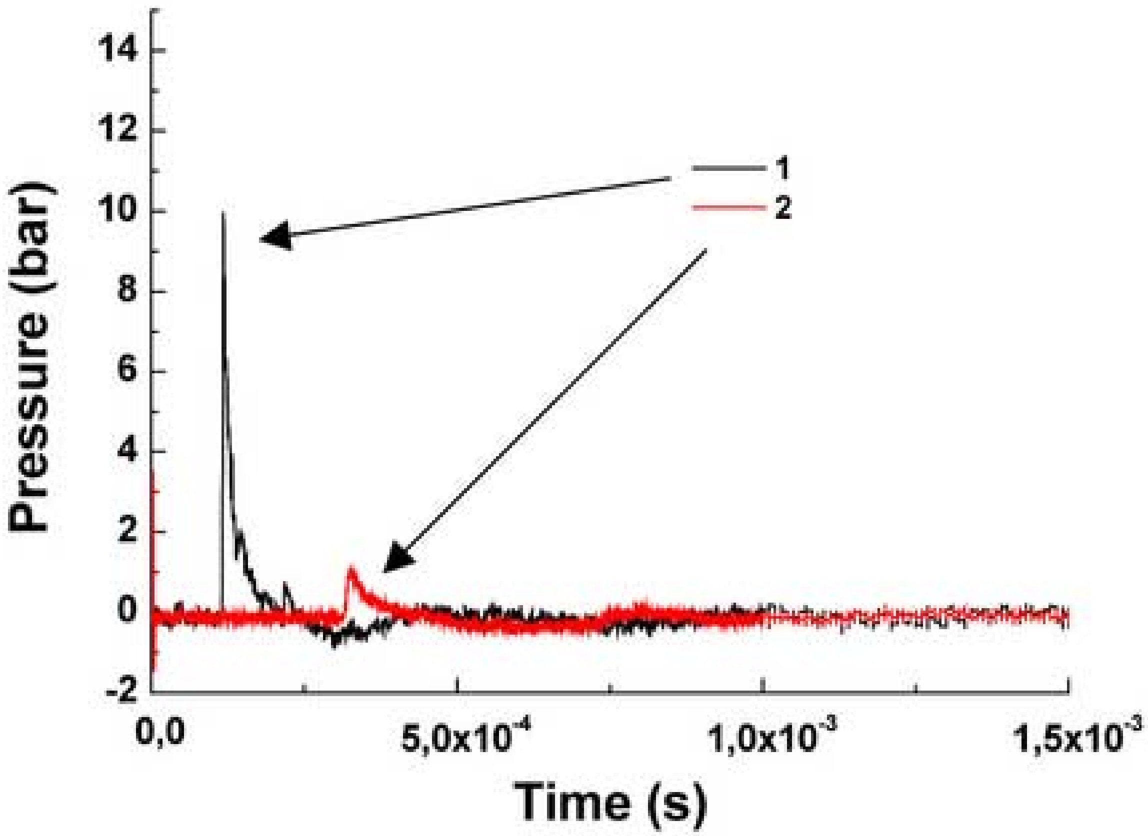

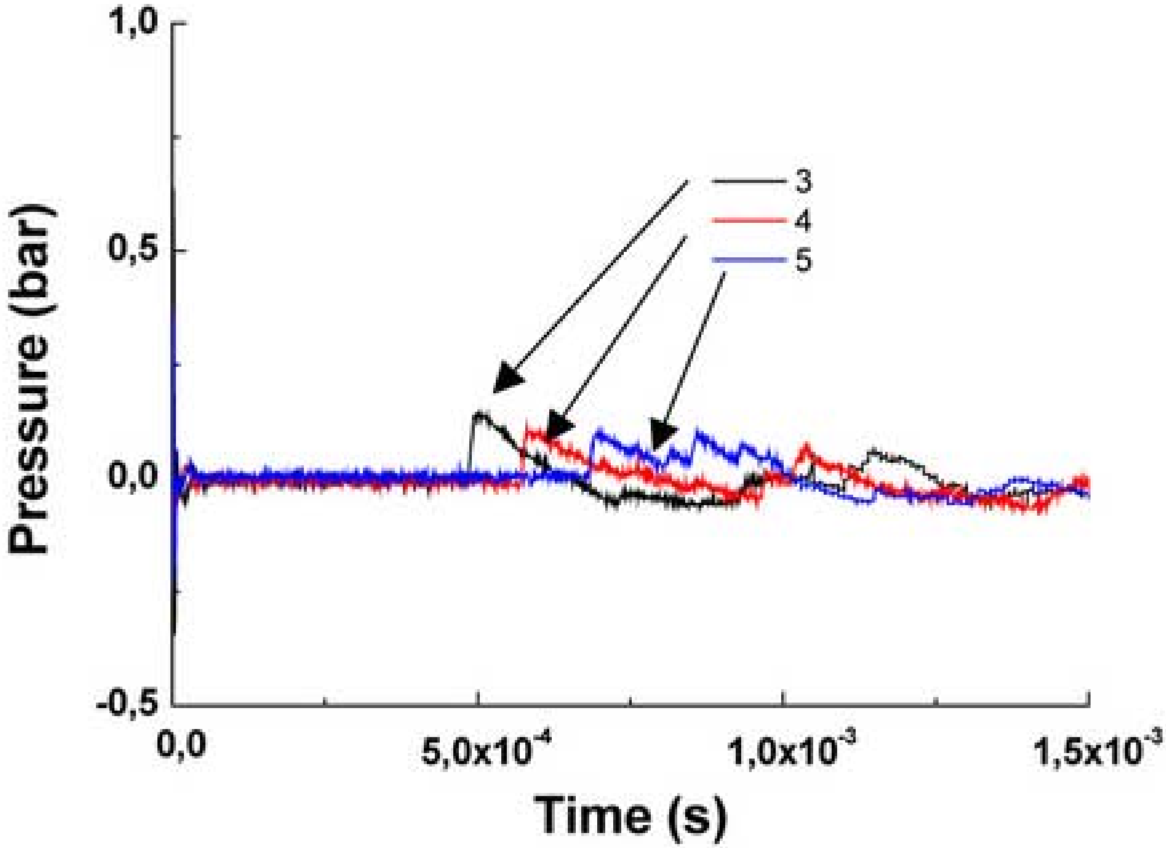

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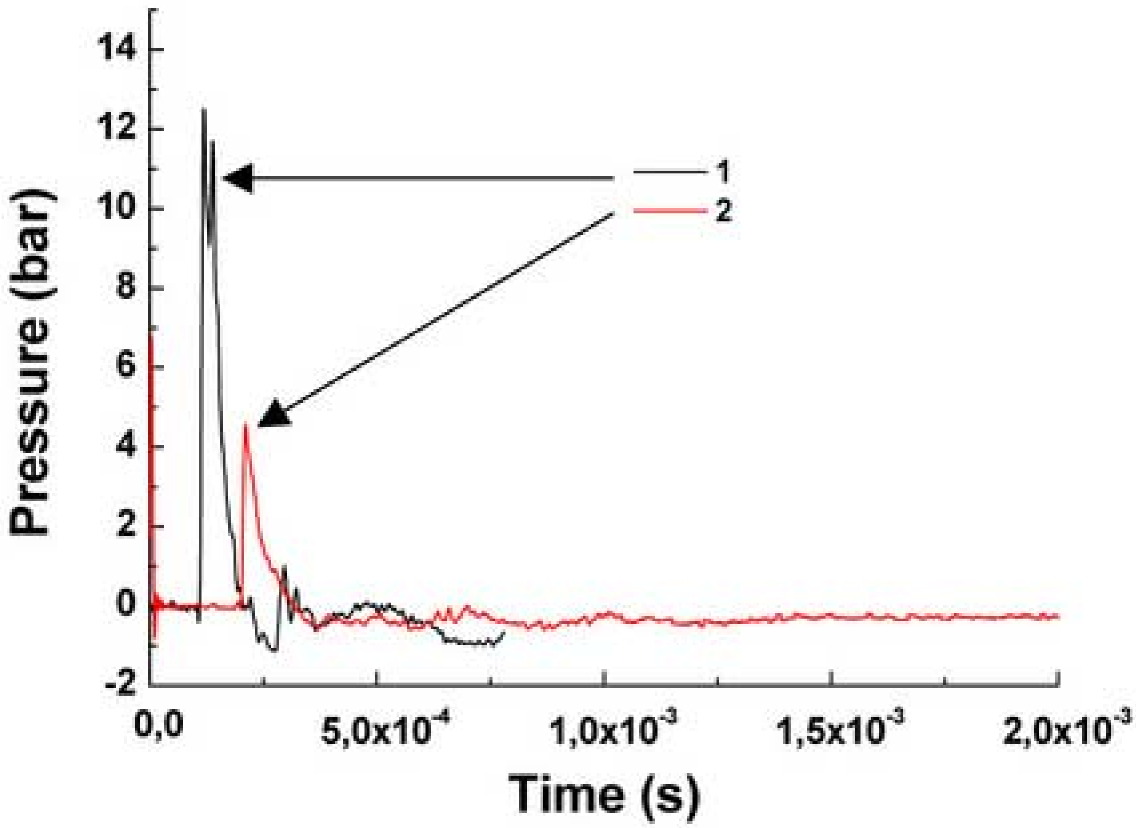

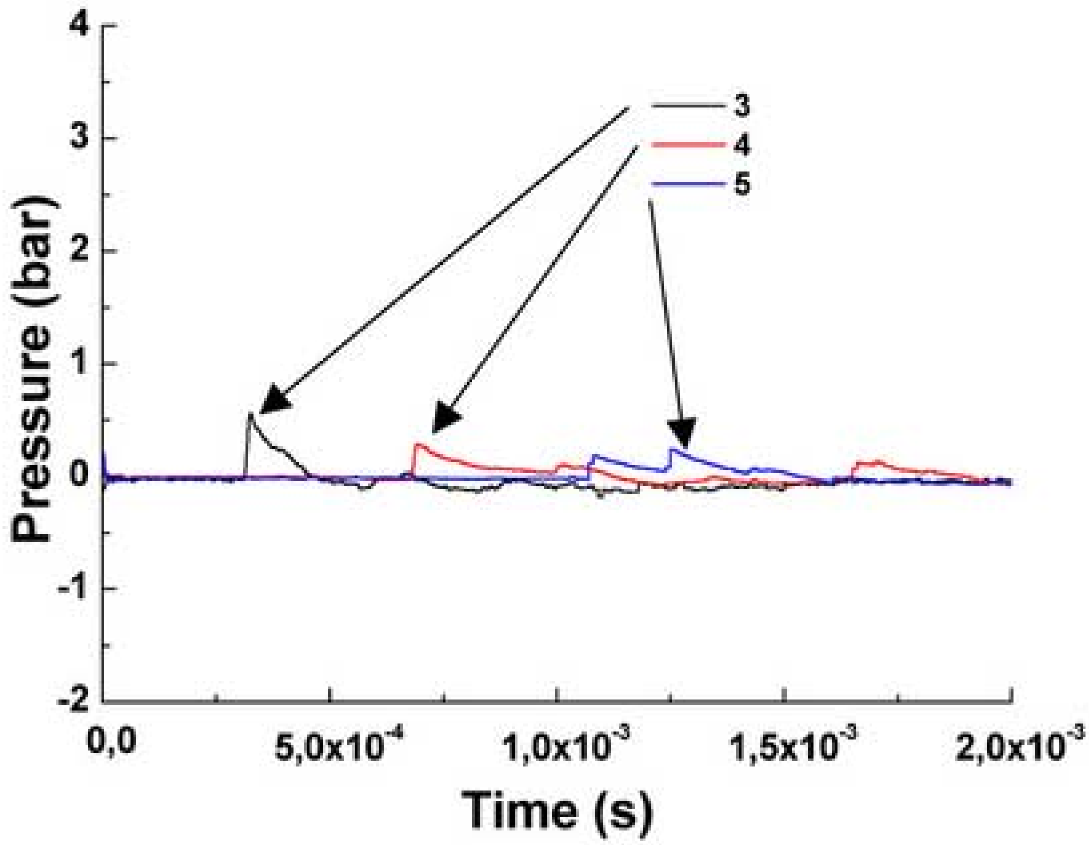

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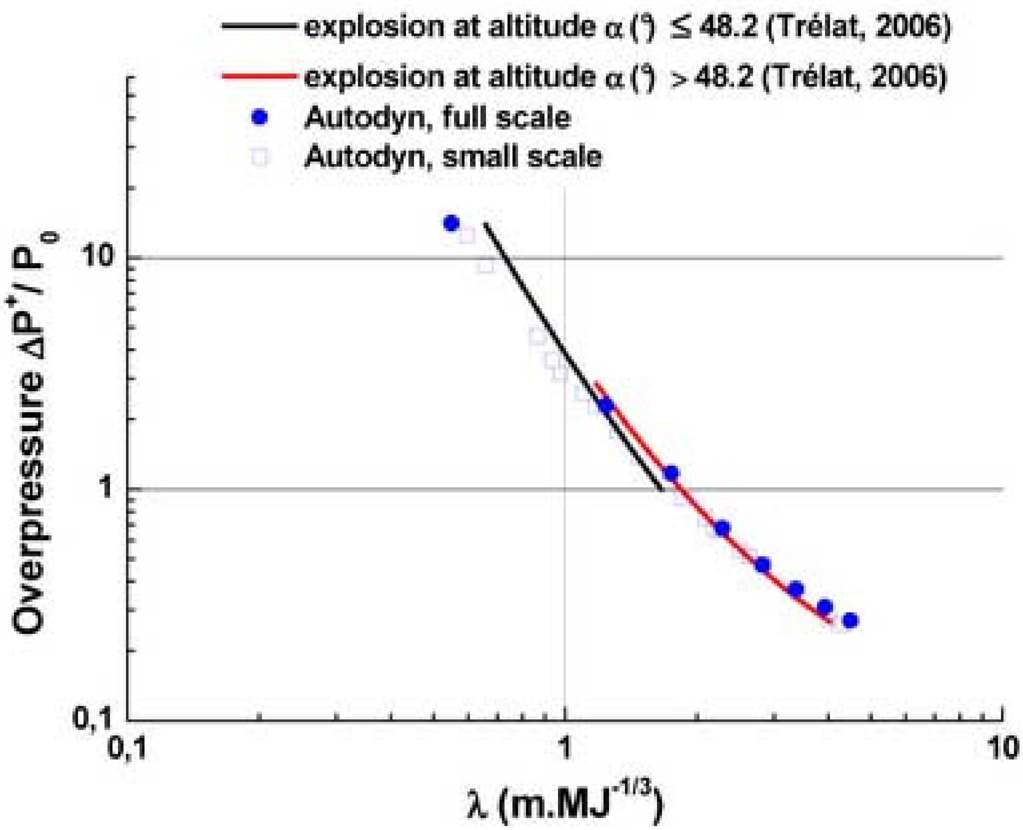

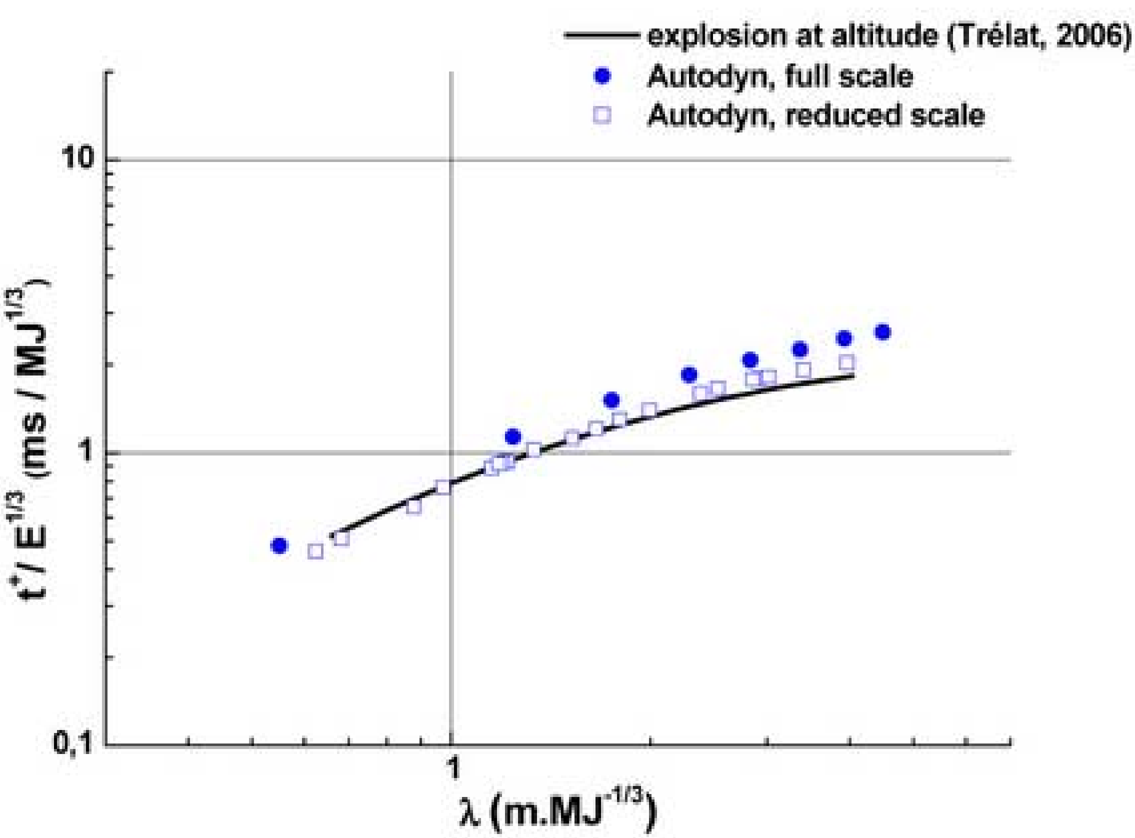

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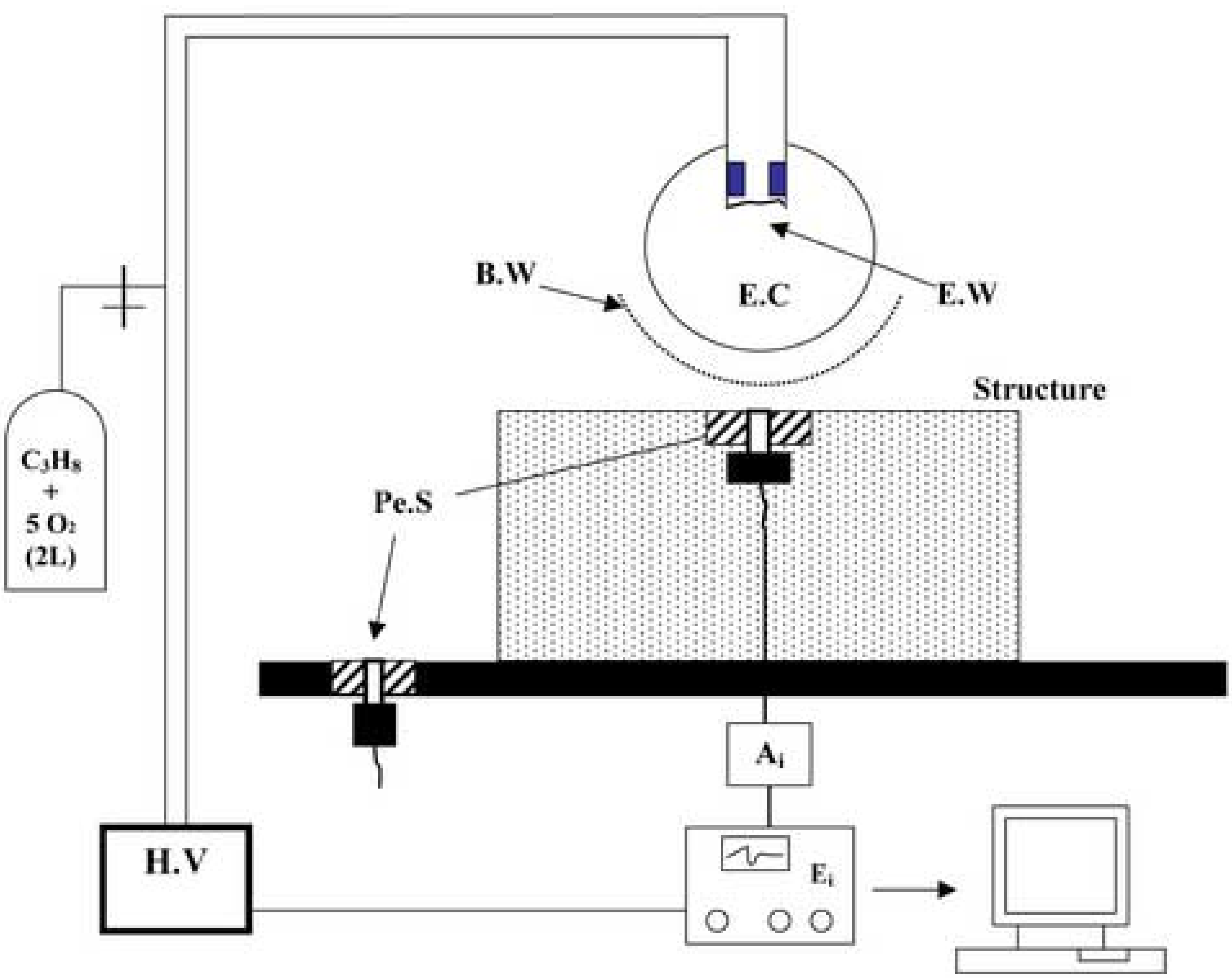

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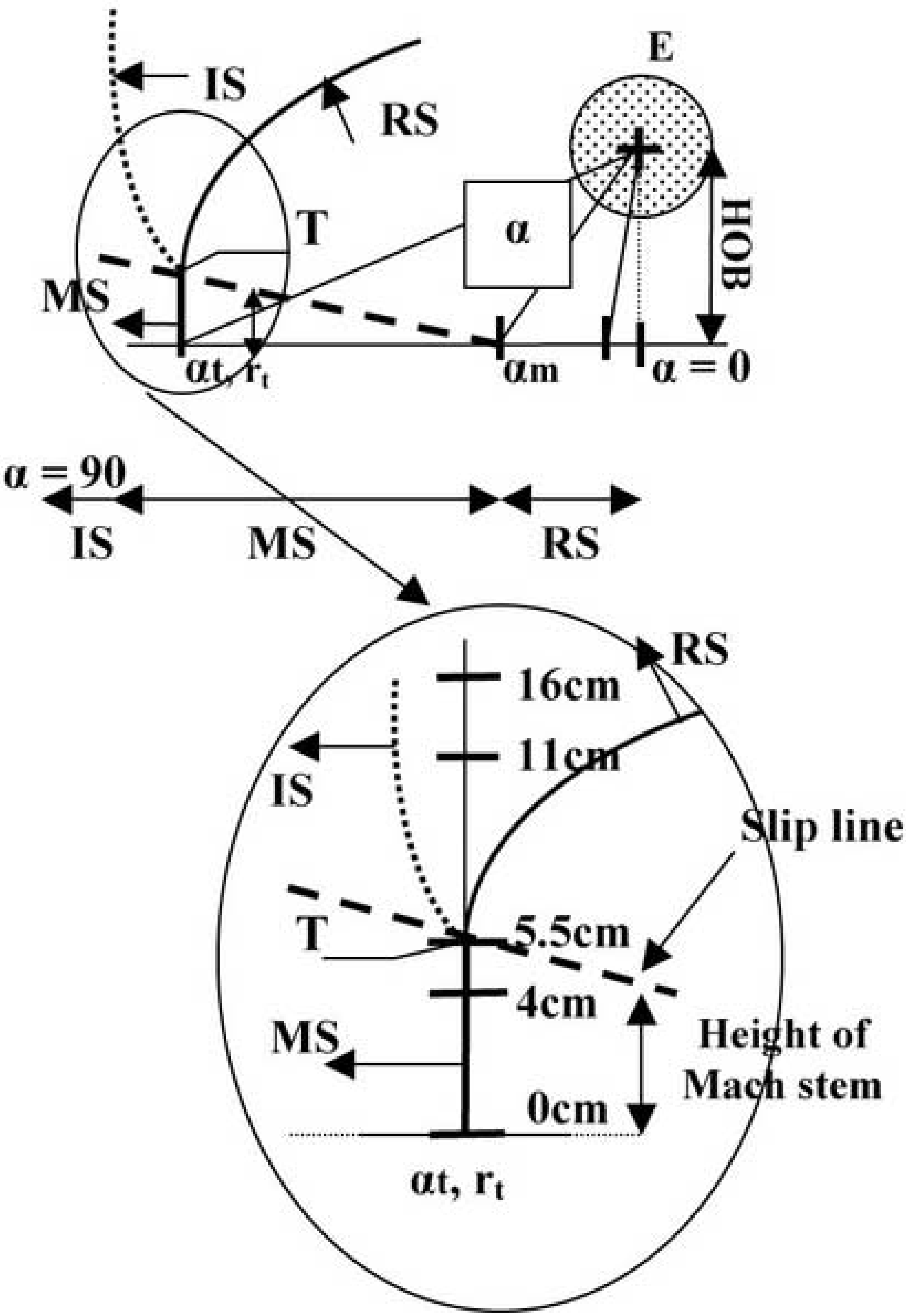

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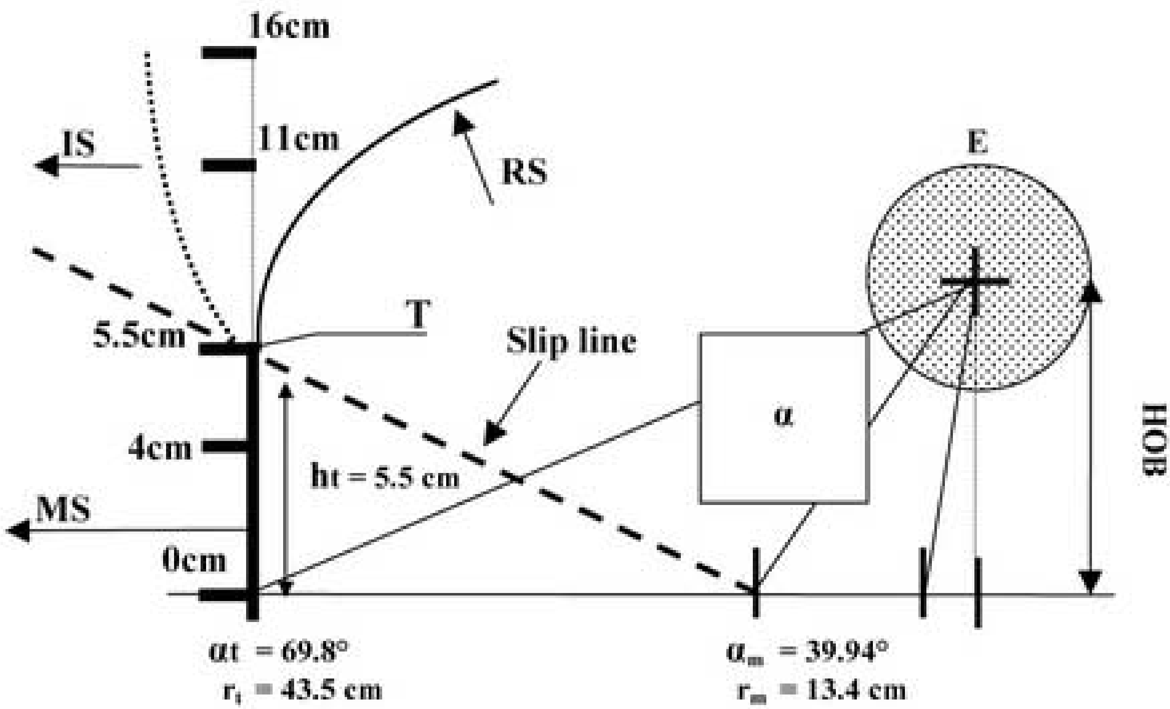

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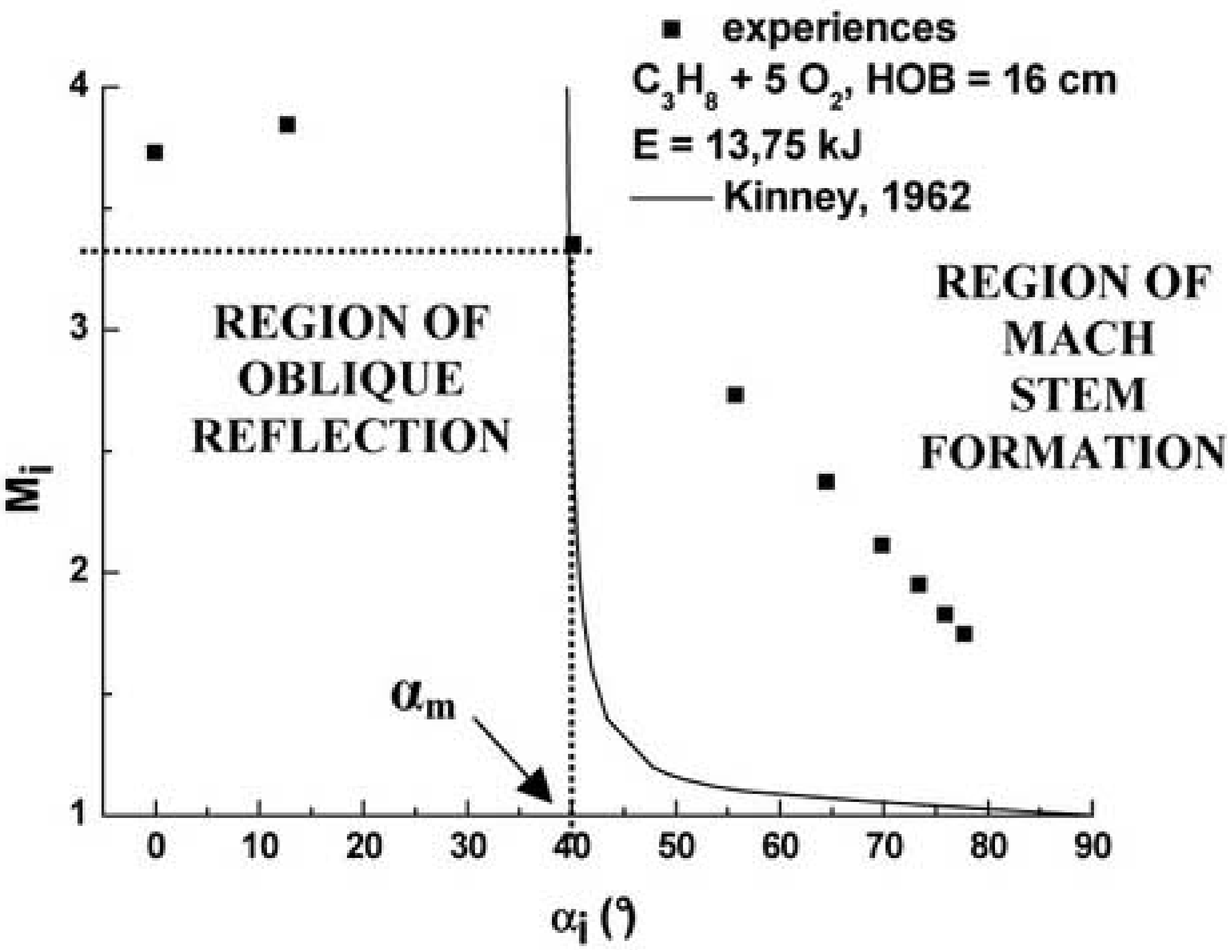

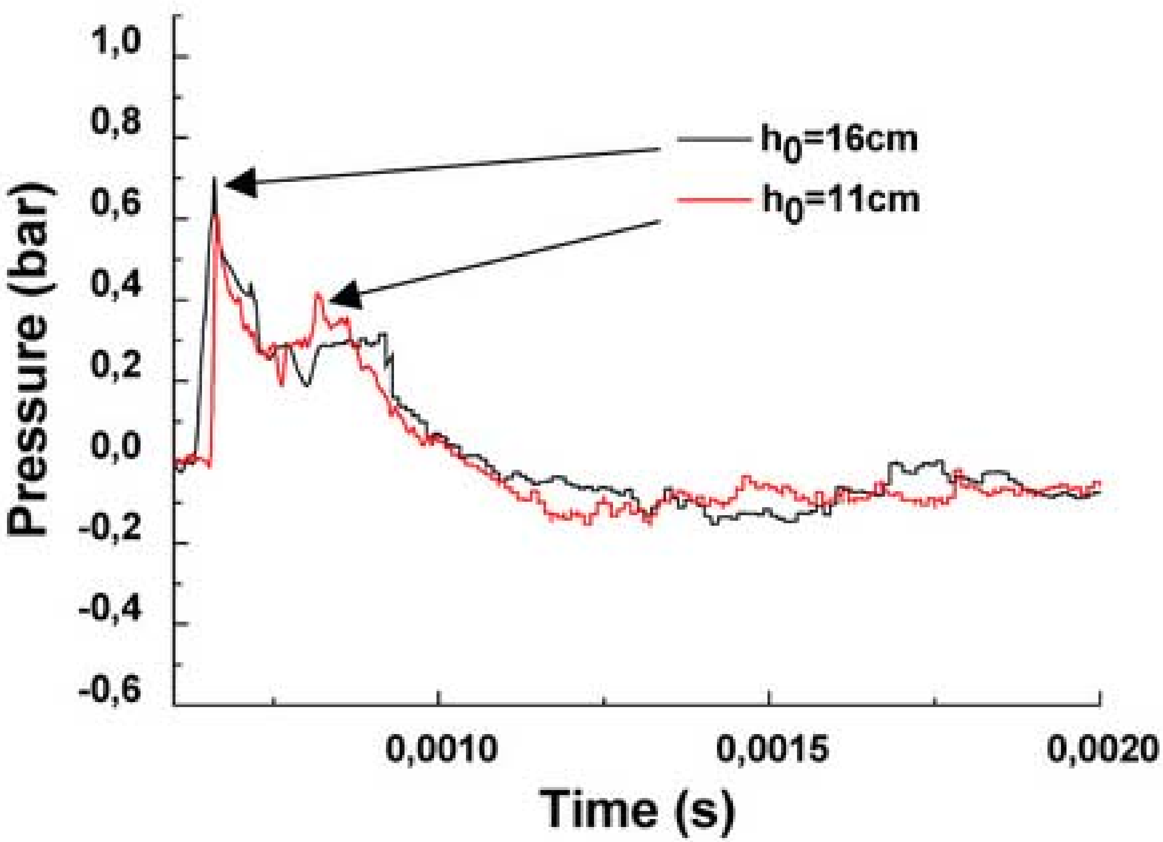
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Pressure (bar)
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h_0=11cm
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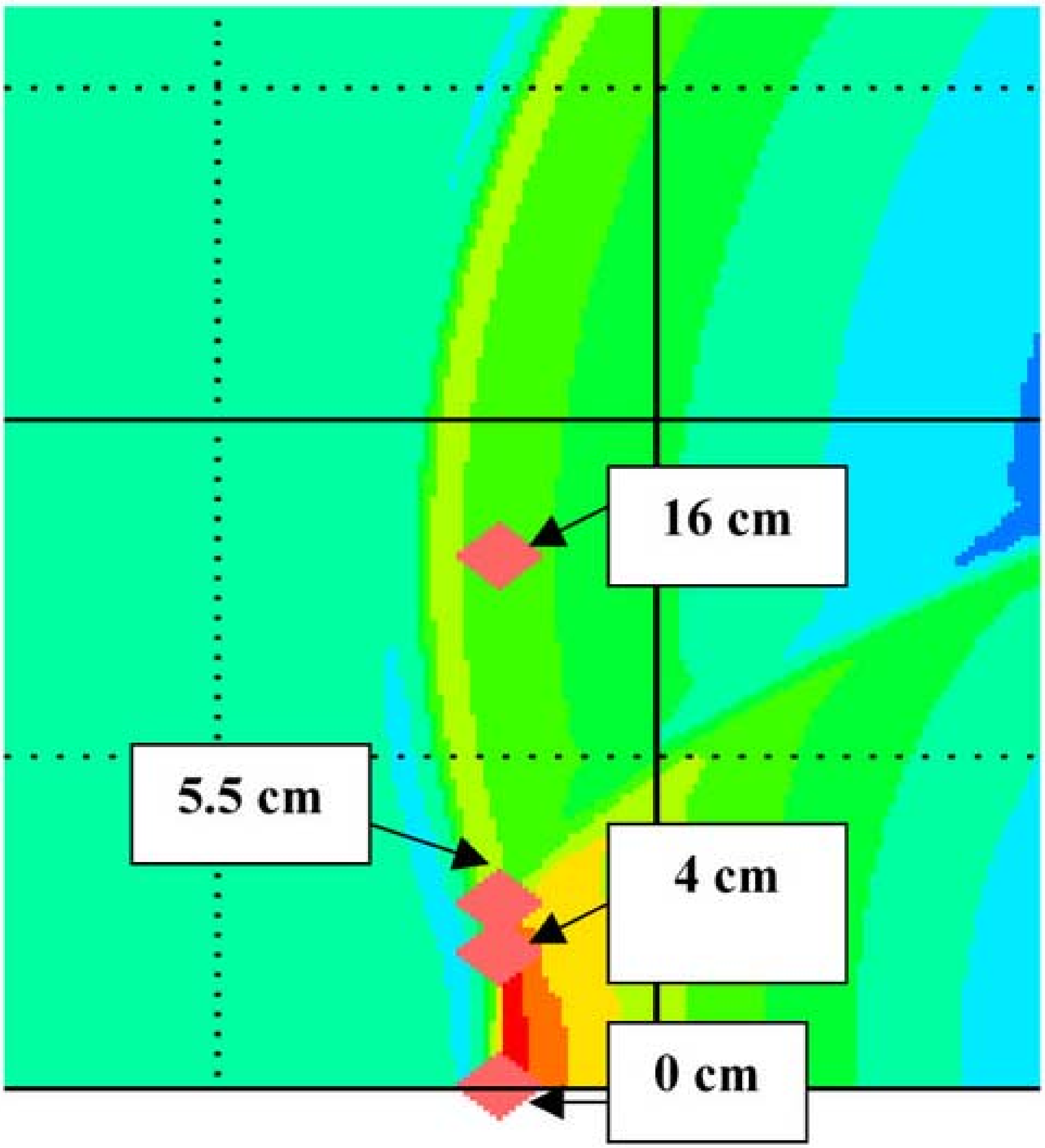
0,0020
Time (s)


16 cm
5.5 cm
4 cm
0 cm

sochet-et-al._figure9

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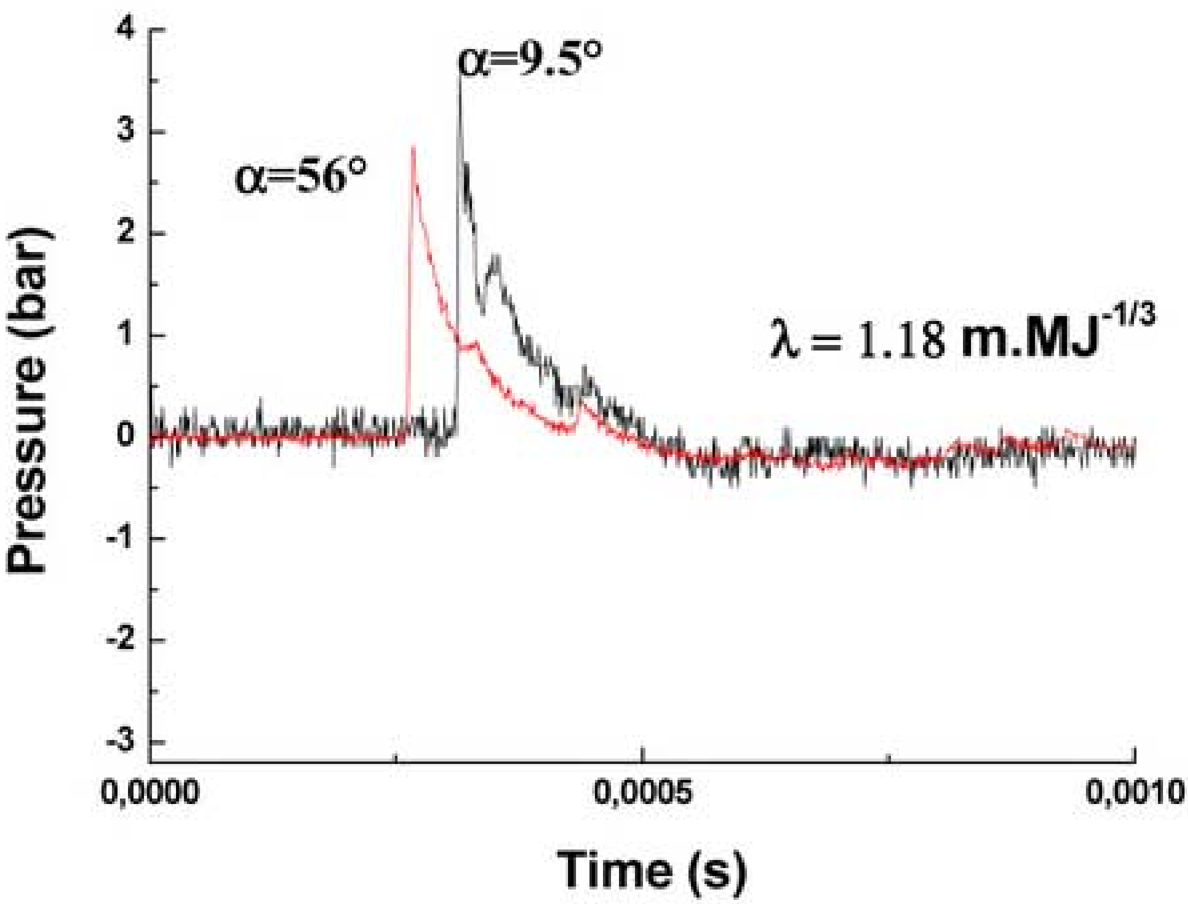

sochet-et-al.figure6
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