Numerical simulation and performances evaluation of the pulse detonation engine

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Abstract. A pulse detonation engine (PDE) is a type of propulsion system that uses detonation waves to combust the fuel and oxidizer mixture. The engine is pulsed because the mixture must be renewed in the combustor between each detonation wave. Theoretically, a PDE can operate from subsonic up to hypersonic flight speed. Pulsed detonation engines offer many advantages over conventional propulsion systems and are regarded as potential replacements for air breathing and rocket propulsion systems, for platforms ranging from subsonic unmanned vehicles, long range transports, high-speed vehicles, space launchers to space vehicles. The article highlights elements of the current state of the art, but also theoretical and numerical aspects of these types of unconventional engines. This paper presents a numerical simulation of a PDE at h=10000 m with methane as working fluid for stoichiometric combustion, in order to find out the detonation conditions.

1 Introduction

According to scientific literature [1-4] there has been preoccupation, since 1940, with propulsion systems based on detonation, which presupposes the elimination of at least the rotating constructive elements placed after the combustion chamber (turbine). Implementation of the PDE concept has encountered difficulties due to the need for speed and frequency of fuel blending, especially at high propulsion system operating speeds, and support for a stable and controlled detonation process. Then serious research began with the 1950s at the University of Michigan when researchers published a series of scientific papers about PDE.

The concept of PDE operation is similar to the impulse jet engine, but the difference is the combustion rate of the fuel mixture and the oxidant (deflection versus detonation). The combustion mixture is ignited in an open chamber, the resulting combustion increases the mixture pressure to about 10 MPa, which then expands into a nozzle at thousands of meters per second, which can be numerically modelled as a constant volume combustion process, where more chemical energy is released as heat than the constant pressure process found in conventional turbine engines. All potential chemical energy stored in the fuel is transformed into the internal energy of the gas.

Experimental tests have encountered a number of difficulties regarding both the transition of subsonic deflagration into a supersonic detonation wave and the correct mixing of the fuel and the oxidant to result in uniform detonation. PDE is an intermittent combustion propulsion system in which detonations occur at high frequencies by burning and accelerating the fuel and oxidant mixture. Fired gases move either at subsonic speed or at supersonic speed based on the geometric parameters of the nozzle, the fuel injection rate and the frequency of detonation. PDE uses the detonation waves for combustion of the fuel and oxidant mixture; theoretically, this type of engine can operate from a subsonic regime to hypersonic regimes (Mach> 5), [1-5].

The operation of a detonation engine consists of four major stages: filling the tube with the desired mixture; initiating detonation; propagation of detonation along the tube and evacuating products to the atmosphere see Fig. 1, [6].

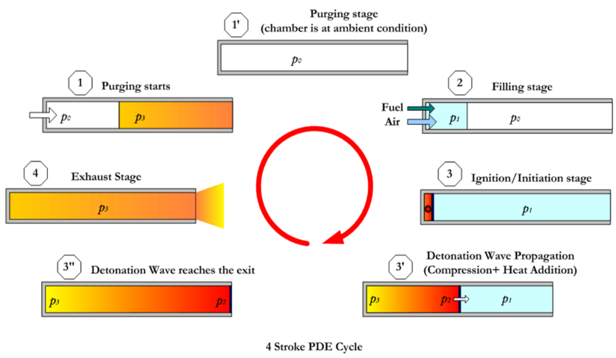

Fig. 1. PDE cycle, [6].

According to [7, 8] a positioning of the propulsion concept PDE according to Mach number versus traction can be as shown in Fig. 2, as the specific impulse of the PDE is greater than that of missiles and lower than that of turbojet engines.

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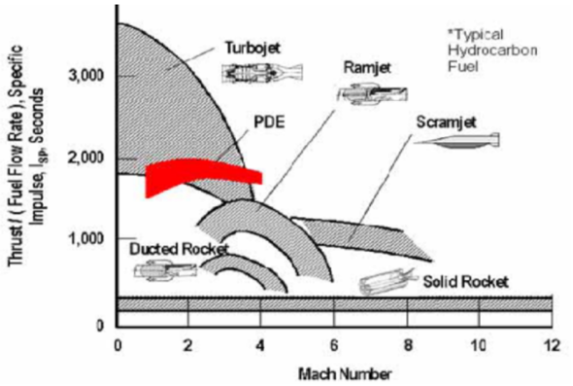

Fig. 2. PDE propulsion (Mach number vs. thrust/ specific impulse), [7, 8].

The need to optimize the mass and thrust values of jet engines used in the aerospace industry has led to the elimination of the rotating constructive elements that de-energized and drastically limited the maximum gas temperature (less mechanical complexity). Elimination of the turbine makes it possible to increase the temperature and speed of combustion gases through a more efficient supersonic combustion (detonation) and is capable of providing gas velocities and pressures far superior to conventional combustion (deflagration). Detonation bursting with shock waves almost doubles the thermodynamic efficiency of the engine cycle; high-frequency detonation has significant implications for noise, vibration and pollution levels.

For detonation, either the burning process must be strong enough, or downstream deflagration must be transformed into a supersonic wave in a process known as deflection-detonation transition (DDT). DTT can be induced by position internal ramps on the combustion wave path to increase the turbulence level, offering significant improvements (at least 27%) to the total pressure loss of a spiral with the same performance [9].

References to scientific literature reveal aspects of both the use of materials with optimal high temperature properties in view of the extremely high heat released on the fired combustion unit as well as the use of cooling elements and streams and the minimization of the DDT transition period [10].

Scientific references indicate the PDE classification by design type: pure (PDE with / without pre-dielectric, with / without ejector, single tube PDE, multi-tube PDE, PDE-turbojet PDE-rocket) of the fuel used [11, 12].

2 Theoretical considerations

2.1. Definition of detonation

Detonation takes place in a mixture of fuel and air moving at a subsonic speed that is compressed by a normal shock wave propagating to a high Mach, which is then followed by a rapid heat release and a sudden increase in pressure, see Figure 3. Detonation is a violent, rapid, exothermic reaction that produces a tough environment in which it is difficult to dynamically model and dynamically modify local pressures, speeds and temperatures. The detonation process results in pressure increases due to adiabatic compression (20-30 bar, 50 bar maximum pressure) and the combustion products exhibit a high temperature gradient due to inherent compression and lower molecular dissociation.

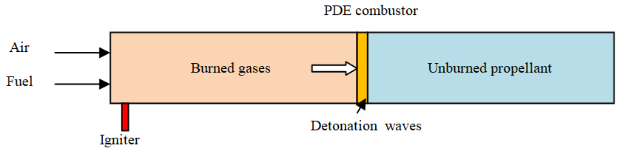

Fig. 3. Detonation process – PDE.

Specific thrust is one of the most important elements for designing the pulse detonator. According to the usual practice, the traction of a PDE can be characterized by the specific impulse (I_{sp}), defined as the impulse per unit of fuel mass [13]:

$$I_{sp} = \frac{I}{m_f g}, \tag{1}$$

where I_{sp} is specific impulse, I– impulse, m_f– fuel mass, g – gravitational acceleration.

2.2. Requirements and performance of PDE

Assuming PDE with a combustion chamber of an jet engine, we can define a series of general requirements that can characterize such a propulsion system, [14, 15]: ensure a stable combustion process; the efficiency of the combustion process is the highest possible with the least possible total and static pressure losses; have a low thermal load and a high operating resource; have a reduced dimensioning with positive implications for the mass and mechanical strength.

According to [6, 11] PDE performance is influenced by a series of parameters, the most relevant is: the diameter of the detonation tube d; the length of the detonation tube L; the frequency of the detonation cycle f; equivalence ratio r; cell size λ:

$$T = I_v V f = I_v L \frac{\pi d^2}{4} f, \tag{2}$$

where T is thrust, V – volume of the detonation tube, I_v–impulse per unit volume.

3 Numerical simulation of PDE

3.1. Geometry of PDE

According to [16, 17], for CFD analysis we propose a simple geometry (see Fig. 4) of pre-detonator PDE and Laval nozzle, having the characteristics of Table 1.

Table1.PDE characteristics.

Parameters	Values	Parameters	Values
Nozzle ramp	150	Diameter	100 mm
PDE length	1000 mm	Nozzle type	Laval

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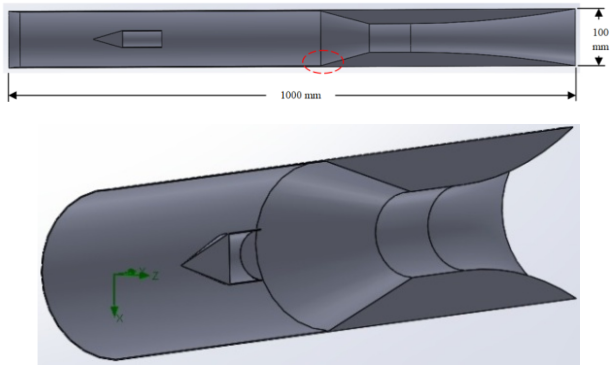

Fig. 4. PDE geometry.

3.2. CFD analysis conditions

For CFD 2D deeper flow analysis around the admission to the Laval nozzle was used Ansys 18 [18] and a simple geometry of the PDE propulsion system with the initial conditions in Table 2 for stoichiometric burning:

$$CH_4+2O_2=CO_2+2H_2O. \qquad (3)$$

Table2. Initial condition for PDE analysis.

Parameters	Values	Parameters	Values
Altitude	10000 m	Fluid	CH_4
Admission pressure	26436 Pa	Admission speed	7 Mach
Admission temperature	223.16 K	Cells number/type	quadrilaterals / 33696
Wall type	adiabatic		

Nitrogen N_2 has been assumed to be inert gas and does not participate in chemical reactions. For stoichiometric burning ($\lambda = 1$) on input or imposed the following chemical compositions (molar): $CH_4 = 0.095$, $O_2 = 0.19$, $N_2 = 0.715$. The quadrilateral cell mesh grid is highlighted in Fig. 5.

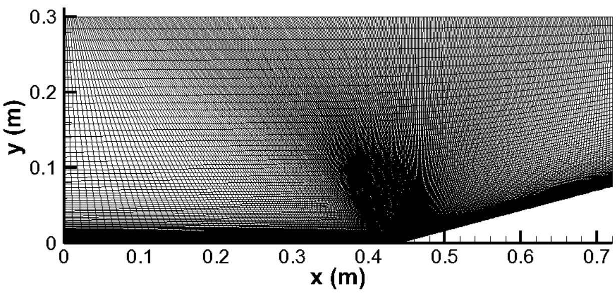

Fig. 5. The mesh grid CFD, Tecplot.

3.3. CFD 2D analysis

For the 2D analysis, we selected the Laval nozzle input region of Fig. 4, following the distribution of the molar fraction of the methane that is shownon Fig. 6, the pressure (Fig. 7) and the Mach number (Fig. 8).

The meshing scale required for 2D analyses was optimized on the Laval nozzle inlet wall and on the vertical zone between $x = 0.4 \div 0.5$. The distribution of the concentration level of CH_4 in the approach of the wall (boundary layer) depends on the wall distance (Fig. 6).

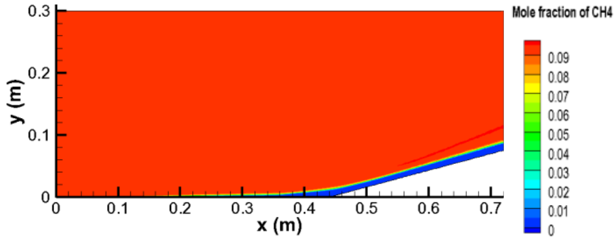

Fig. 6. Molar fraction, CH_4Tecplot.

Fig. 7 shows the variation of the pressure gradient in the approach of the inlet nozzle along the x axis with a maximum of 2.4×10^5 Pa at $x = 0.6$ m. The Mach number drops to zero, which indicates the boundary layer in the vicinity of the nozzle ramp (Fig. 8).

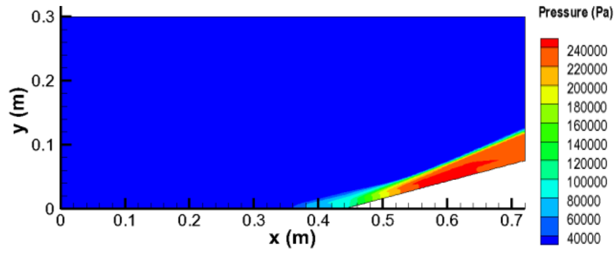

Fig. 7. Pressure, Tecplot.

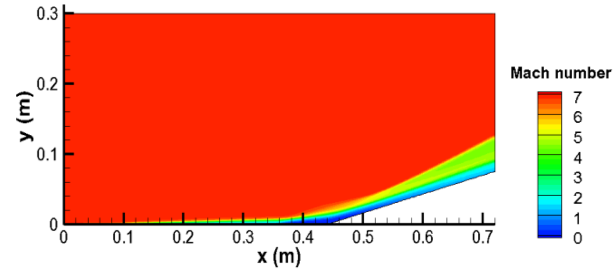

Fig. 8. Mach number, Tecplot.

Fig. 9 shows the variation of temperature in relation to the distance to the wall (nozzle ramp) with implications upon the thickness of the boundary layer.

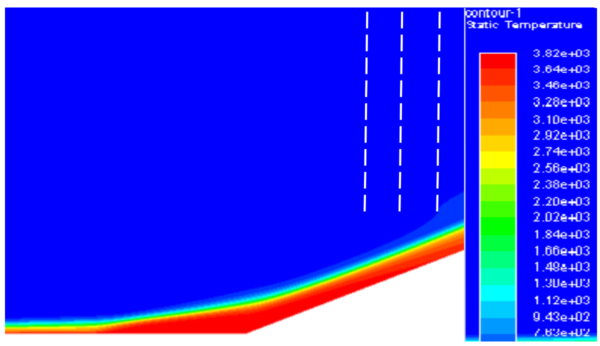

Fig. 9. Static temperature.

To better understand the 2D fluid behaviour in the approach of the nozzle ramp we extracted the values of the variation of the boundary layer and the variation of the total pressure to the corresponding vertical $x = 0.4$ m. The thickness of the limit layer corresponding to a Mach 99% of the flight speed (6.93 Mach) is 0.064 m (see Fig. 10) and the total pressure drops to 2.8×10^4 Pa (see Fig. 11).

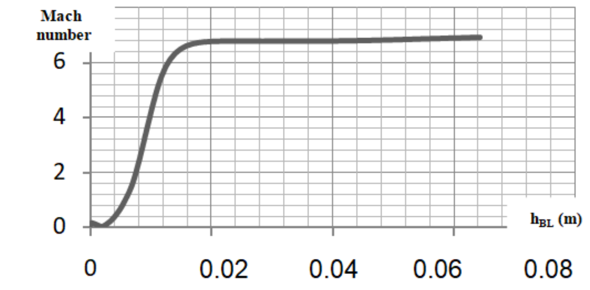

Fig. 10. Boundary layer thickness (h_{BL}) at $x = 0.4$ m.

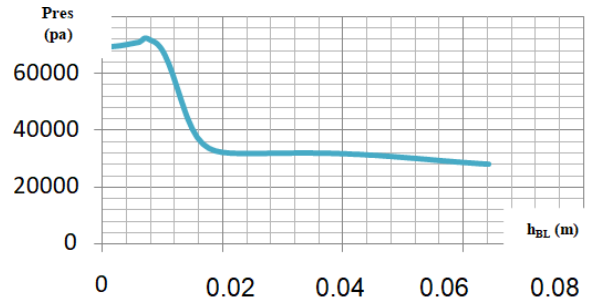

Fig. 11. Total pressure at $x = 0.4$ m.

Boundary layer thickness at $x = 0.45$ m (at the ramp application point of 15^0) is 0,069 m (Fig. 12), total pressure down at 2.79×10^4 Pa (see Fig. 13).

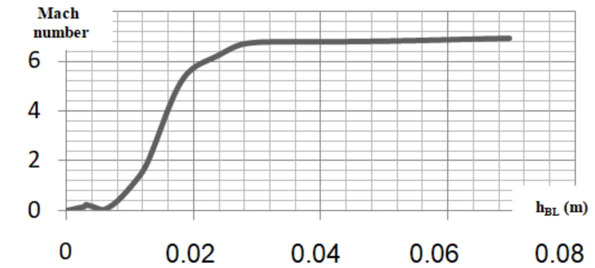

Fig 12. Boundary layer thickness (h_{BL}) at $x = 0.45$ m.

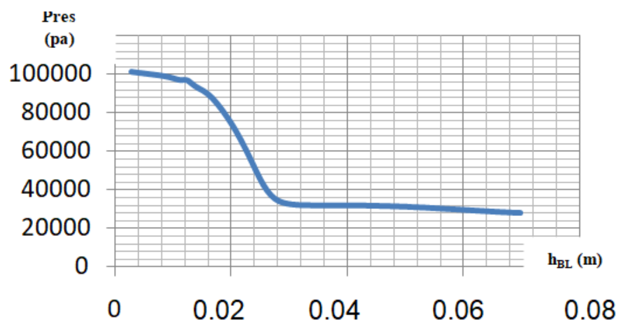

Fig. 13. Total pressure at $x = 0.45$ m.

The thickness of the boundary layer at $x = 0.5$ m is 0.076 m (Fig. 14) and the total pressure increases to 2.82×10^4 Pa (see Fig. 15). Thus, as is normal, the thickness of the boundary layer increases downstream with the increase of the Mach gradient, to a 0.95% molar methane fraction, Fig. 16.

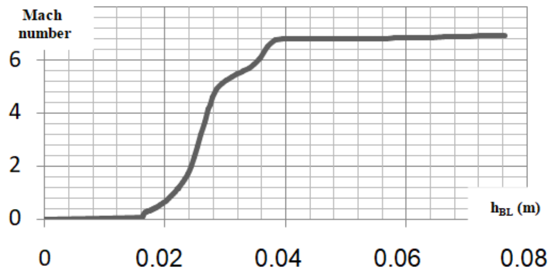

Fig. 14. Boundary layer thickness at $x = 0.5$ m.

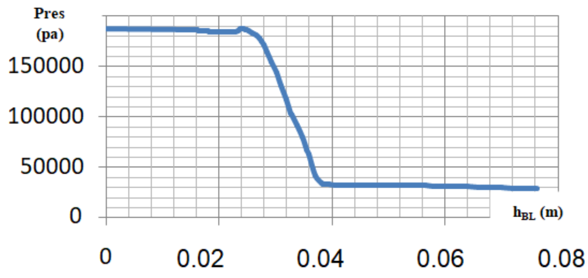

Fig. 15. Total pressure at $x = 0.5$ m.

Following the variation of the Mach number and the corresponding total pressures, a slight shock wave is observed at the extreme edge of the nozzle ramp.

The shock wave interacts with the boundary layer due to the upstream propagation of the pressure disturbances favouring the separation of the flow, depending on the Mach number and the angle nozzle ramp [16].

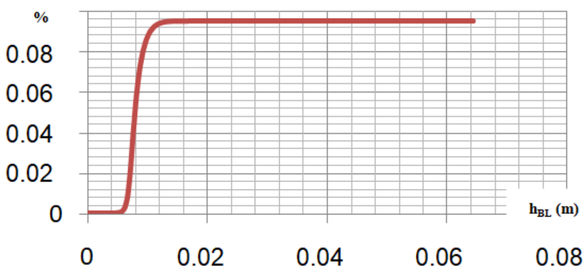

Fig. 16. Methane molar fraction at $x = 0.4$ m.

4 Conclusions

PDE studies require interdisciplinary concepts, methods and technologies, based on applied mathematics, combustion theory and computational fluid dynamics. Understanding the detonation process is essential for future assessments of heat transfer at constant volume and supersonic speeds of the combustion wave. Theoretically, PDEs offer many advantages over current turbo propulsion systems or missiles. Experimental development has faced many challenges, such as vibration, cooling or optimal detonation control.

The numerical simulation was focused on the angle of the nozzle ramp (15^0) at a Mach number high enough to ensure the detonation of the working agent (methane) without taking into account the three-dimensional effects.

Knowing that the fuel-oxidant mixture has narrower detonation limits than combustion limits, it is necessary to be considered in numerical simulations, a number of effects due to the ramp angle, wall temperature, initial mixing speed, and 3D space implications (finite effects).

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