24th COBEM - 2017

24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-0453
DEVELOPMENT OF IONIZATION SENSOR FOR SHOCKWAVE SPEED MEASUREMENTS

Rafael Augusto Cintra
Universidade Federal de Itajubá, Av. BPS, nº 1303, Bairro Pinheirinho, CEP. 37. 500-903, Itajubá, MG, Brasil
rafaelcintra94@outlook.com

Tiago Cavalcanti Rolim
Lucas Alexandre Gonçalves Ribeiro
Instituto de Estudos Avançados, Trevo Coronel Aviador José Alberto Albano do Amarante, nº 1, Putim, CEP. 12.228-001, São José dos Campos, SP, Brasil
tiagorolim@ieav.cta.br
lucasag@ieav.cta.br

Abstract. *Recently, there is a growing interest in studies concerning ionization sensors for aerospace applications, power generation and fundamental research. In aerospace research, they have been used for studies on shock and detonation waves. Two key features of these sensors are their short response time, in order of microseconds, and the fact that they are activated when exposed to high temperature air. This work describes the development of ionization sensor to be used in shock tube facilities. The sensor consists of two thorium-tungsten electrodes insulated by a ceramic, with aluminum adapter for proper mounting, and two copper seal rings. An electrical circuit was also built with two main purposes: to provide the electrodes a sufficient large voltage difference in order to ease ionization of the gas and to assure a short time response of the sensor. The tests were done in a shock tube, with the objective of determine the shockwave speed in air and in argon. The results proved the functionality of the ionization sensors to acquire the instant of the shockwave passage. Also, the sensors proved to be useful to measure the shockwave speed with a low difference in comparison to the PCB sensors, in which the greatest difference in the tests was 3.06%.*

Keywords: *Ionization sensors, Shock tubes, Shockwaves.*

1. INTRODUCTION

Recently, there is a growing interest in the study of ionization sensors for aerospace applications, energy generation and fundamental research. In aerospace research, the ionization sensors are generally used in studies on shock and detonation waves (Gupta, 2013; Panicker, 2008).

In studies of shockwaves, the interest lies on the possibility of using these sensors on shock tube improvement since they can detect high temperature air with an appropriate response time. Shock tubes are used to simulate the flight conditions of high speed flight, for example, atmospheric vehicle reentry. Shockwaves formed in these tubes can achieve very high Mach numbers.

Basically, a detonation wave is a conjugate shockwave with a combustion reaction zone, in which the released energy is the responsible for sustaining the shockwave propagation (Zeldovich, 1950). The reaction zone is divided in two sections, one for induction zone and another for heat addition. The detonation phenomenon is a highly energetic and can be applied to propulsion systems (for example, pulse detonation engine), power generation and as a driver for shock tubes (Lu and Marren, 2002).

In general, the high temperature created by the shockwave allows the dissociation of N_2 and O_2 molecules present in the air, however, the temperature is not enough to do a direct ionization when it is below 9000 K (Anderson, 1989). Under these circumstances, it is used an ionization sensor to create a voltage potential between two electrodes, permitting the ionization of the air, when it happens, a voltage signal is measure. Therefore, by using a pair of sensors with a known distance, and measured the delay between the signals acquired from the first and the second sensors, it is possible to determine the shock or detonation wave speed.

In previous work (Cintra, *et. al*., 2017), the ionization sensor was tested in a shocktube under stagnation condition, in which case was observed a fast and consistent response of the sensor signal, and it was used as base for the present work.

In this work, we show the development of ionization sensor for shock tube applications, in the condition induced by the incident shockwave. The tests were carried out in the shock tube T1 of the Instituto de Estudos Avançados, with the objective to measure the incident shockwave speed.

2. EXPERIMENTAL PROCEDURE

The ionization sensor development is shown in Fig. 1. The sensor is comprised of two electrodes of tungsten-thorium (Ø1 mm), mounted diametrically opposite, and 1.0 mm apart. This material was chosen due to its capability to support high temperatures with low erosion. In addition to that, the thorium helps the passage of electric current and it also gives more stability and longevity to the sensor. Furthermore, it was used an alumina ceramic material for a good electrical and thermal insulation even at high temperatures. The electrodes were fixed to the ceramic by means of a bicomponent epoxy resin. Two seal rings were used for sealing the sensor. Moreover, it was fabricated with stainless steel a clamp nut and a seal for adequate seal, and an aluminum adapter for the sensor to be used in the wall of shock tube.

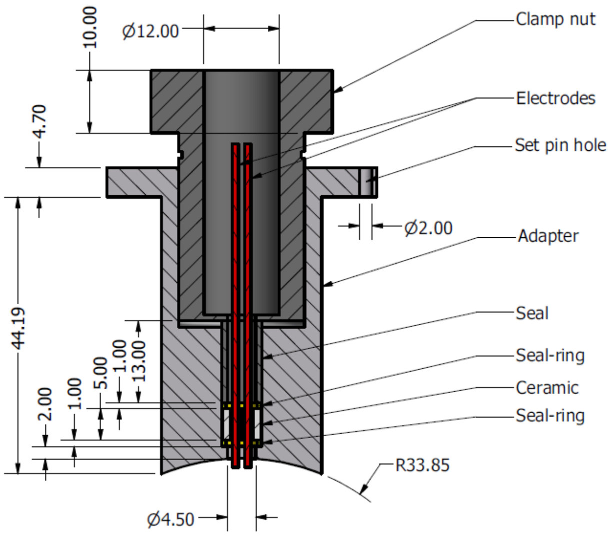

Figure 1. Sectional view of the developed ionization sensor. Dimensions in mm.

Figure 2 shows the electrical circuit used for the tests. The choice of the voltage, resistances, and capacitance was based on the study of Glass and Hall (1959). These values provide quick response of the sensor, high voltage between the electrodes, and a high-level output signal. In this circuit, the discharge time can be estimated using Eq. (1), and the charge time can be estimated using Eq. (2), as follows:

$$\tau_{discharge} \approx (47\times10^{3}\Omega)(0.5\times10^{-9}F) = 23.5\mu s \tag{1}$$

$$\tau_{charge} \approx (10\times10^{3}\Omega)(0.5\times10^{-9}F) = 5ms \tag{2}$$

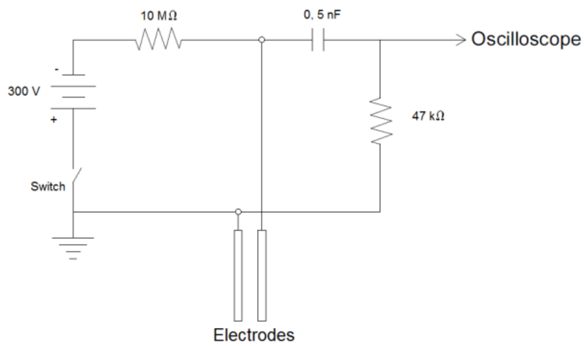

Figure 2: Electrical circuit used with the ionization sensor.

2.1 Shock Tube Description

During these tests we used the shock tube T1 of the Instituto de Estudos Avançados. The shock tube is comprised of two reservoirs, one filled with high-pressure gas denominated driver and the other one filled with a low-pressure gas denominated driven. These two reservoirs are separated by a Double Diaphragm Section (DDS), in which two diaphragms with known rupture pressures are used to control the test start. This section remains at an intermediate pressure. The diaphragm used was of aluminum material with 2.0 mm of thickness and risk with 0.5 mm of depth.

For the experiments we used two shock tube configurations, one using a driver extender, shown in Fig. 3, and the other without the extender, the utilization of the extender did not affect the incident shockwave properties. The entire tube has an internal diameter of 68.00 mm. The driver section has a length of 527.10 mm and an extender of 1692.00 mm; the driven section, of 2,853.45 mm; and the DDS, of 35.70 mm.

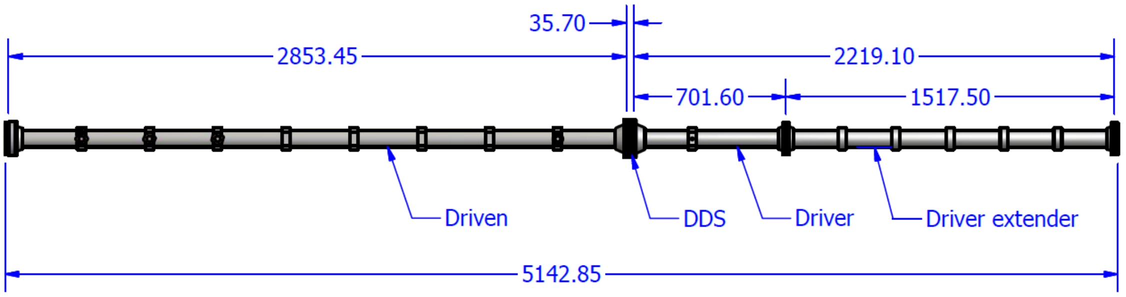

Figure 3. Dimensions of shock tube T1 (in mm), with the driver extender

After the diaphragm rupture, a shockwave is formed and moves from the driver to the driven, modifying the properties of the initial gas of driven, for example, increasing pressure, temperature and density of the gas in this section.

2.2 Experimental apparatus

The experimental apparatus for the tests is presented in Fig. 4. Using a pair of ionization sensors positioned at the wall of the driven and three piezoelectric sensors type PCB 113B26 (PCB Piezotronics 2013) that were used to measure the pressure along the tube and to estimate the incident shockwave speed by time of flight (TOF), the technical specifications are shown in the Tab. 1. The choice of a piezoelectric sensor was due to its fast response required in studies of shockwaves. The data acquisition system was a Yokogawa oscilloscope type DL850E ScopeCorder with 16 channels, using a signal conditioner type PCB 481 for the pressure sensors. Also, it was used a power suplly fabricated in-house, to provide 300 V to the circuit with a ripple factor of 1 %. After a few tests, modification were made to the test configuration, the positions of the ionization sensors were varied and the extender was removed. The purpose of these modifications was to analyse the response of the ionization sensors in different situations.

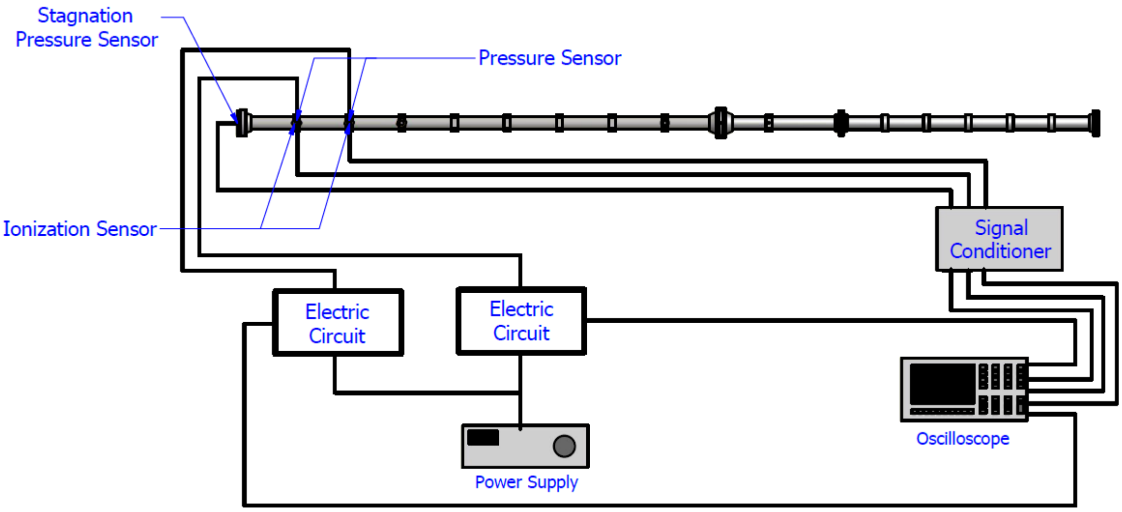

Figure 4. Schematics of the shock tube tests, using the driver extender

Table 1. General specification of the sensor PCB 113B26 (PCB Piezotronics, 2013).

Specification	Value
Measurement range	500 lbf/in²
Sensitivity	10 mV/(lbf/in²)
Maximum pressure	10,000 lbf/in²
Resolution	0.002 lbf/in²
Discharge time constant	≥50 s
Rise time	≤1μs
Output impedance	< 100 Ω
Uncertainty	±1.3%

The positions of the ionization sensors along the tunnel are shown in Fig. 5, with a known distance between the sensors, Δx, and measuring the delay response between the first sensor and the second sensor, Δt, and knowing that the shockwave moves from driver to driven, it is possible to determine the shockwave speed, by the Eq. (3). Parallel to the ionization sensor, it was used a pair of pressure sensors, and other pressure sensor in the end of the driven section (position P5), used for the reflected shockwave pressure measurement and triggering.

$$u = \frac{\Delta x}{\Delta t} \tag{3}$$

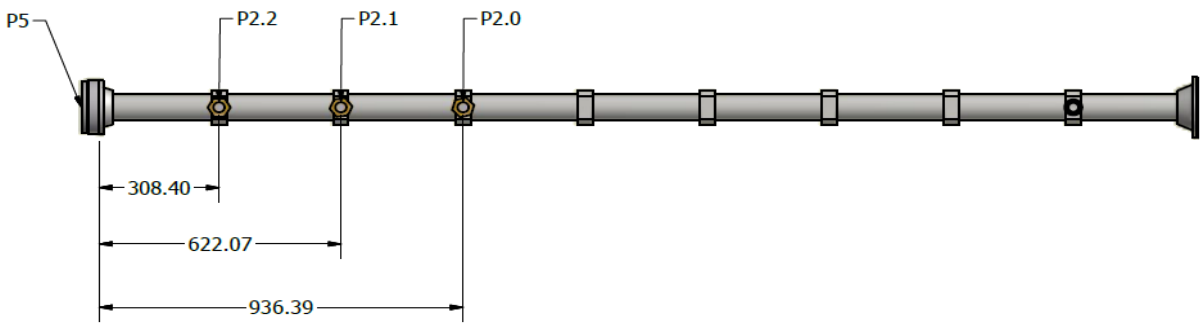

Figure 5. Position of the pressure sensors along the driven (dimensions in mm).

In order to acquire the instant of the shockwave passage, a minimum voltage value was established, in which the signal sensor had to exceed to be considered a shockwave passage. The minimum voltage for the pressure sensor was set in 0.1 V, while for the ionization sensor these values were adjusted throughout the tests. These voltages are higher than the amplitude of the signal noise from the sensors. To analyse the experimental data, the MATLAB software (MATLAB, 2010) was used to reduce data, to determine the instant of the shockwave passage and to plot the graphs.

3. RESULTS AND DISCUSSION

It was tested the functionality of the ionization sensors to acquire the instant of the shockwave passage. In Tab. 2 is shown the test matrix. For the tests, it was following the scheme shown in Fig. 4. In which for the tests 1 and 2, was used the driver extender, while for the tests 3 and 4 without the driver extender. For the four tests performed, initially, it was made vacuum in the driven, then it was pressurized the driven and driver up to the desired pressures, as shown in Tab.2. It was decided to test with argon as the driven gas to observe the response of ionization sensor, to test with a gas with higher ionization potential in comparison to the air. The results of the tests are shown in Tab. 3, Figs. 6, 7, 8 and 9.

Tab. 2. Test matrix.

Test	Initial driven pressure [mmHg]	Gas in driven	Vacuum pressure [mmHg]	Initial driver pressure [kgf/cm²]	Gas in driver	Condition
1	300	Synthetic air	50	70	Helium	Incident shockwave
2	250	Synthetic air	41	55	Helium	Incident shockwave
3	200	Argon	45	60	Helium	Incident shockwave
4	200	Argon	45	60	Helium	Incident shockwave

Table. 3. Summary of results.

PARAMETER	RESULTS				UNITY
Test number	1	2	3	4	-
Ambient temperature	295.2 ± 0.5	300.2 ± 0.5	301.2 ± 0.5	301.2 ± 0.5	K
Ambient pressure	99.99 ± 0.67	99.99 ± 0.67	100.26 ± 0.67	100.26 ± 0.67	kPa
Gas in driver	Helium	Helium	Helium	Helium	-
Initial driver temperature	295.2 ± 0.5	300.2 ± 0.5	301.2 ± 0.5	301.2 ± 0.5	K
Initial driver pressure	6864.66 ± 49.03	5393.66 ± 49.03	5883.99 ± 49.03	5883.99 ± 49.03	kPa
Gas in driven	Synthetic air	Synthetic air	Argon	Argon	-
Vacuum pressure in driven	6666.12 ± 666.61	5466.22 ± 666.61	5999.51 ± 666.61	5999.51 ± 666.61	Pa
Initial driven temperature	295.2 ± 0.5	300.2 ± 0.5	301.2 ± 0.5	301.2 ± 0.5	K
Initial driven pressure	40.00 ± 0.67	33.33 ± 0.67	26.66 ± 0.67	26.66 ± 0.67	kPa
Time interval between PCB sensors signals at incident shockwave	236.0 ± 0.2	253.0 ± 0.2	236.0 ± 0.2	235.0 ± 0.2	µs
Incident shockwave speed measured by PCB sensor.	1330.5 ± 2.4	1241.1 ± 2.2	1330.5 ± 2.4	1336.2 ± 2.4	m/s
Pressure before incident shockwave	0.57 ± 0.01	0.42 ± 0.01	0.46 ± 0.01	0.48 ± 0.01	MPa
Pressure before reflected shockwave	3.45 ± 0.05	2.35 ± 0.03	2.20 ± 0.03	2.25 ± 0.03	MPa
Time interval between ionization sensors signals at incident shockwave	231.0 ± 0.2	261.0 ± 0.2	238.0 ± 0.2	236.0 ± 0.2	µs
Incident shockwave speed measured by ionizations sensor.	1359.3 ± 2.5	1203.1 ± 2.1	1319.3 ± 2.4	1330.5 ± 2.4	m/s
Maximum voltage of ionization sensor 01	31.0 ± 0.1	7.7 ± 0.1	121.0 ± 0.1	92.3 ± 0.1	mV
Maximum amplitude of noise, for the ionization sensor 01	6.6 ± 0.1	2.7 ± 0.1	3.2 ± 0.1	4.1 ± 0.1	mV
Noise standard deviation, for the ionization sensor 01	1.12	0.78	1.07	0.98	mV
Maximum voltage of ionization sensor 02	16.7 ± 0.1	4.1 ± 0.1	249.7 ± 0.1	148.7 ± 0.1	mV
Maximum amplitude of noise, for the ionization sensor 02	8.88 ± 0.05	3.2 ± 0.1	6.3 ± 0.1	5.6 ± 0.1	mV
Noise standard deviation, for the ionization sensor 02	1.12	0.78	1.07	0.98	mV

In Figs. 6 and 7 the results are shown, using the schematic of Fig. 4, with synthetic air in the driven and the sensors was positioned at P2.0 and P2.1. The trigger of oscilloscope was set in the channel PCB sensor P5, when it reached the level of 200 mV, the trigger was positioned in 75%.

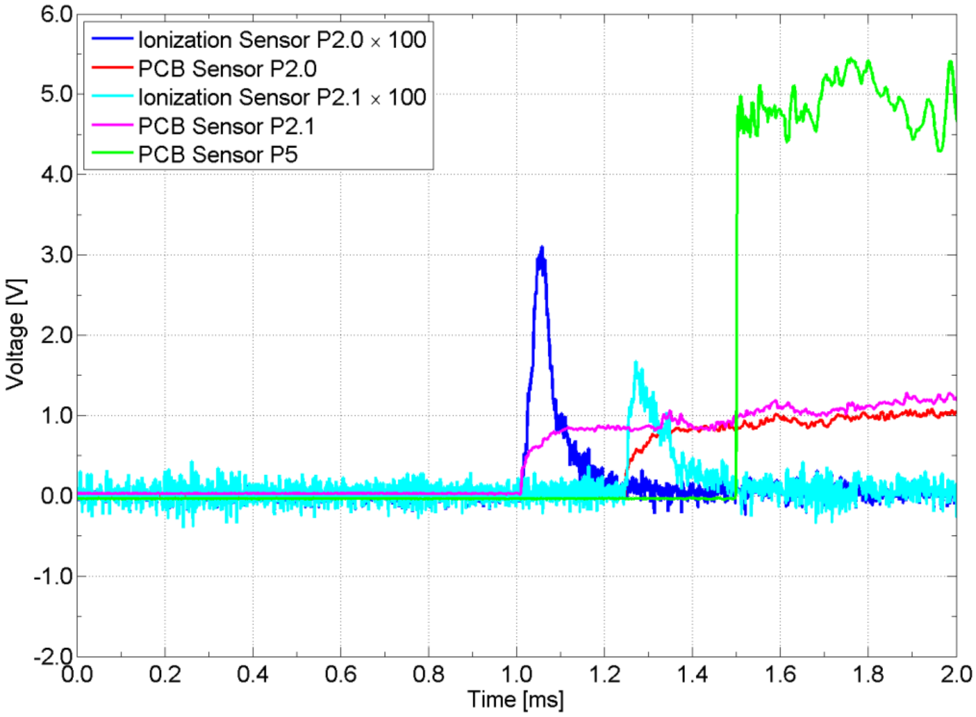

Figure 6. Result for the test 1, with synthetic air in driven.

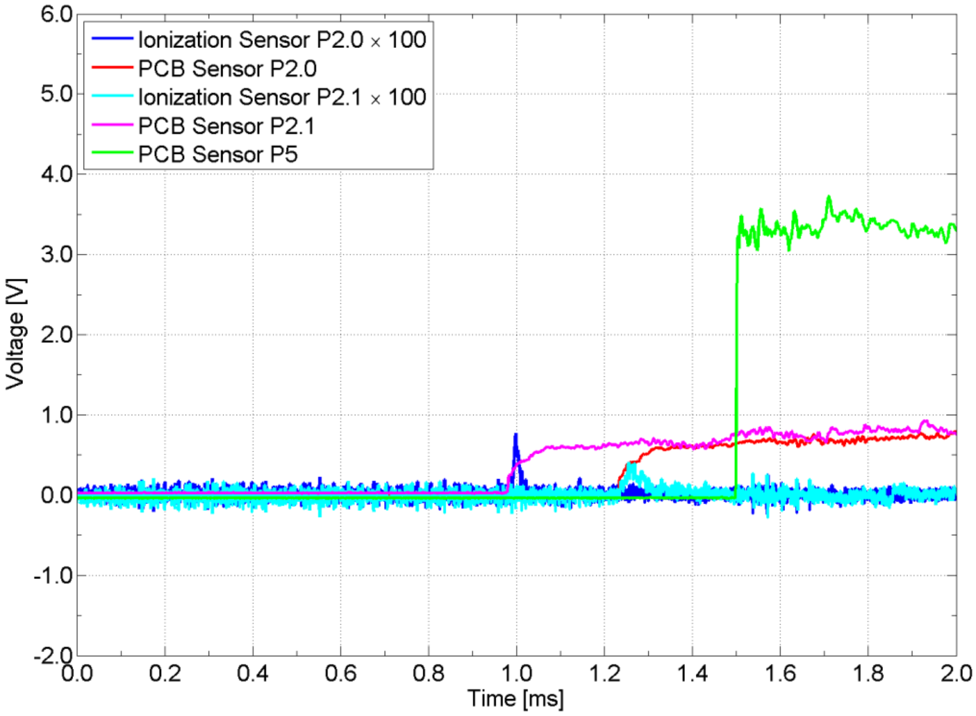

Figure 7. Result for the test 2, with synthetic air in driven.

In Figs. 8 and 9 the results are shown, using the schematic of Fig. 4, without driver extender, with argon in the driven and the sensors was positioned at P2.1 and P2.2. The trigger of oscilloscope was set in the channel PCB sensor P5, when it reached the level of 200 mV, the trigger was positioned in 50%.

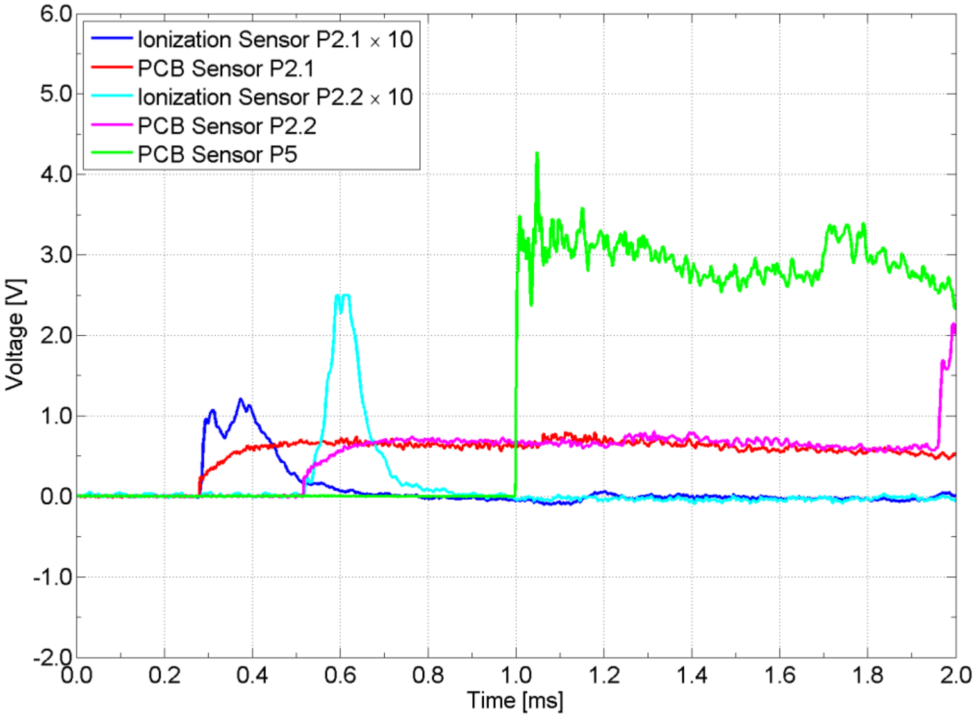

Figure 8. Result for the test 3, with argon in driven.

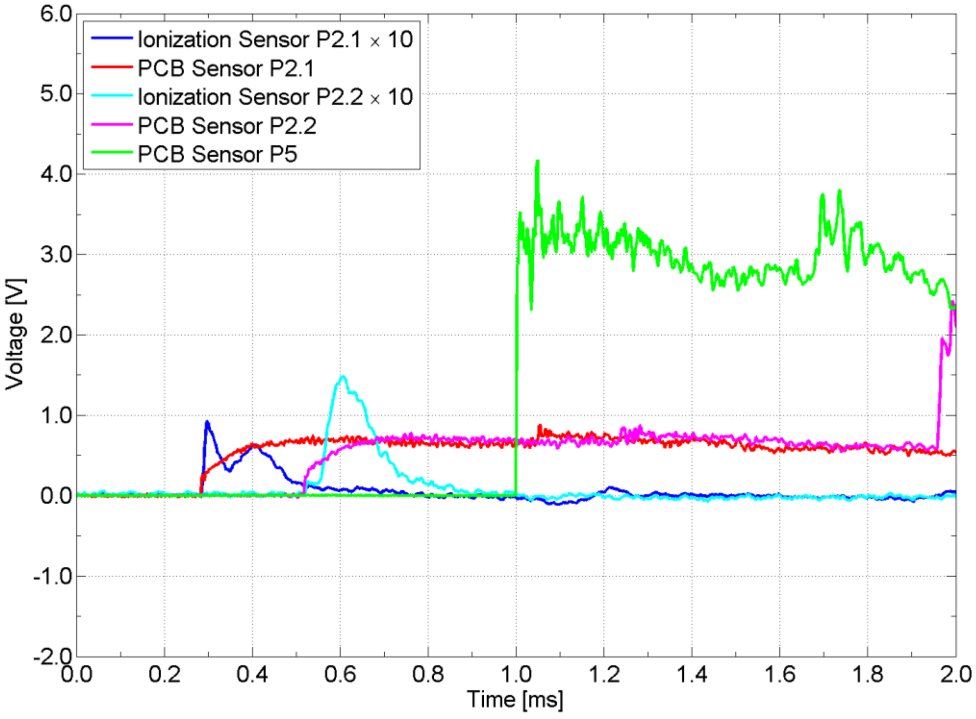

Figure 9. Result for the test 4, with argon in driven.

For the tests, 1, 3 and 4, the minimum voltage value of the ionization sensors, to consider the instant of the shockwave passage, was set at 10 mV, in the test 2, was established in 4 mV, because the noise was lower than the other tests, and the maximum voltage was less than 10 mV. The details of the results are shown in Tab. 3.

The tests were also used to make improvements in the ionization sensors, one of the biggest problems was the high noise level, because of that, we switched from a two core copper cable to a low noise coaxial cable (BELDEN low noise silver-plated 50 ohms coaxial cable, RG type 316/U), with a blatant decrease in noise signal. Also, the position of the ionization sensors in the shock tube were interchanged, but no significant difference was observed.

In general, response of the sensors was close to those obtained by the PCB sensors. The largest difference was observed in test 2, equal to 3.06%, for the measurement of shockwave speed. Also, the ionization sensors obtained different responses from each other, for the same run. It was also observed that using the argon in the driven, the amplitudes of the signal were larger in comparison to the synthetic air.

4. CONCLUSION

This work shows the results of using tungsten-thorium ionization sensors in a shock tube. The sensors proved to be able to measure the shockwave speed with a low difference in comparison to the PCB sensors. When using argon, a species that presents greater potential of ionization in comparison to the air, the sensors presented a higher signal amplitude. This is probably due to the fact that more ions are formed for the same voltage potential when using argon.

For future work, it is suggested to make adjustments to protect the electrical circuit, from external electrical interference and augment the repeatability of tests by improving the manufacturing process. Furthermore, it is necessary to perform more tests, to determine the limits of operation of the ionization sensors, for that, it is suggested to modify the pressure and temperature conditions that the sensors will be submitted along with the gas mixture in driven.

5. ACKNOWLEDGEMENTS

This work was supported by the project COMAER PROPHIPER 14-X. Also, the authors want to express their gratitude to Paulo G. P. Toro, Davi Neves, Carla S. T. Marques, Sgt. Joely E. Ferraz, Marcos V. R. Santos, Luiz C. M. Lavras, Valéria S. F. O. Leite, José B. Chanes Jr, Jaime T. Watanuki for contributing to this project.

6. REFERENCES

Anderson, J.D., 1989. *Hypersonic and High Temperature Gas Dynamics*. McGraw-Hill, London, 2nd edition.

Cintra, R.A., Rolim, T.C. and Lima, B.C., 2017. "Experimental Investigation of Ionization Sensors under Shock Tube Stagnation Conditions". *Journal of Aerospace Technology and Management*, Vol. 9, n.2, p. 218-224.

Glass, I.I. and Hall, J.G., 1959. *Handbook of Supersonic Aerodynamics*. Johns Hopkins University Applied Physics Laboratory.

Gupta, N.K.M., 2015. *Point Measurement of Detonation Wave Propagation Using Ion Gauge*. Master dissertation. The University of Texas At Arlington, Arlington.

Lu, F.K. and Marren, D.E., 2002. "Advanced Hypersonic Test Facilities". *AIAA Progress in Astronautics and Aeronautics series*, Vol. 198.

MATLAB, 2010. Version 7.10.0 (R2010a). Natick, Massachusetts: The Math Works Inc.

Panicker, P.K., 2008. *The Development and Testing of Pulsed Detonation Engine Ground Demonstrators*. Doctoral thesis. The University of Texas At Arlington, Arlington.

PCB PIEZOTRONICS, 2013. Model 113B26 ICP Pressure Sensor Installation and Operating Manual.

Zeldovich, Y.N.,1950. NACA Tech. Memo n. 1261.

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