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NUMERICAL INVESTIGATION OF A MOVABLE WALL RESPONSE ON A FLAME PROPAGATION

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Abstract

This paper contains a description of a shock wave (called a flame when the deflagration is considered) propagation pattern impact on a motion of a barrier. Here, the numerical research was conducted on a model of a pyrotechnic actuator, hence, the piston is understood as a movable barrier. The processes occurring within the pyrotechnic actuators after ignition of a pyrotechnic propellants have been explained. The investigations are focused on the dependence of a shape of the actuator's combustion chamber and the piston stroke time. It appears that the appropriate design of the combustion chamber can decrease the time required for a piston total stroke using this same type of a propellant. The visualization of the flame occurring due to ignition of the propellant is crucial for understanding the dependence between the construction of the actuators interior and the piston stroke time. Therefore, the approach of simulating numerically the flames aroused. The simulation was conducted on a full scale 3D model of a pyrotechnic actuator which is a detail representation of a real object on which the verification test will be conducted. However, only the flame propagation was considered here. The material of an actuators members was not investigated, hence the AUTODYN solver considered them as a single rigid bodies with its own mass and inertia.

Keywords: *pyrotechnic actuators, shock wave, AUTODYN, flame propagation, pyrotechnic actuator*

1. Introduction

A shock wave propagation pattern was investigated by vast number of researchers which led to in depth understanding of this phenomenon. However, little is known about shock wave influence on movable wall such as for example a piston in pyrotechnic actuators. Most of shock wave test are performed in shock tube. This however requires simplifications which affect fully accurate results of phenomenon occurring within a pyrotechnic actuators. Literature based knowledge suggests that it is possible to alter the performance of a pyrotechnic actuator by appropriate shaping of its interior, but such a relationship was not yet fully tested. Latest achievements in numerical computation methods allows to perform investigation revealing such dependence. This work constitutes an approach to identify the dependence of a flame propagation pattern on the movable wall (in this case a piston) motion characteristic. This numerical investigations enriched by the stationary tests will provide a full information about the flame shaping on the pyrotechnical devices performance.

2. The shock wave

The phenomenon of the formation of the shock wave was exactly described by the Rankine already in 1870 and later, independently, by Hugoniot in 1889. The shock wave is defined as a very thin region in which the pressure, density, temperature and speed changes by a very large value. It is therefore a rapid increase in these values finished with slow expiration [1], [2]. Here the shock wave is generated by means of ignition of a pyrotechnic charge. The charge is considered as low energy explosive. Therefore the combustion process occurs under deflagration regime rather than detonation. The shock wave occurring as a consequence of a deflagrating material is usually called the flame, whereas when the detonation is considered the shock wave is called a detonation wave [3].

Bull et al.[4] investigated the properties of the reflected shock interaction, and stated that wave reflection process is subject to two mechanisms, which are leading to failure of the ideal theory of the reflected wave's behaviour. The first mechanism is a result of reflected wave's interaction with the boundary layer formed along the tube wall, behind the incident shock. The second is related to the instabilities which may develop in the contact region. Thus the contact region no longer remains a flat plane, but may prematurely encroach upon the region of the shock heated gas of the closed end of the tube. A incident shock wave bifurcates after the reflection. In another words the reflected incident wave develops a Mach interaction near the wall of the tube. Then, the Mach stem and transverse shock grows as the reflected shock recedes from the end plate. It has been shown that the bifurcation of the shock arise due to interaction with the boundary layer wall because the stagnation pressure of the gas is lower than freestream gas under certain conditions. Therefore the penetration of the reflected shock is impossible. Hence, this is the origin of the triple point.

The numerical investigation of shock wave properties reflected from the cylindrical reflector has been performed by Henshaw et al. [5] What was investigated was the shock wave with various Mach number reflected from the circular reflector. The shock wave was divided in to the weak and strong wave. The reflected shock wave generates so called shock- shocks at location being dependant on the shock wave Mach number and the curvature of the reflector. The shock-shocks arise as a consequence of shock wave reflection from the concave wall towards the centre of the chamber and arise from discontinuities in the shock front. In another words the shock-shocks are a 3D equivalent of the 2D triple points. It has been found that the Mach number can be significantly increased at the point of shock-shocks occurrence. The increase can be significant enough for the weak wave to be considered as a strong one. Similar behaviour has been observed by Johansson et al. [6]. They had investigated the possibility to form a specific shape of the shock wave enclosed in the confine polygonal space. This investigation has proven that the shock wave can be formed in the way to resemble shape of the reflector. In this investigation polygonal shape of a shock wave was obtained with corresponding location of the shock-shocks. Hence the energy of the shock wave is changed with accordance to the shape of the reflector. Moreover, Gui et al. [7] Gui, M., Fan, B., Dong, G., Ye, J., *Interaction of a reflected shock from a concave wall with a flame distorted by an incident shock*, Shock Waves, Vol. 18, pp. 487-494, 2009 investigated the shock wave reflection from the planar and cylindrical wall of a shock tube. It appears that the shock wave reflected from a planar surface has lower velocity comparing with the shock wave reflected from the concave wall. This suggests that the wave reflected from concave surface is capable of maintaining during longer period of time, hence to perform the work (i.e. piston movement).

The total energy carried by the waves of pressure depends on the pressure inside the wave, its velocity and density. Gushanov [8] demonstrated that there is a mathematical relationship between the shape of the shock wave, and its speed. Therefore, it can be assumed that the different wave form carries a different energy which can be utilized in this case to propel the piston.

Taking the above into consideration it can be assumed that the piston movement of an actuator is dependent on the shape of the piston surface and the bottom of a cylinder. Therefore, the approach of a numerical modelling of such a relationship arose. The model presented here is a theoretical comparison of two different piston constructions. The output value of this investigation is the piston velocity and the shock wave distribution which force the piston to accelerate.

3. The numerical investigation

The numerical investigation were performed on a model which resembles a pyrotechnic actuator prepared as a test station. Therefore, here the movable wall is a piston with the flat and a concave shape. Numerical investigations have been carried out using ANSYS Work bench 14.5. In the first phase, the model was developed in the module Explicit Dynamics that allows to prepare the construction of the actuator and the establishment of Lagrange elements mesh. As a „solver" to such prepared cylinder model the AUTODYN was used. Numerical investigations were carried out on the 3D model at full scale, without neglecting the influence of different moments of inertia and masses of individual components or aspects of a physical nature (e.g. friction), because, as it turns out, the phenomenon is not axiallysymmetric. The disadvantage of this solution is significantly extended computing time and required very large computing power. All elements of the model are assigned as „Rigid EOS" (Rigid Equation of State) because in this work the effects of the material response on the forces occurring as a consequence of the actuator operation was not under investigation. According to [9] and [10] elements filled with a non-elasticmaterial will behave like a single rigid elements of its own weight and inertia. Each model was equipped with 2 measuring gauges depicted in Fig. 1. Gauge number 1 is located on the piston and measures its velocity and acceleration. Gauge 2 is fixed on side of the cylinder due to the fact that in the case of real object experiments at this same place will be located quartz pressure sensor. Hence, gauge 2 measures only the dynamic pressure.

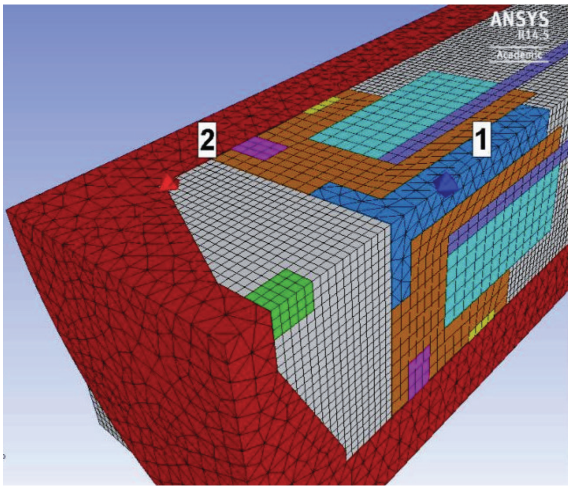

Fig. 1. The descried model

4. Results and discussion

The results presented here are a comparison of two embodiments of piston (i.e. piston with flat and concave surface). Both of embodiments here have this same mass and are subjected to this same boundary conditions.

In the case of actuator with a flat piston (see Fig. 2), the greatest pressure created by the accumulation of incident and reflected wave (compression wave) is applying pressure on a small area of the piston. This wave propagates then symmetrically toward the sides of the cylinder to form the greatest pressure there. The pressure in the later stages propagated toward the axis of the cylinder. The wave reflected from the bottom cylinder now propagates in the direction of the flat walls of the cylinder, where it is reflected and created the biggest pressure around the cylinder wall. Later reflected wave from the bottom cylinder has a low pressure field in the axis of the piston. When this pressure reaches the piston, motion begins.

The flame propagation in the pyrotechnic actuator equipped with the concave piston surface differs significantly from the previous case (see Fig. 3). On the beginning of the process the flame is propagating with accordance to the first embodiment. When the flame reaches the concave surface the velocity of reflected shock increases. This is manifested by greater pressure on sides of the cylinder. The flame is then reflecting from the conical surface of the bottom of cylinder and focuses on the axis. When this wave reached the piston, its motion was begun.

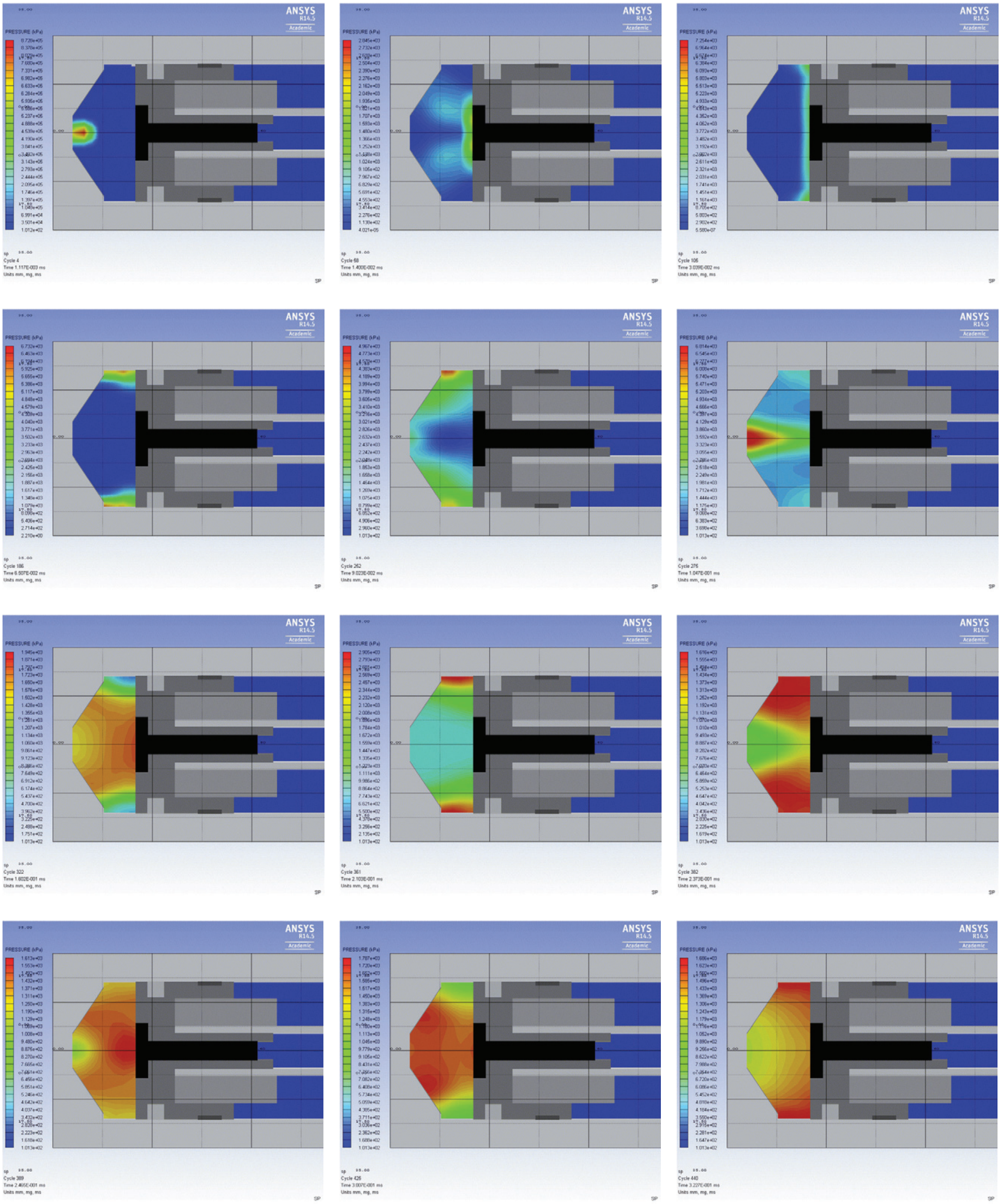

Fig. 2. The flame propagation pattern in actuator equipped with flat piston surface

The measurements taken by both gauges are proving the validity of appropriate flame shaping. As it can be seen in Fig. 4 the velocity of the flat piston (Fig. 4 a) is lower comparing with the concave piston (Fig. 4 b). This is due to the flame propagation pattern and mainly its velocity. As it was already mentioned, the energy of a shock wave can be altered by orders of magnitude with appropriate shock wave surrounding. Increased velocity of the flame reflected from the concave piston provoked it faster movement as well as greater acceleration.

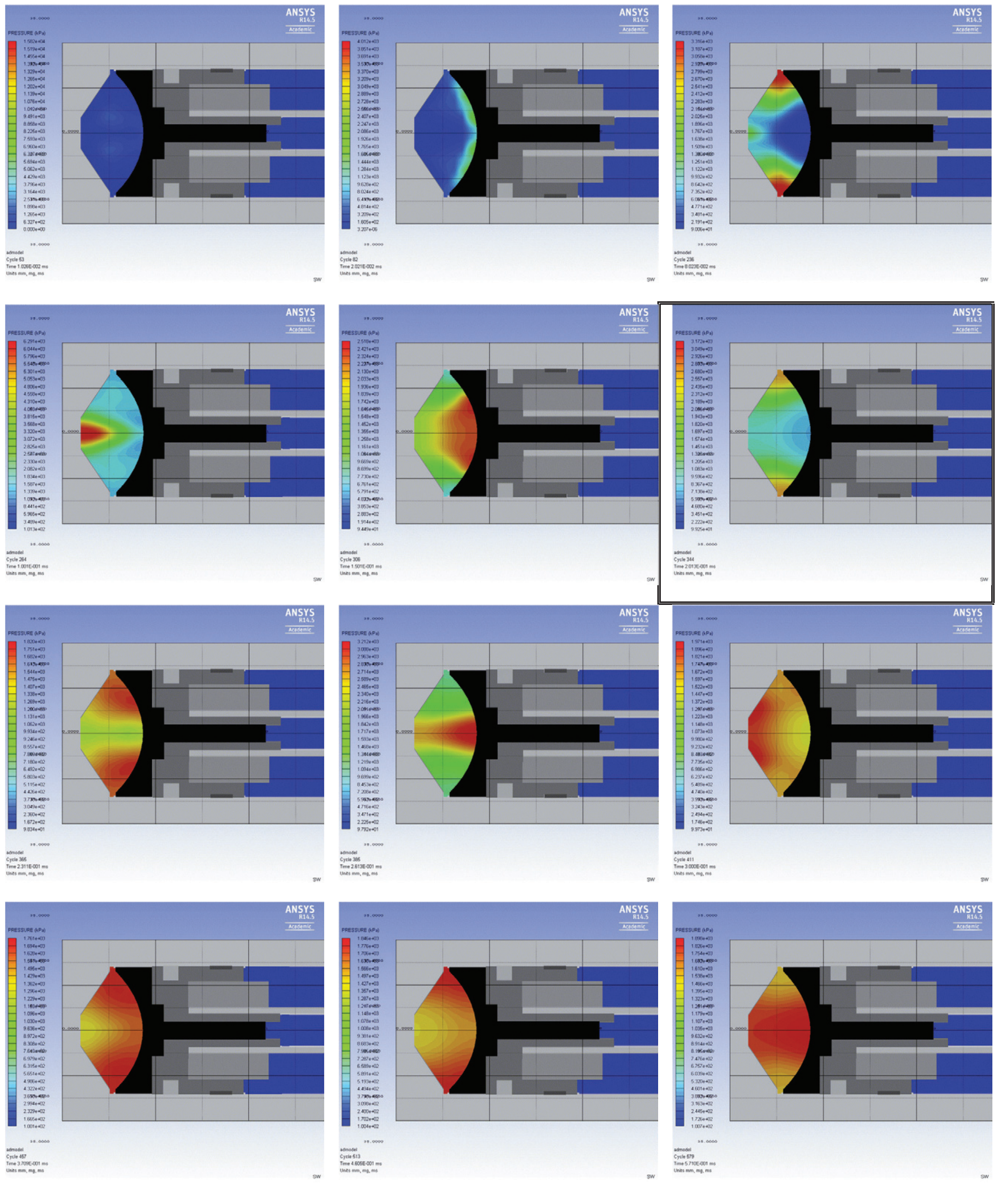

Fig. 3. The flame propagation pattern in actuator equipped with concave piston surface

The pressure measurements provided by gauge 2 seems to justify the difference of piston velocities. As it can be seen in Fig. 5 there is a significant difference in pressure read by the gauge 2. In the case of flat piston (Fig 5 a) pressure is much lower than in the case of concave piston (Fig. 5 b). It should be also noted that in the case of the concave piston the pressure increased much faster. This clearly indicates the difference of flame velocities and therefore its influence on movable wall response.

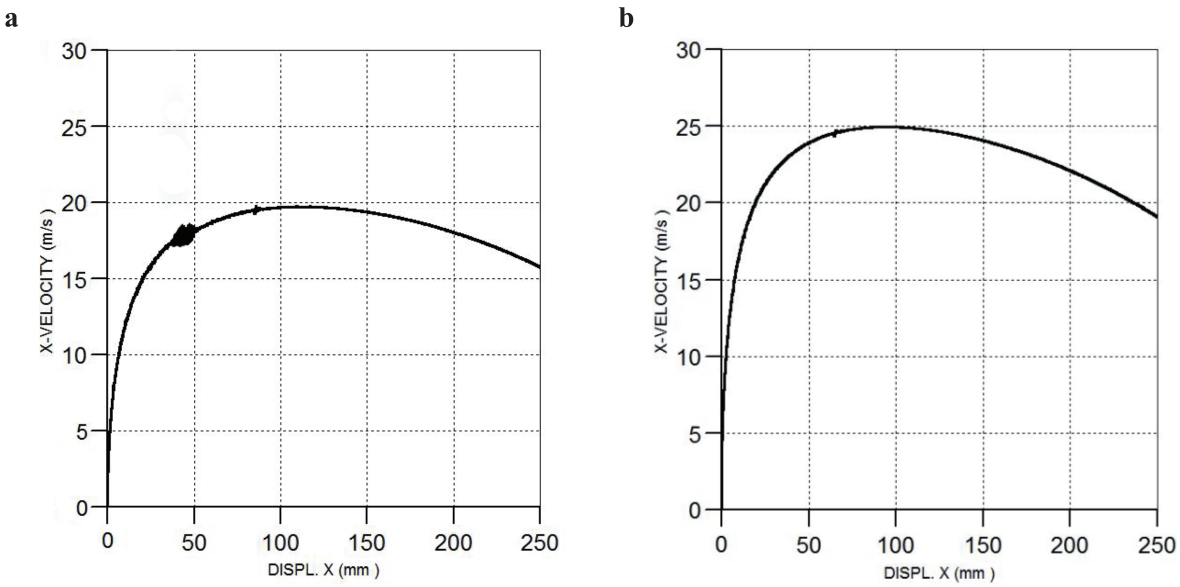

Fig. 4. The piston velocity (a- flat piston surface, b- concave piston surface)

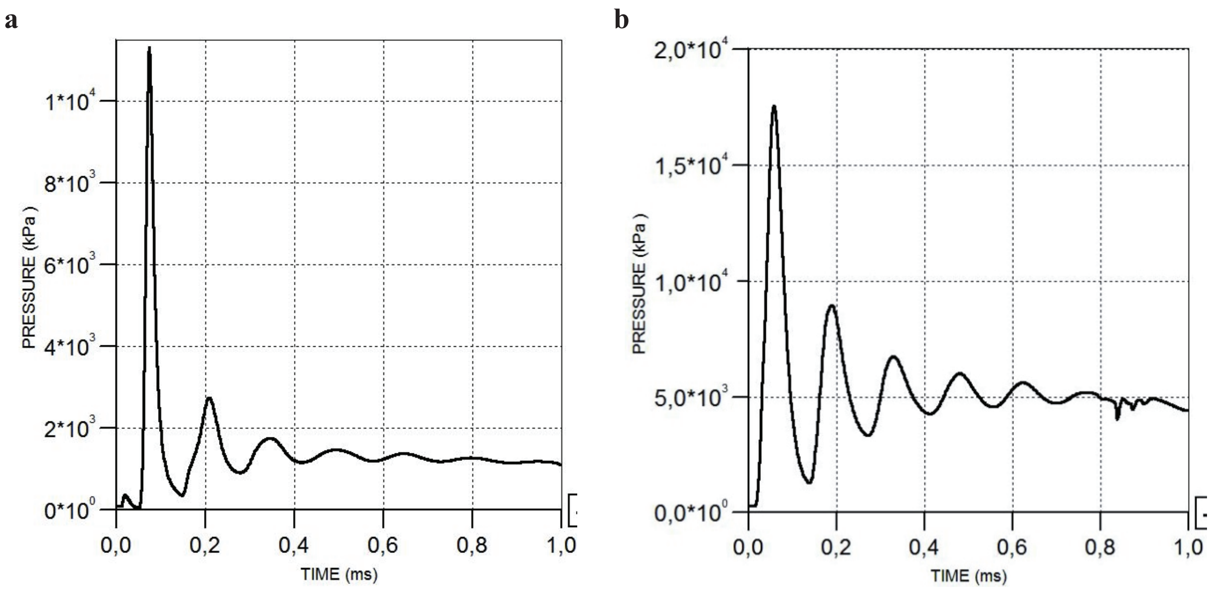

Fig. 5. Pressure at gauge 2 (a-flat piston surface, b- concave piston surface)

5. Conclusion

What was under investigation was the influence of the flame propagation pattern on movable wall response. The flame propagation was altered by means of changed shape of a wall which in this case was a piston of a pyrotechnic actuator. The results clearly indicate that the performance of a movable wall with different shapes significantly depends on a flame propagation. The velocity and acceleration of the movable wall is changeable with accordance to its shape. This suggests that with aid of an optimisation tool it is possible to find a shape which will increase to maximum available velocity of a movable wall using propellant with this same characteristics.

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