ROTATING DETONATION ENGINE SIMULATIONS IN-HOUSE CODE – REFLOPS

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Abstract

The paper presents the results of three-dimensional preliminary simulations of a detonation propagating in Rotating Detonation Engine chamber. Simulations were performed using in-house code REFloPS (Reactive Euler Flow Solver for Propulsion Systems)[1]. The description of the code and presented results are also included in MSc thesis of Folusiak and Swiderski [2]

1. INTRODUCTION

It is very difficult to perform the simulation of detonation process in the RDE due to physical and chemical nature of the detonation phenomenon and also due to geometrical complexity of the detonation wave structure in this engine. The first problem imposes the requirement of using proper numerical methods, which are able to reconstruct the discontinuities propagation processes in the flow. Due to problem specificity the simulation must include shock waves as well as rarefaction waves precisely and also separation areas, oblique waves and Mach stems must be taken into account. Thus, these simulations set high requirements for the solver. On the other hand as far as the RDE engine is concerned there is a strong coupling between phenomena at different time and space scales. The details of the wave's head are 10 μm order of magnitude or smaller, whereas these details strongly hang on large-scale chamber geometry, e.g. chamber diameter or passage gap. The coupling of different scales results also in a number of grid cells used to represent the simulation target. The number of cells is 10^6 order of magnitude or many more.

2. DETONATION WAVE SIMULATIONS IN ANNULAR TUBE

The first simulations of the RDE engine were related to simple, annular chamber geometry. In order to simplify the computations there was assumed that the gas is stationary and the chamber is closed. The simulations performed in this case let one determine the structure of the detonation in macro scale (Fig 1, 2). The detonation propagating in annular tube is characterized by certain pressure, density and temperature gradients resulting from the occurrence of centrifugal forces as well as from wave front deformation.

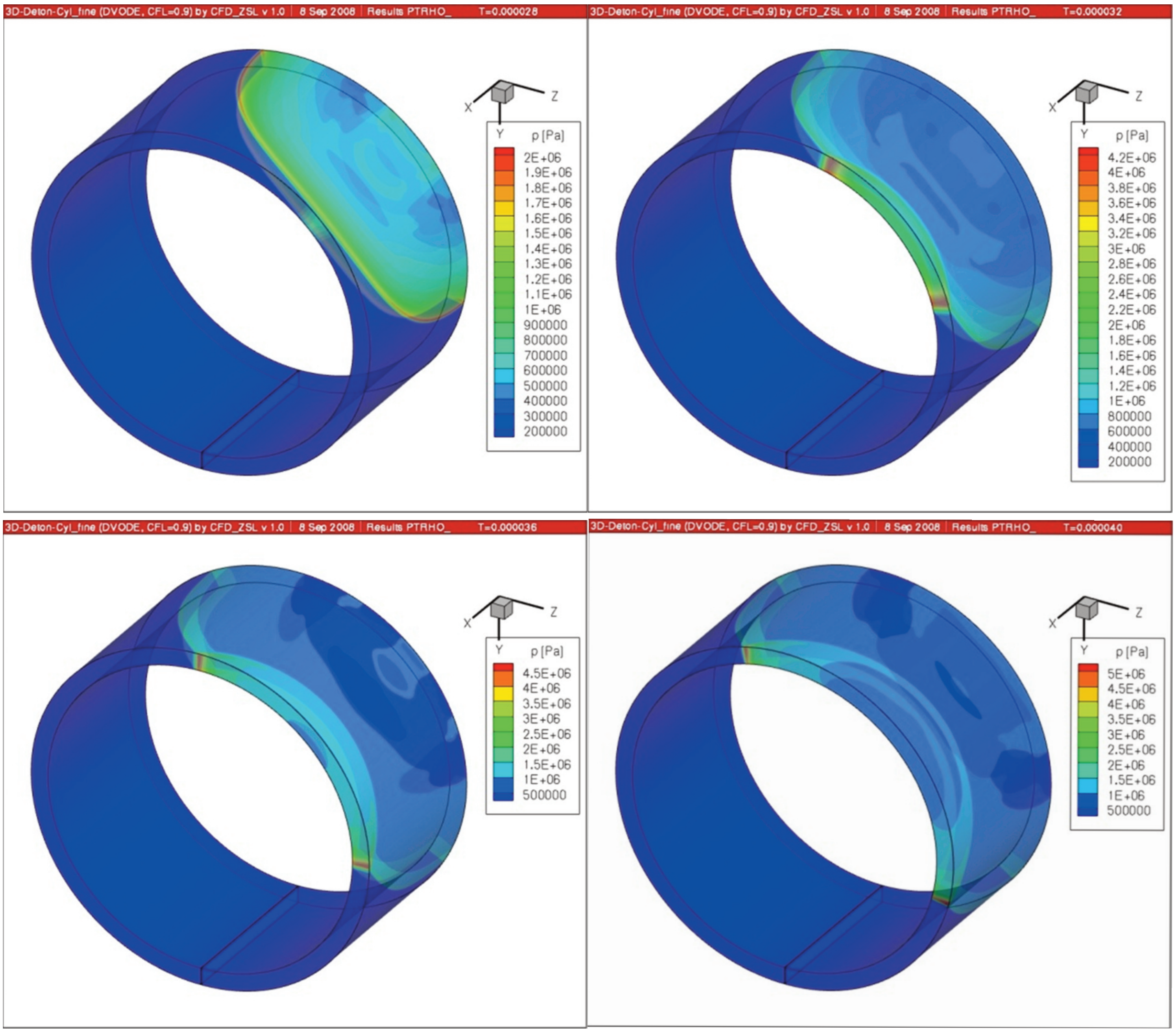


Fig. 1. The shape of detonation wave front for hydrogen-air mixture
Pressure contours vs. time

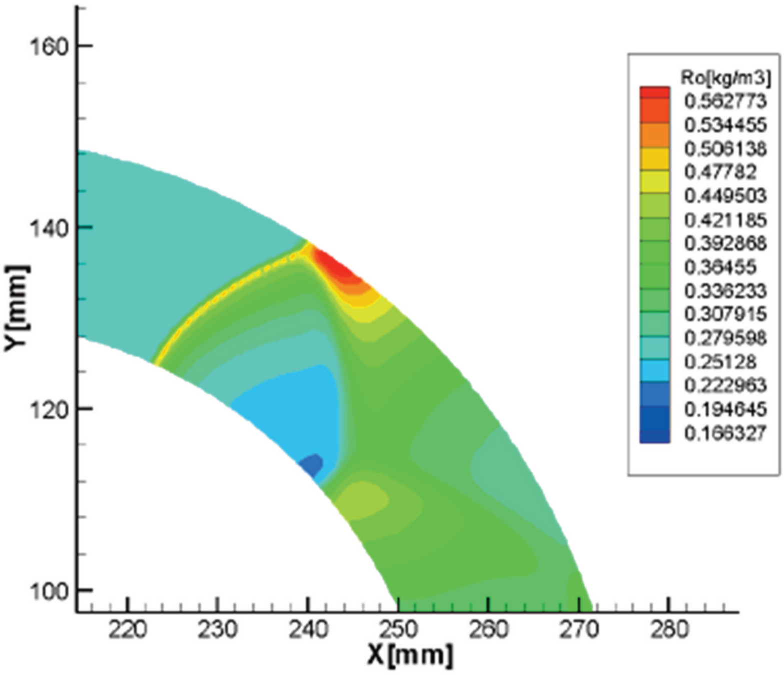


Fig. 2. Density contours behind detonation wave front in annular tube

3. FLOW IN RDE CHAMBER

3.1. Chamber geometry. Boundary conditions

RDE chamber's geometry was adapted from experimental research of Wolanski and Kindracki [3,4]. The computational grid of the considered domain's cross section is shown on Figure 3.

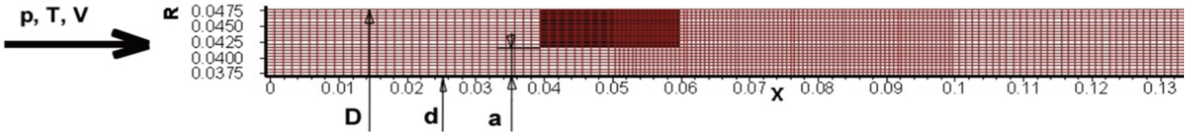


Fig. 3. The computational domain and B.C.'s used in RDE engine simulation

The chamber dimensions are as follows (in mm's)

External diameter	95
Internal diameter	75
Gap size	4
Total length	140
Working part length	80

The domain was split into 160 x 20 x 450 cells along *x, r*, φ directions respectively (Fig. 4), thus the resulting cell's width is around 500μm along each direction.

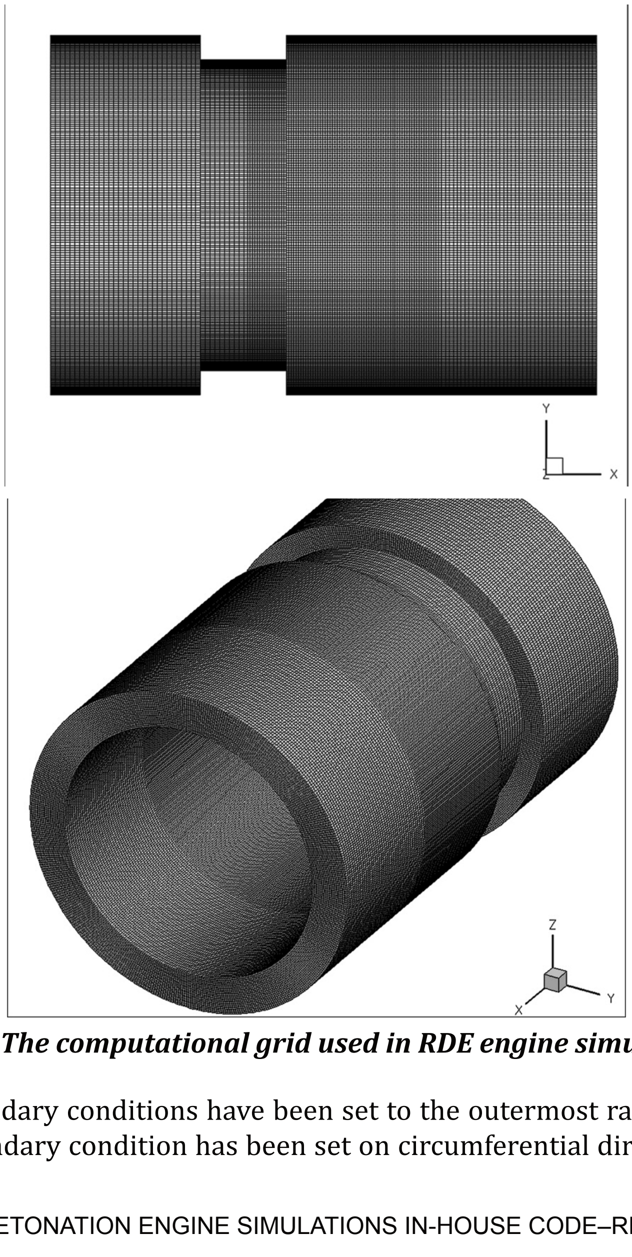


Fig. 4. The computational grid used in RDE engine simulation

The REFLECTIVE boundary conditions have been set to the outermost radial boundaries of the domain. The PERIODIC boundary condition has been set on circumferential direction. On inlet, boundary condition of fixed values of velocity, pressure and temperature was set, so that total pressure and temperature are to be constant parameters of feeding system. The following flow parameters have been assigned to the boundary:

Feeding pressure	11 bar
Feeding temperature	300 K
Feeding velocity	76,2 m/s
Mixture	hydrogen - air
Stoichiometry coefficient	1.

PRESSURE OUTLET boundary condition has been set to the other outermost axial boundary.

The subsonic flow is relaxing at specified length to the conditions defined by user.

Otherwise, if the flow is supersonic, TRANSMISSIVE boundary condition is set to the considered boundary (which is equivalent to infinite length of relaxation distance).

The flow in steady state without detonation

Feeding pressure	0.5 bar
Feeding temperature	300 K
Mixture	hydrogen - air
Stoichiometry coefficient	1.

Before any analyses of reactive flow were performed, the steady state, flow has been simulated. Because of the fact that the chamber as well as the flow are axisymmetric, two-dimensional computations have been performed.

Then the solution was extrapolated into three-dimensional case (along φ direction). The results are presented on Figures 5 and 6. It may be said that solution is converged after 1000 μs.

The solution has been taken for further analysis as initial condition for the initiation of detonation.

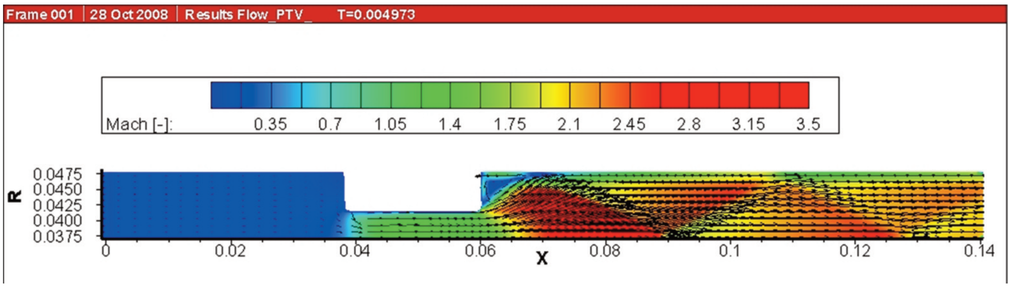
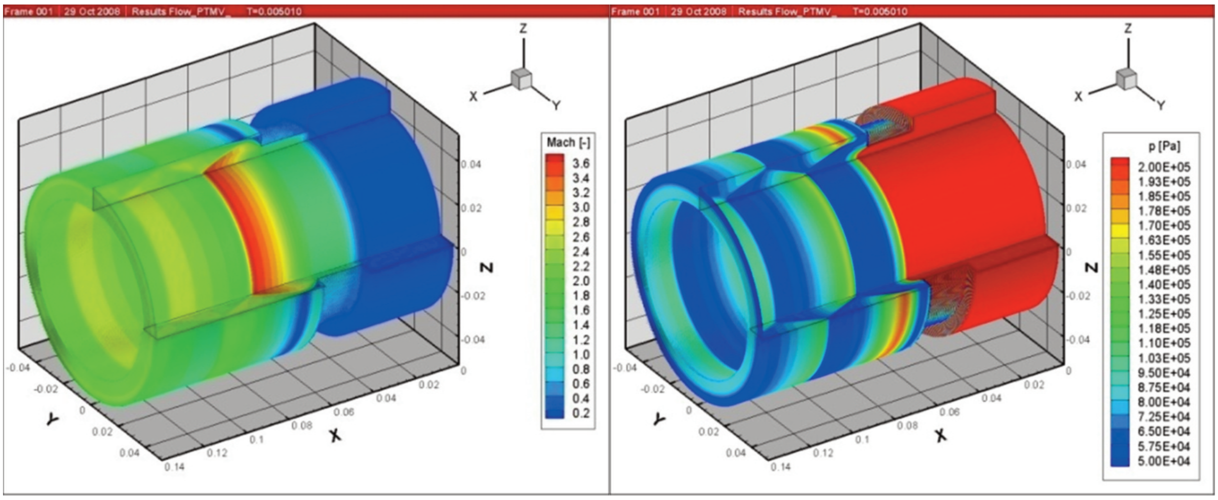
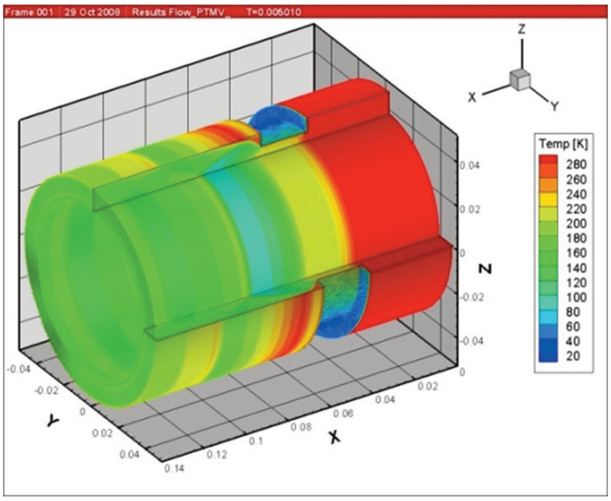


Fig. 5. Stationary flowfield in RDE chamber (without detonation). Two-dimensional case



Mach number ***Pressure***



Temperature

Fig. 6. Stationary flowfield in RDE chamber (without detonation). Three-dimensional case

4. DETONATION WAVE PROPAGATION IN RDE CHAMBER

The last phase of simulations was performing the computations of the detonation wave propagation through the cylindrical domain. The previous results of stationary flowfield have been used as the initial conditions for this simulation. The mixture is ignited in such a way that only one detonation wave is propagating in circumferential direction.

The other is an opposite shockwave, which is propagating through the half of the domain which is initially out of the range of chemistry. Reaction mechanism contains only one reversible reaction, which is defined as follows:

2H2 + O2 = H2O + H20 5.5E16 0.0 8400.0

Previous simulations showed, that 1-step reaction mechanisms as the one above is not appropriate for detonation modeling. Detonation transits in this case into the stationary deflagration near the annular gap. All the fresh mixture that should refill the combustion chamber is being burned there immediately. This is caused by the numerical diffusion, high width of the grid and simplicity of the reaction mechanism.

However, the artificial deflagration may be avoided. It is typical for such simple chemistry models, that chemical reactions are artificially limited by the pressure in the current cell. In these simulations, chemical reactions are considered only if the pressure of 20 bars is exceeded in the computational volume. This approach was successfully used by Davidenko et al [5].

Mixture creation process cannot be modeled in the code yet. Thus, it was decided to inject premixed stoichiometric mixture of reactants directly to the collector. Because of high pressure, flow is choked in the annular gap, and mass flux is limited by its geometry. In the Rotating Detonation Engine, only fuel flows through the bottleneck, and oxidizer is injected from the outer boundary just behind the gap. Because of the lack of an appropriate mechanism of mixture creation, it has been assumed that stoichiometric and homogeneous mixture is created at a distance of 2.5 mm from the gap end.

Therefore, combustion zone has been limited to the region 4 cells below the gap. Ignition process is showed on Figures 7 and 8.

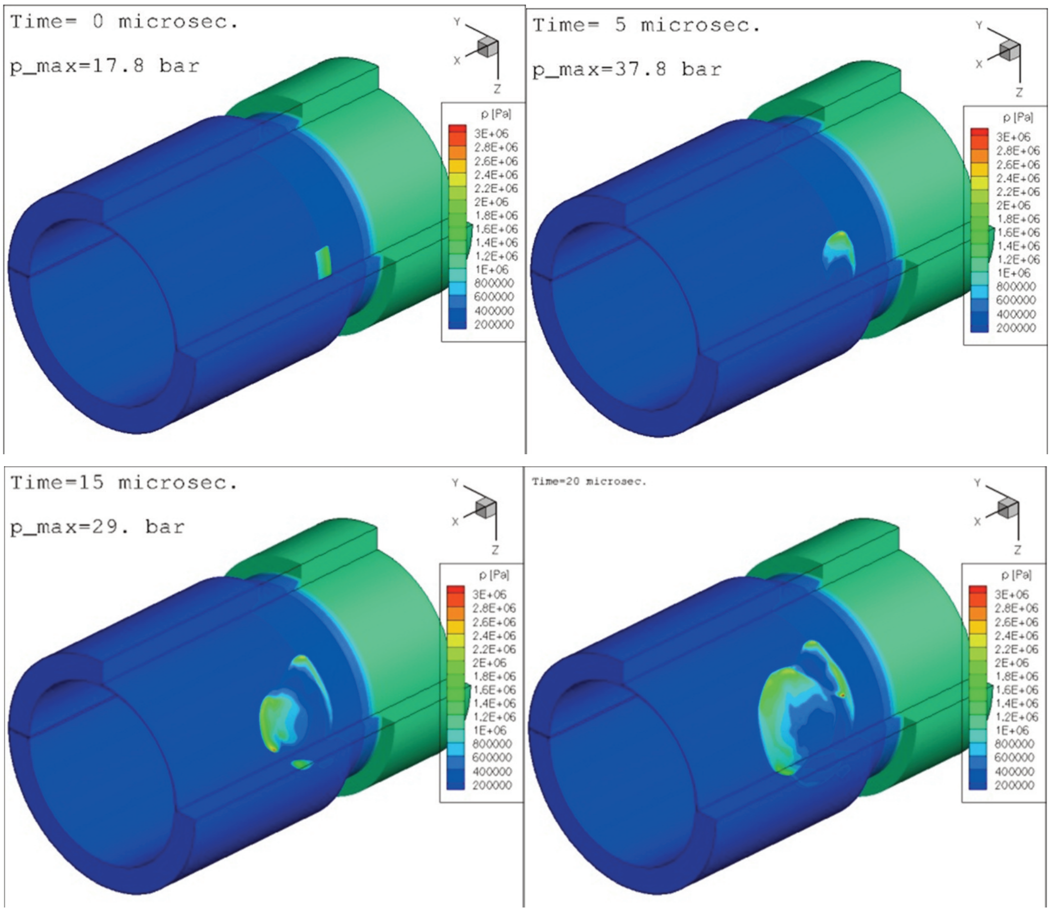


Fig. 7. Ignition process used in RDE's simulation. Pressure contours

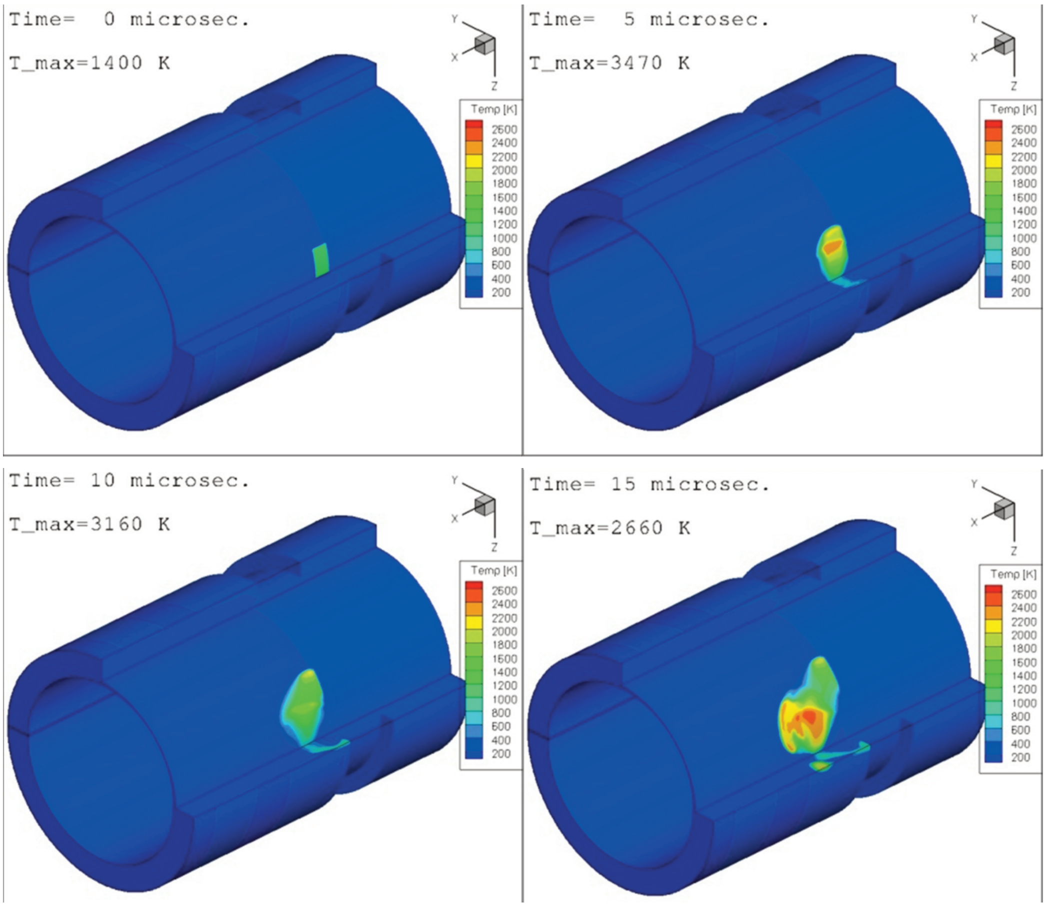


Fig. 8. Ignition process used in RDE's simulation. Temperature contours

After ignition the rotating detonation develops and propagates along the channel.

The first analyses of the results showed that the structure of the detonation front is three-dimensional and highly influenced by the structure of the initial supersonic flow of the mixture.
The structure of the wave is completely different in the inner and outer surface of the chamber (Fig. 9, 10).

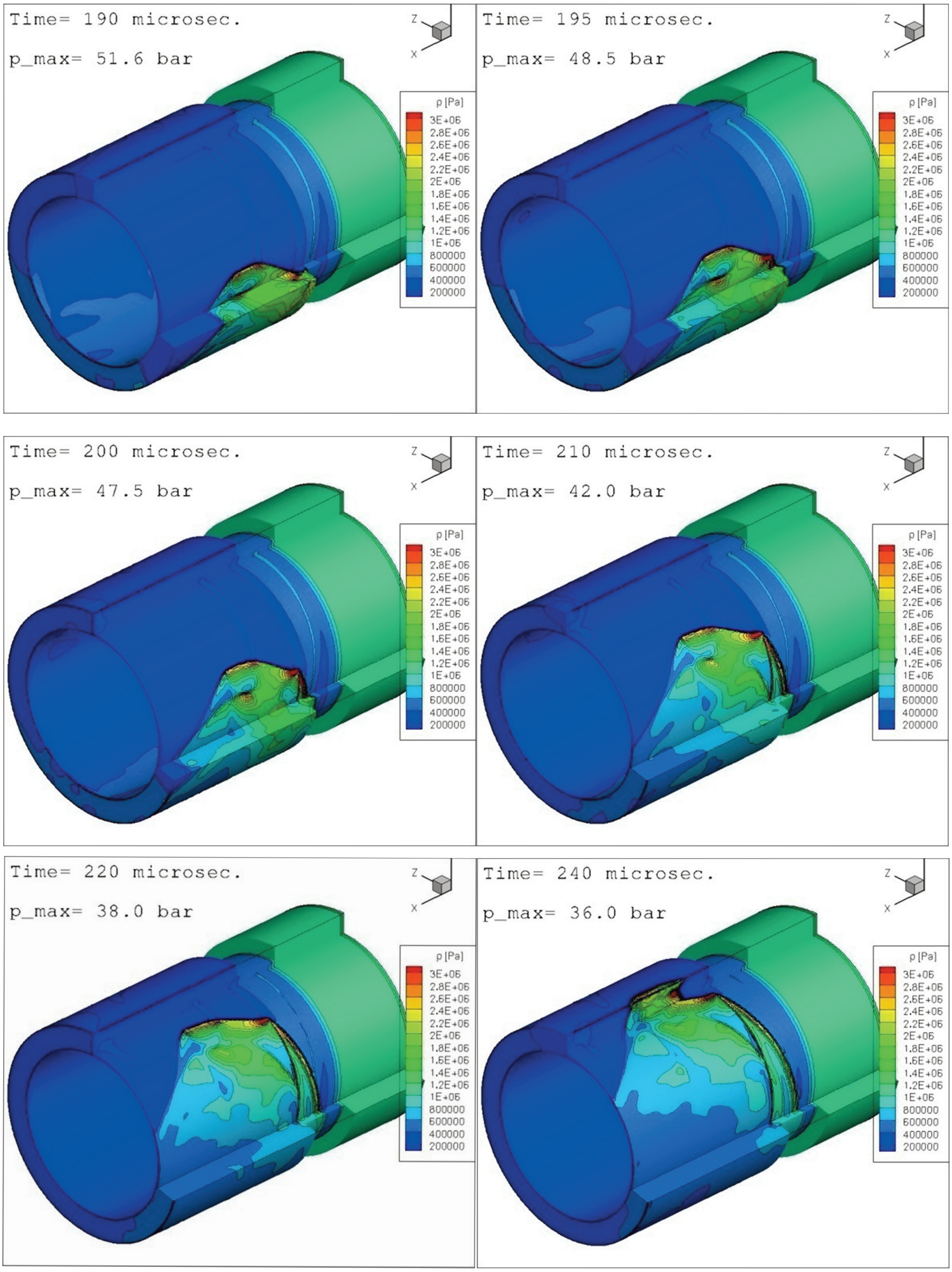


Fig. 9. Propagation of the detonation in RDE. Pressure field

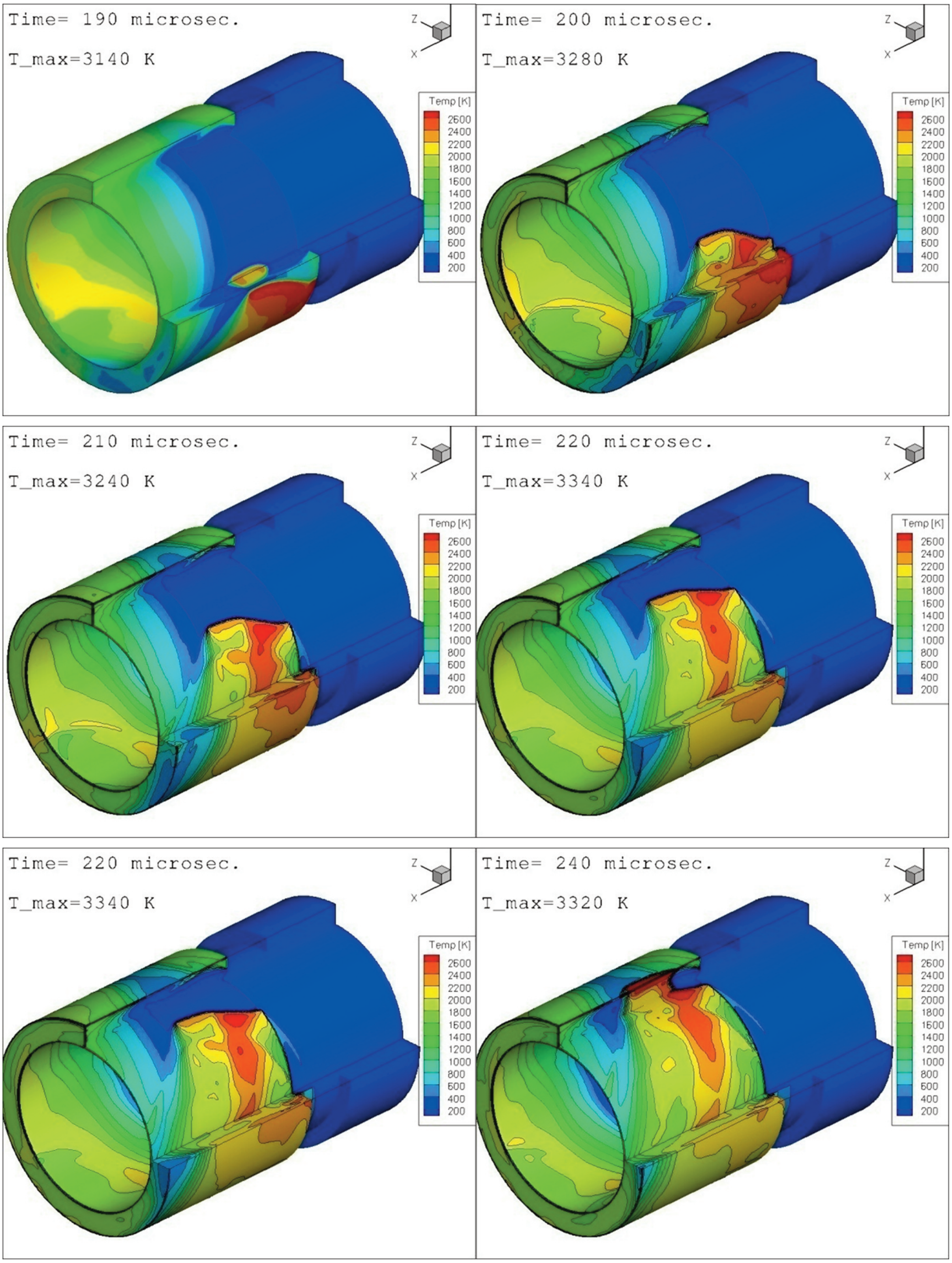


Fig. 10. Propagation of the detonation in RDE. Temperature field

For better understanding of the phenomena occurring in the flow, the two dimensional structure of the wave has been also studied. The structure of the wave at the inner wall is presented on Figure 11.

On the picture presented above, one can see Mach stem wave (MS), resulting from the collision of two waves in A-point, because of the fact that dynamic equilibrium must be conserved in this point. Also the chemical influence – chemistry limiting line, which plays important role in this process, must be pointed out. In more complex simulations, the shape of MS wave will depend on the injection method and the mixing process.

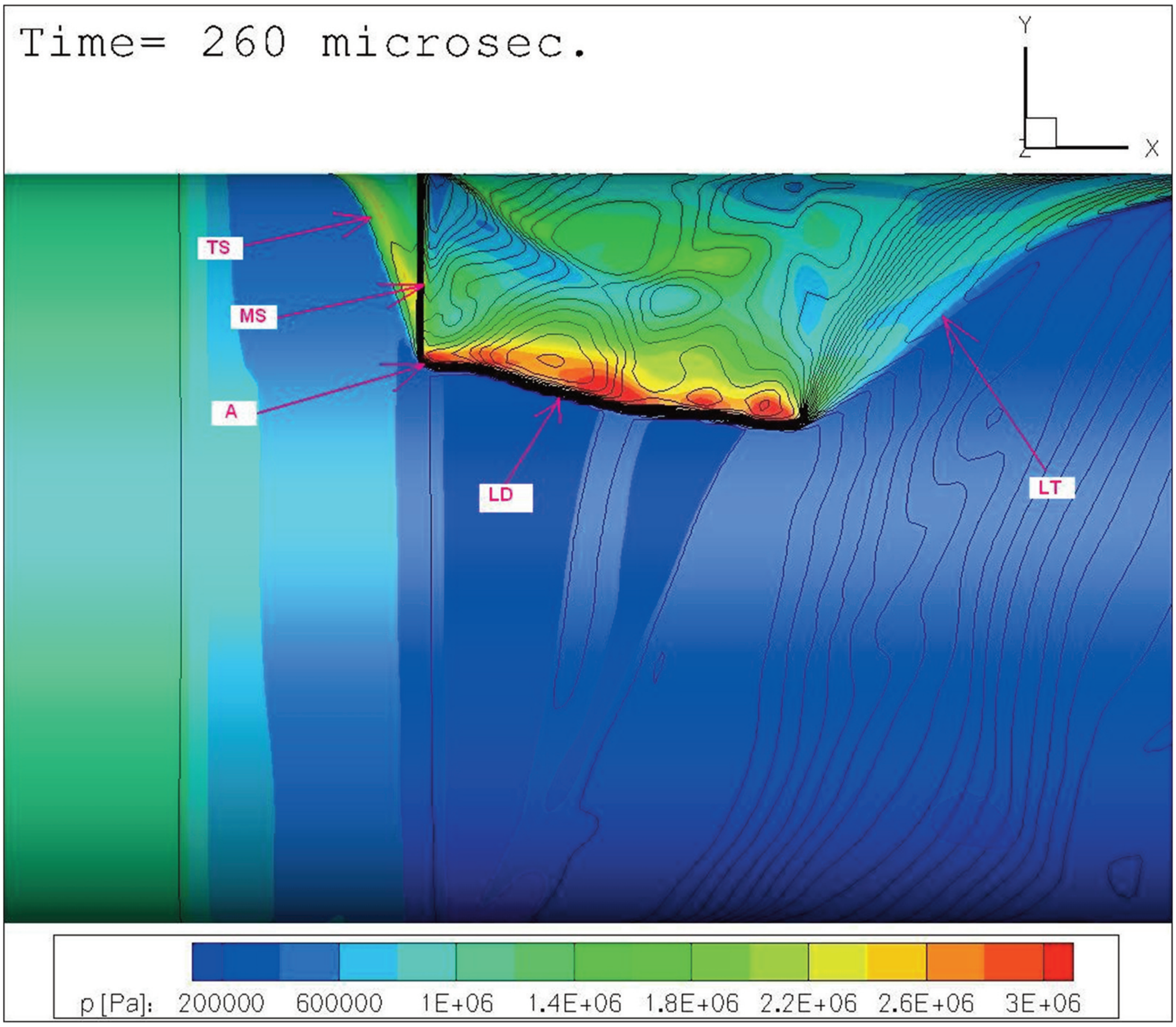


Figure 11. Structure of the waves at the inner wall

A-point is the triple point in this case. However, it is not the same triple point like in cellular structure of detonation, which cannot be observed in macroscale simulation. LD is the leading detonation wave or detonation head. At the right end of LD wave, one can see another wave, between this point and long tail wave (LT). This short wave propagates downstream. There is also one more wave which propagates upstream – transverse shock (TS). The shape of the shock wave, as an iso-surface of the pressure, is shown on Figure 12.

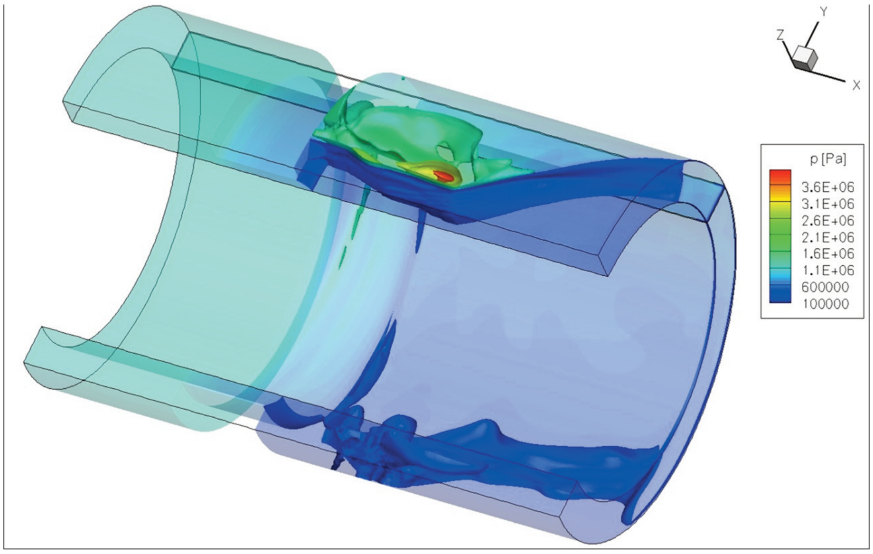


Fig. 12. Iso-surface of the pressure

SUMMARY

Performed computations of the detonation wave propagation in the RDE engine demonstrated that the REFloPS code is a useful tool in research of this type of engine. The preliminary results for the three-dimensional simulation of the RDE has given some information about the structure of the detonation wave. It also has risen some question e.g. about the role of deflagrative combustion in the region of mixing of the hot gases with the fresh mixture. The simulations showed also that special attention must be paid the interactions of the numerical diffusivity and proper mechanism of the chemical reactions.

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SYMULACJE SILNIKA Z WIRUJĄCĄ DETONACJĄ (RDE) W KODZIE REFLOPS

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Abstrakt

W artykule przedstawiono wyniki trójwymiarowych symulacji detonacji w komorze silnika z wirującą detonacją (RDE). Symulacje przeprowadzono przy użyciu kodu REFloPS, który jest wynikiem pracy magisterskiej dwóch pracowników Instytutu Lotnictwa.