

## MEASUREMENTS OF PRESSURE IN FRONT OF SHOCK WAVE – ASSESSMENT OF METHODOLOGY INFLUENCE ON THE MEASUREMENT RESULTS ON THE BASIS OF EXPERIMENTS WITH THE SHOCK TUBE

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### Abstract

*The experiments, described in the article, are related to research of a rotating detonation that has been conducted in the Institute of Aviation in Warsaw since 2009, under the OPIE project: “Turbine engine with detonation combustion chamber”. Measurements of the shock wave parameters, are among the most difficult in the art. This is due to high speed of the wave transition, and above all, a very small thickness of the shock wave. For the purposes of the mentioned project, a methodology for measuring pressure on the rotating detonation wave was developed. It included the type of sensors, their location and their protection from heat and flames. In order to determine the capabilities, limitations and accuracy of the method that was used, a series of experiments were planned and carried out. They enabled the assessment of the impact, on the measurement of pressure in the shock wave, of the following factors: the location of the sensor (frontal and lateral) relative to the shock wave front, protrusion or retraction of the sensor in its housing, the covering of the sensor with a protective layer (such as a high temperature silicon). This paper presents the results of the experiments that were carried out with use of a small shock tube of a simple design. The high-pressure part of the tube (so-called “driver”) was charged with the compressed nitrogen gas. The membrane was designed to be torn by pressure and pressure magnitude of the shock wave were measured by a “twin pair” of the Kistler 603B type piezoelectric sensors, one of which was always the reference sensor.*

**Keywords:** shock wave, shock tube, pressure measurements

### 1. Introduction

The shock wave is defined [2, 3, 4] as a distortion of medium that transits within this medium with supersonic speed, which introduced a step change of medium parameters such as: pressure, density, temperature or flow velocity, from an initial state (before the shock wave) to a final state (behind the shock wave). The measurements of the shock wave parameters are difficult mainly because of the small thickness of the wave. What is more the high velocity of the shock wave make ones even more difficult (we omit stationary shock waves e.g. associated with supersonic flow around a body in a wind tunnel). According to the molecular gas theory it is assumed that the thickness of the shock wave is of the order of the mean free path in the medium. In case of air, at the sea level, it is only about 0.25  $\mu\text{m}$  [2, 3, 5] – in such a thin layer almost the whole pressure magnitude increase is done. It follows that, in practice, regardless of the measurement technique, all attempts to measure the magnitude of pressure jumps in the non-stationary shock wave (e.g. accompanying explosion), leads to measure pressure behind the shock wave, which is averaged in space and time. This averaging is related to the sensor size and its “speed” (response time) and the rate of pressure drop behind the shock wave. In case of pressure measurements in the shock wave that accompanies detonation (for example, combustible gas mixture detonation) additional difficulty is the high temperature (as a result of combustion behind the shock wave), which may adversely

affect the pressure sensor, distorting its indications, or even damaging it. This problem increases with duration of sensor exposure to the high temperature, which for example occurs during tests over a rotating detonation phenomena. Such tests have been carried out at the Institute of Aviation since 2009, among others, measurement of pressure jumps caused by successive detonation wave transitions near the sensor were undertaken. For the purposes of these measurements piezoelectric sensors of Kistler 603B type were selected (their parameters are described later in this article). Research has shown that the use of water-cooled collet that holds the pressure sensors is not enough and there is need to cover the sensors face with extra thermo-ablative protective layer (so-called “high temperature silicone” was used). In order to determine the effect of covering the sensors face with silicone, and to determine the method and inaccuracy of their housing, as well as to carried out the calibration of these sensors, the experiments with the shock tube were undertaken. The results of these experiments are presented in this article.

## 2. Experiment Objectives

The aim of the experiments was to determine how the measurement of the shock wave pressure is affected by following factors:

- 1) the location of the sensor relative to the shock wave (frontal or lateral),
- 2) the sensor face cover with the 2.5 mm protective silicone layer,
- 3) inaccuracy of the sensor housing (ejected, retracted) in range of  $\pm 1$  mm.

## 3. Technique and the course of experiments

During experiments, the shock tube with the following dimensions was used:

- internal diameter and length of the high-pressure section:  $\text{Ø}44 \times 240$  mm,
- internal diameter and length of the low-pressure section:  $\text{Ø}35 \times 1060$  mm.

Low pressure section was open to the environment while the high pressure section was filled up with pressurized nitrogen until the membrane burst. Membrane was made of reinforced, rubberized fabric, used for production of tourist pontoons. Preliminary tests have shown that the membrane has a sufficient strength and its repeatability (burst pressure of between 50 and 70 bar), to obtain a shock wave velocity of approximately 2.2 Ma. What is the most important the membrane burst does not produce slivers that can interference measurement and even damage the sensors placed frontally against the shock wave. The protective silicon cover of sensor face was applied by retracting the sensor in its holder by ca 2.5 mm from the face of the holder, space created in such a way was completely filled with silicone – schematically it is shown in Fig. 4, Fig. 5. The threaded holder of the K1 sensor was mounted with PTFE tape on the thread and the similar holder of the sensor K2 was mounted directly into the socket (without strapping with PTFE tape). Several series of experiments was carried out (each performed three times), during which pressure in the shock tube, using 2 “high-speed” pressure sensors (K1, K2), was recorded. In addition, pressure and temperature in the high-pressure section (P4, T4) and in a low pressure section (P1, T1) was recorded. Two used configurations (A, B) of the sensors location in the shock tube are schematically shown on Fig. 1. Details of the K1 sensor setting and about the prospective protective silicone layer are described in each case together with the presented results (K2 was always a reference sensor). When the sensor was located transversely to the shock wave its ejected or retracted position was referred to a “0” sensor position, in which the sensor’s face was tangential to the cylindrical inner surface of the shock tube.

The characteristics of the measuring system used is shown in Tab. 1 and 2.

## 4. The results of the experiments

The obtained results were presented in form of graphs of pressure course that was recorded by K1 and K2 sensors. Graphs are shown in Fig. 2-9. Sensor K2 was always a reference sensor. Charts

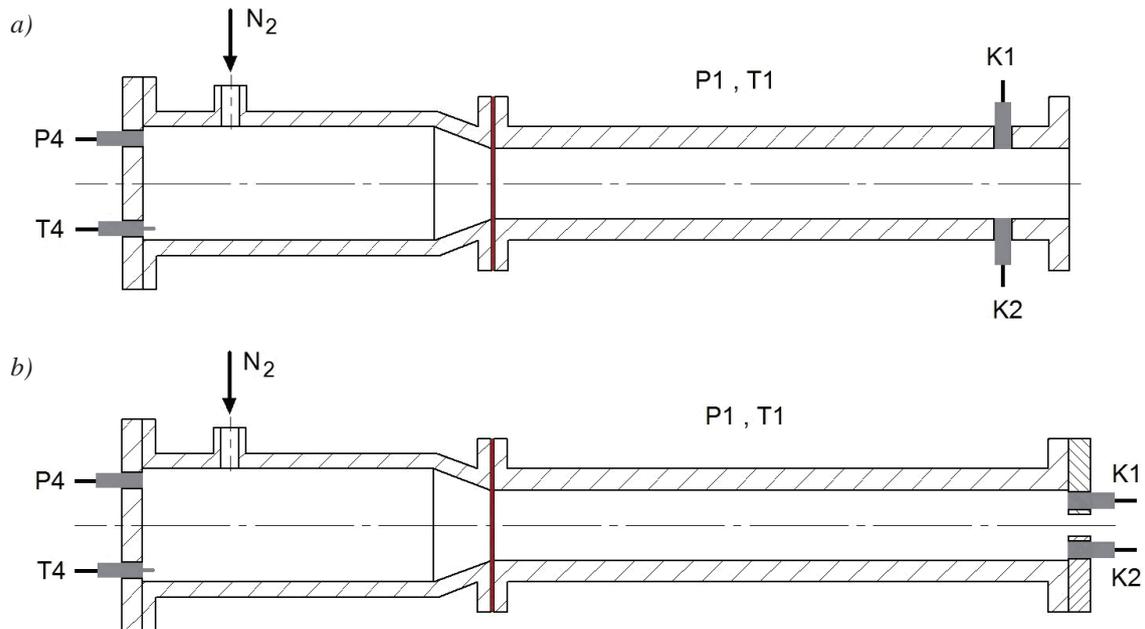


Fig. 1. The K1 and K2 sensors configurations (A, B), mounted on the shock tube (P4 and T4 – pressure and temperature sensors of nitrogen, in high-pressure section of the shock tube)

Tab. 1. Components of used measurement channels

Channel	Measured parameter	Sensor type	Amplifier type	DAQ device
„fast” $f = 2 \text{ MHz}$	K1 pressure	Kistler 603B	Kistler 5018A1000	NI USB-6366_ch01
	K2 pressure	Kistler 603B	Kistler 5018A1000	NI USB-6366_ch02
„slow” $f = 1 \text{ kHz}$	P4 pressure	Kobold 100	—	NI PCI-6259_ch04
	P1 pressure	Kobold 10	—	NI PCI-6259_ch05
	T4 temperature	K thermocouple	SCC-TC02_01	NI PCI-6259
	T1 temperature	K thermocouple	SCC-TC02_02	NI PCI-6259

Tab. 2. Main parameters of Kistler 603B type piezoelectric sensor

Crystal type	Face diameter	Range	Natural frequency	Acceleration compensation
quartz	~5.5 mm	200 bar	> 300 kHz	yes

are presented in pairs (A and B configuration - see Fig. 1), in order to highlight the impact of the location of the sensors. For each chart, the diagram that illustrate the sensors placement is attached on the right. For ease of comparison, for each chart a uniform time interval of 2 ms were applied.

## 5. Summary and conclusions

- 1) The location of the sensor, relative to the shock wave, had a significant impact on the measured pressure. The sensor located laterally recorded pressure behind the initial shock wave, while the sensor located frontally recorded pressure behind the shock wave that was reflected from the sensor and its mounting (see pairs of drawings: Fig. 2-3, Fig. 4-5, Fig. 6-7, Fig. 8-9).
- 2) During the measurements often the effect of sensor “ringing” occurred [1, 6]. This happened when the shock wave strike caused vibrations connected to the sensor mounting. This can be seen as the “boost” of first pressure pulse. It is especially noticeable when the sensor was located frontally relative to the front of the shock wave (Fig. 3, Fig. 5, Fig. 7).
- 3) The sensor silicone cover layer (2.5 mm) had a minor impact on the course of the average pressure (Fig. 4, Fig. 5).

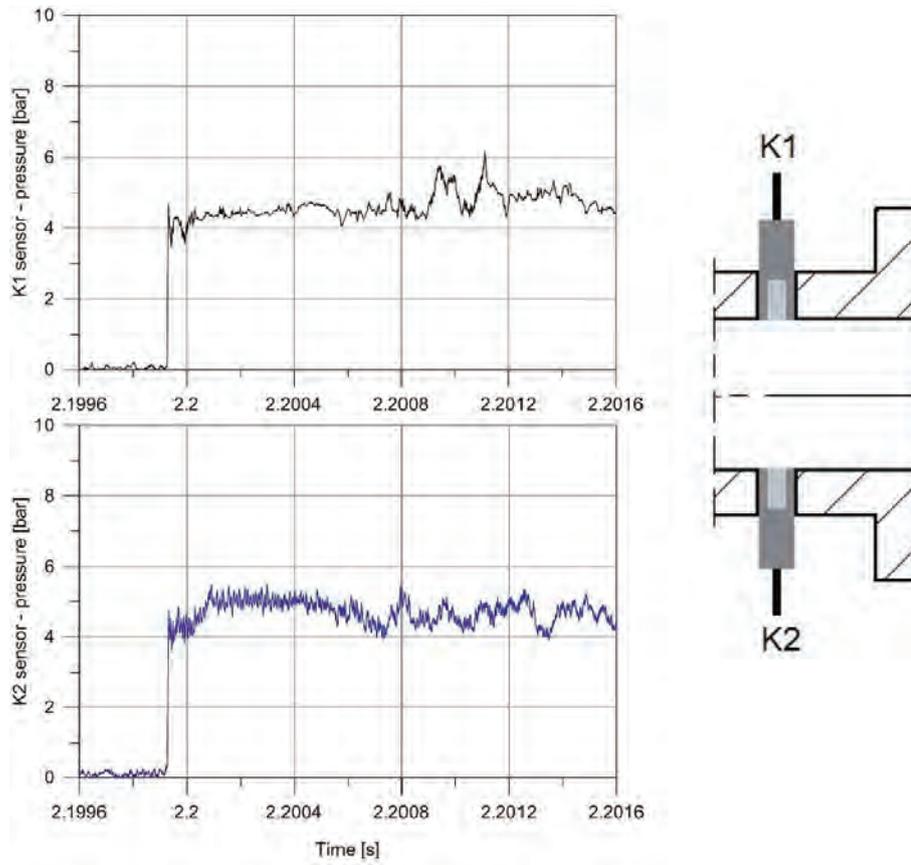


Fig. 2. Configuration A, both sensors in position "0", no coating

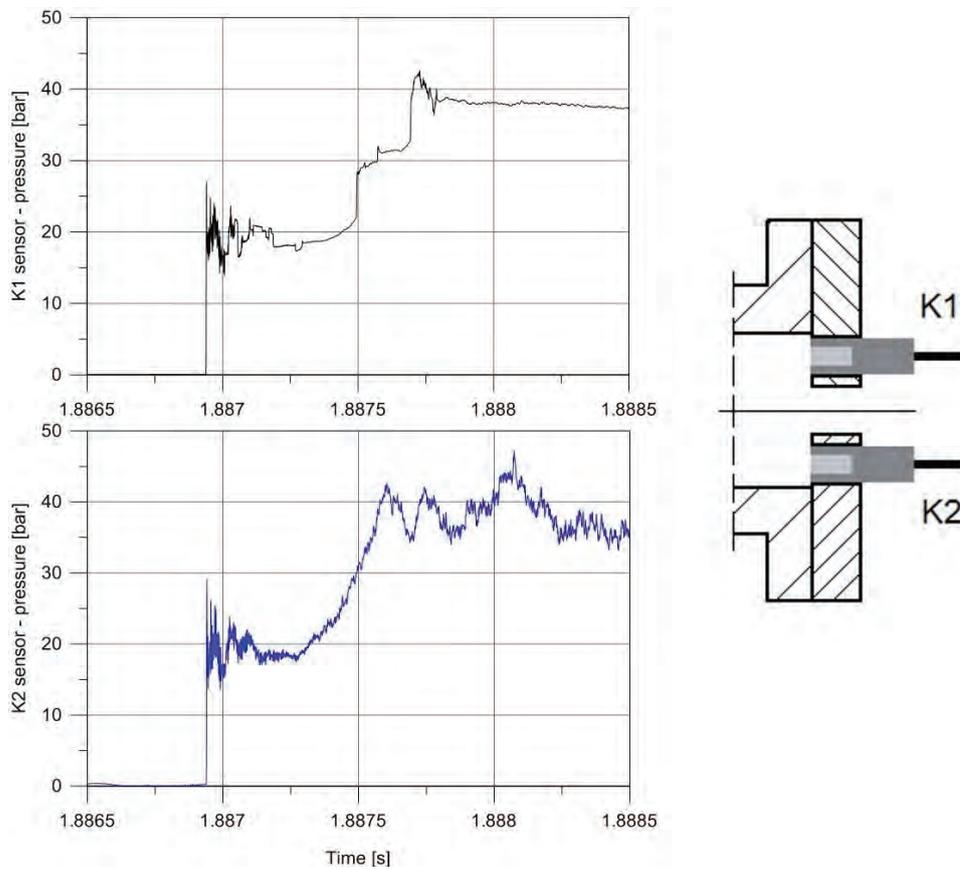


Fig. 3. Configuration B, both sensors in position "0", no coating

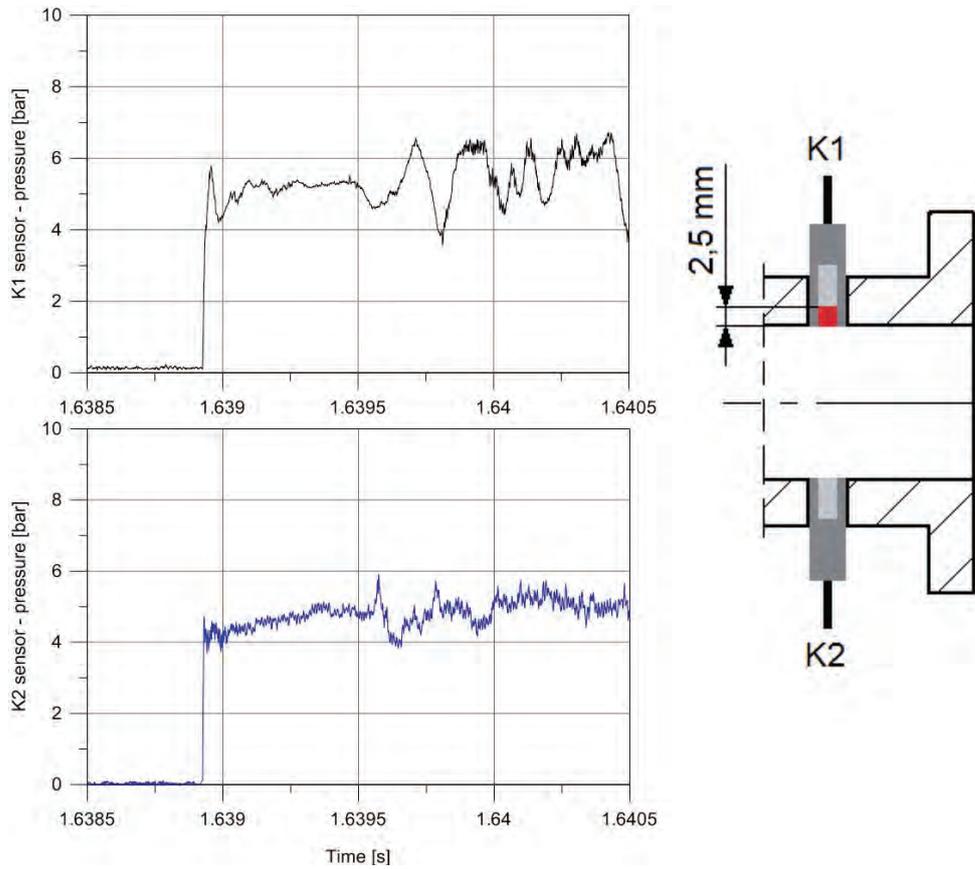


Fig. 4. Configuration A, both sensors in position “0”, K1 coated with silicone

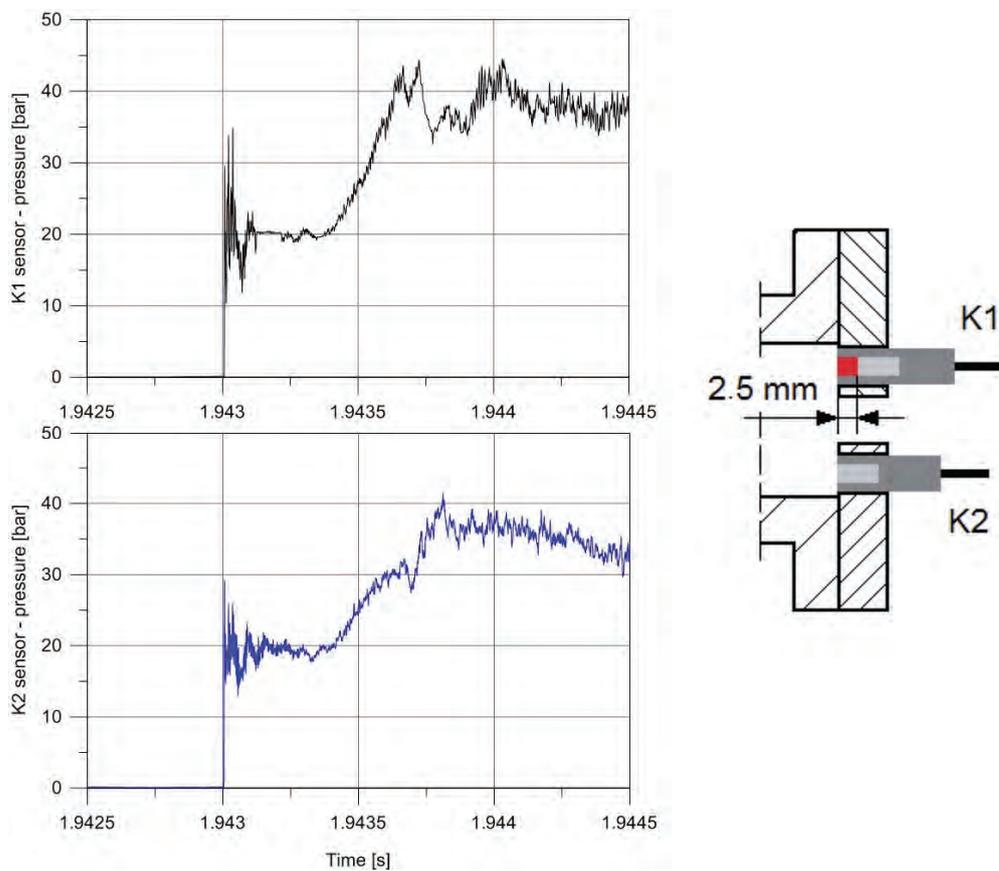


Fig. 5. Configuration B, both sensors in position “0”, K1 coated with silicone

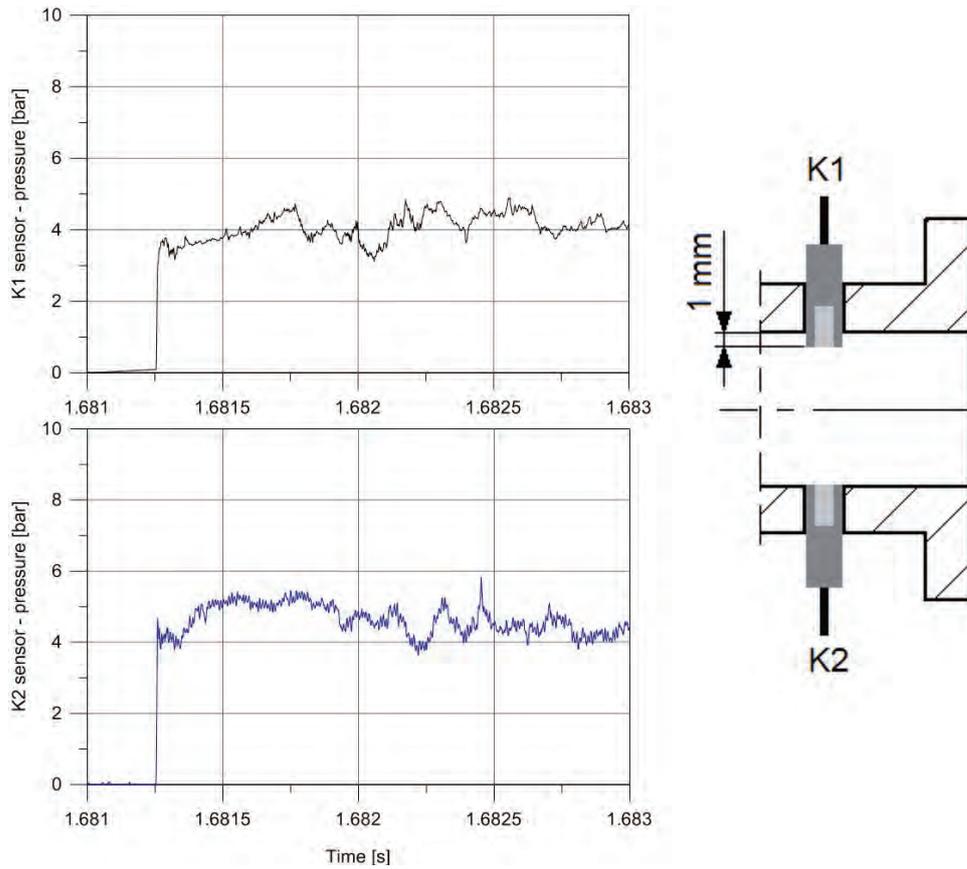


Fig. 6. Configuration A, K2 sensor in position "0", K1 ejected by 1 mm

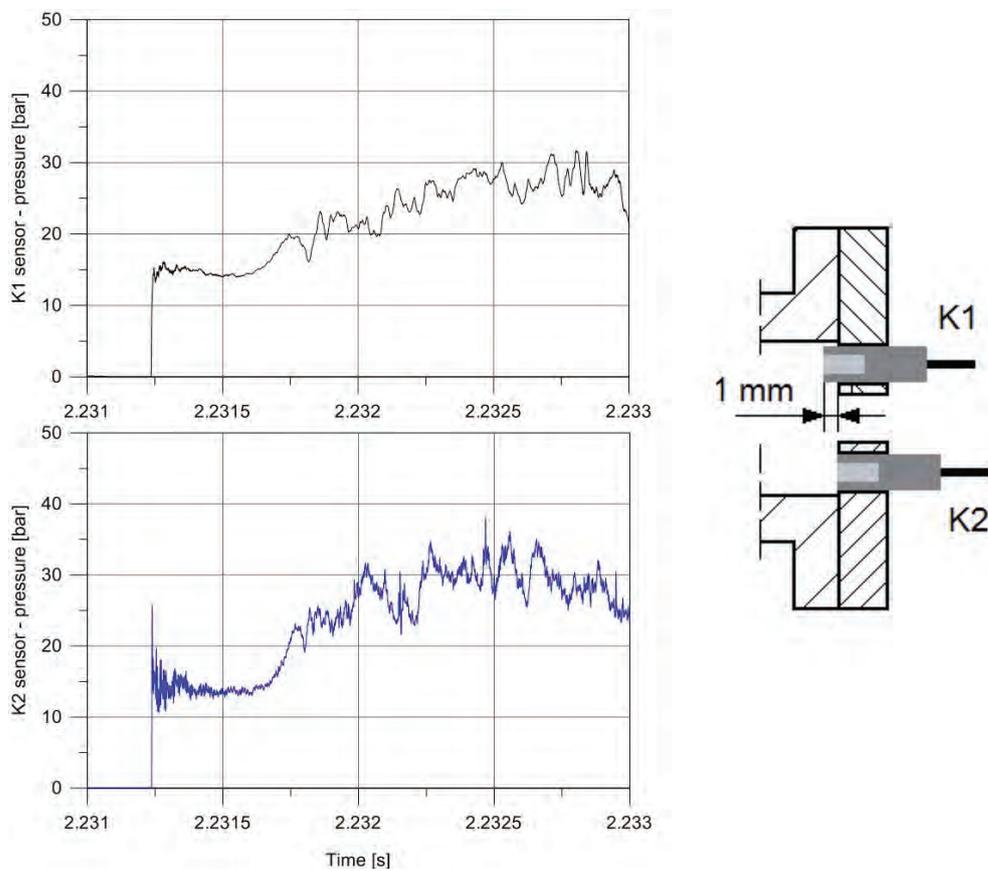


Fig. 7. Configuration B, K2 sensor in position "0", K1 ejected by 1 mm

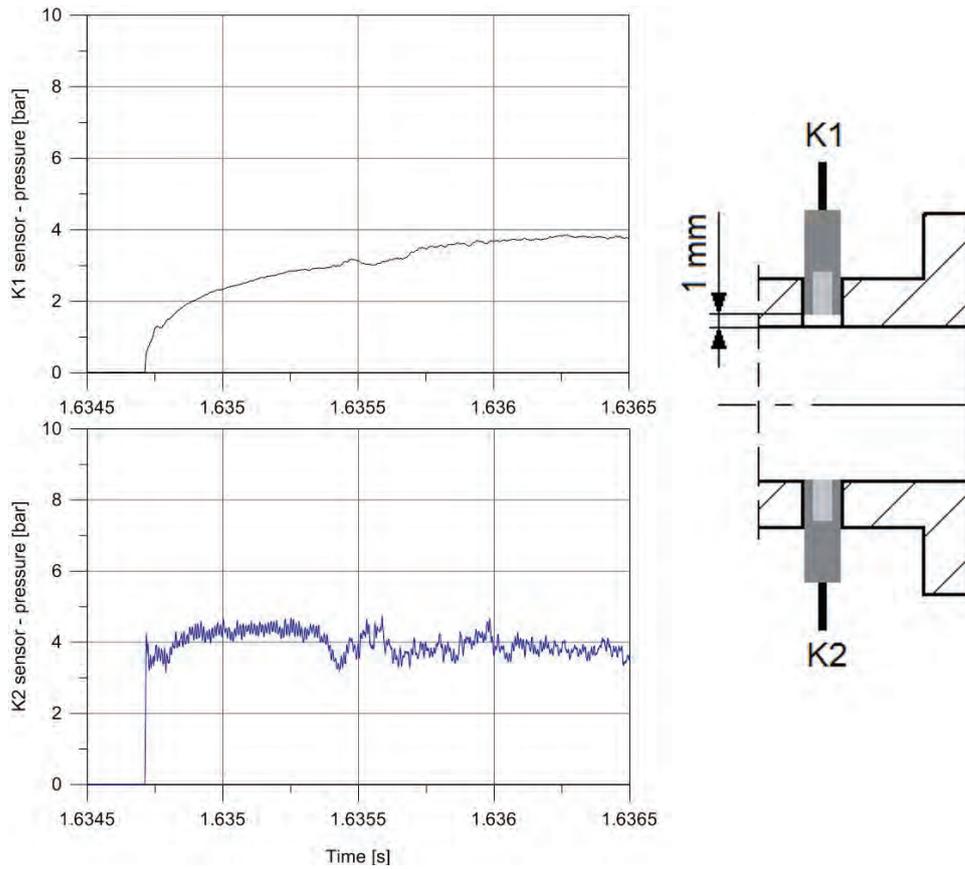


Fig. 8. Configuration A, K2 sensor in position "0", K1 retracted by 1 mm

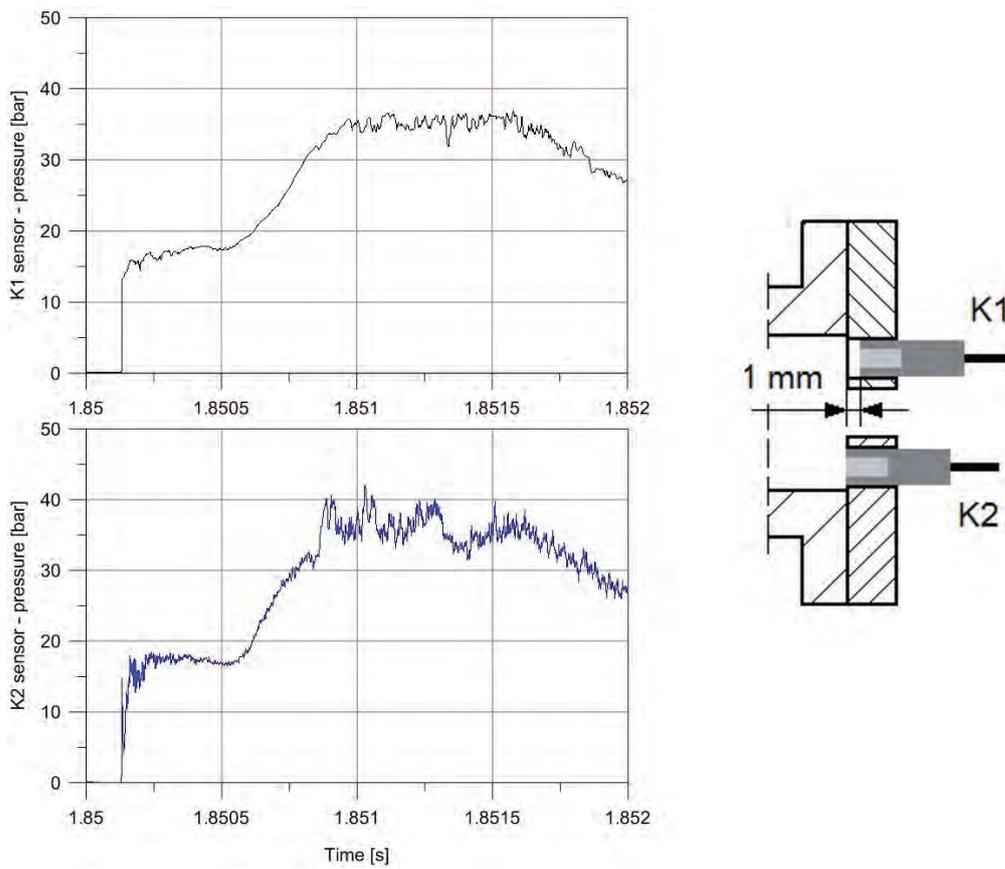


Fig. 9. Configuration B, K2 sensor in position "0", K1 retracted by 1 mm

- 4) The sensor ejection, beyond the inner surface of the shock tube, seems to does not have a significant effect on the recorded pressure. (Fig. 6, Fig. 7).
- 5) Retraction of the sensor, beneath the inner surface of the shock tube, have a major impact on the recorded pressure for the lateral location of sensor (Fig. 8) and seems to have a small effect for the sensor located frontally to the shock wave (Fig. 9).

## References

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