Preliminary study of a resonant igniter for Rocket Engines

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Abstract. The work reported herein is a preliminary numerical study of a resonant igniter for rocket engines. Resonant igniters are very attractive and promising for in-space thrusters, since they are simple, highly reliable and lightweight. Fine-tuning of various parameters is required to initiate and maintain the resonance conditions required for heat generation. A numerical study based on a finite element discretisation of the compressible Navier-Stokes equations is performed in order to analyze the main physical phenomena which govern the behaviour of the igniter.

INTRODUCTION

It is well known that under-expanded gas jets can produce high intensity wave oscillations if the jets are made to interact with a cavity [1]. Nozzle diameter, nozzle-resonance cavity opening distance, resonator geometry (form, diameter, length), and thermodynamic properties of the operating gas (speed of sound, heat capacity, density and supply pressure) are driven parameters on gas-dynamic resonance. The cavity walls can rapidly increase to a higher temperature when an under-expanded gas jet enters into a resonance tube. Depending on design characteristics, the temperature can be far higher than the gas jet stagnation temperature [2]. These phenomena are of great interest in rocketry, since the temperature growth can be exploited for achieving the ignition of liquid propellant engines. Even though the resonant igniter concept is not new, some commercial attempts to design and produce devices for space applications have been made recently.

The electrical spark has been proven to be the safest, most reliable and widely used method of igniting a combustor, e.g. by adopting internal combustion engine sparkplugs. However, electric ignition adds complexity, requires electrical power and a high-voltage electrical source. It is also susceptible to electromagnetic damage.

The resonant igniter model is simple, highly reliable and lightweight, since it does not require movable parts, electrical systems or external power supplies. These advantages are important for long missions, where a high number of ignitions are required. Several studies demonstrated that when the cavity is placed in the regions of instability, the detached shock oscillates, leading to resonance. An acoustic igniter has two main operating modes when the nozzle pressure ratio is increased beyond the critical limit: the Jet Regurgitant Mode (JRM) and the Jet Screech Mode (JSM). The JRM is characterized by an inflow phase, where the jet stream enters the cavity and travels inside the cavity towards the closed end. If the cavity is long enough, the waves coalesce to a single shockwave which is reflected at the closed end and travel towards the opening. The gas leaves the cavity and displaces the free stream jet; the cavity is emptied, and a new cycle starts. Under certain conditions, a small fraction of the resonance gas can remain inside the cavity, causing gradual heating due to irreversible phenomena, and the gas temperatures can increase to a value beyond the stagnation temperature at the closed end of the resonator. The JSM is characterized by an almost normal shock oscillating at high frequencies. Depending upon the geometrical parameters and flow parameters, both the JRM and JSM modes can be observed. Extensive fine-tuning of various parameters is required to initiate and maintain the resonance conditions required for heat generation. In this preliminary study, numerical simulatios are performed to investigate the gas-dynamic oscillatory phenomena which govern the behaviour of the igniter.

NUMERICAL FRAMEWORK

In this preliminary study the flow field inside the igniter is described by the axisymmetric compressible Navier-Stokes equations. The equations are discretised in space by a Discontinuous Galerkin finite element approach, while an explicit Runge-Kutta scheme is used for time integration. Second order accurate schemes are used for both space and time discretisations. The convective terms in the fluxes are discretised by means of an approximate Riemann problem solver [3], while diffusive terms are evaluted by means of a recovery based approach [4]. The numerical schemes are implemented in a parallel Fortran 90 solver which has been tested in both inviscid and viscoud test cases [5, 6, 7, 8]. The computational domain is discretised by a mixed structure-unstructured mesh with 130000 elements generated by Gmsh [9].

DESIGN CHARACTERISTICS

A resonant igniter is made of a sonic nozzle and a resonant cavity. (Fig. 1) The gas is accelerated through the sonic nozzle and the under-expanded jet is expelled into the surrounding environment. The resonant cavity is placed in front of the nozzle exit. The cavity has a first frustoconical portion leading to a second shorter cylindrical section.

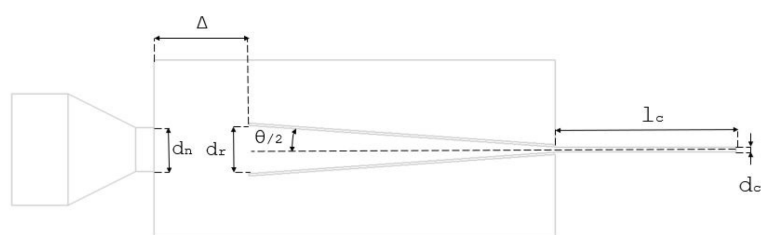


FIGURE 1. Resonant igniter geometry

The under-expanded jet with a typical barrel shock structure is generated when the nozzle pressure ratio is increased beyond the critical limit. (see Fig. 2, 3) It was demonstrated that if the entry edges of the resonance tube are located in the compression areas between the Mach disk, reflected shocks, and the end of the jet's cell, high-frequency oscillations that lead to maximum heating occur [10, 11]. A simple and quite accurate method for calculating the geometry of supersonic jets was formulated by Avduevskii et al. [12]. An approximate calculation of the jet's axial dimensions can be made by means of the following empirical relations:

$$X_m/d = [0.8 + 0.085 \cdot (M_e - 2.1^2] \cdot M_e \cdot (n - 0.5)^{0.5} \tag{1}$$

$$X_c/X_m = 1.3 + 0.5 \cdot n^3 \tag{2}$$

where d is the nozzle diameter, X_m is the distance to the Mach disk, X_c is the length of the jet's first cell, M_e is the Mach number at the nozzle exit section and $n = p_e/p_a$ is the ratio between jet pressure in the nozzle exit and ambient pressure around the jet (see Figure 2). To obtain the optimum size of the gap between the nozzle and the resonance tube, the distance between the sonic nozzle and the cavity should be in the range from X_m to X_c, taking into consideration any possible errors in calculations and manufacturing tolerances. Another relation suggested by Hartmann and Troll [13] for the determination of the length of jet's first cell is:

$$S/d = 1.8 \cdot (pe/pa - 1.9)^{0.5} \tag{3}$$

where d is the nozzle diameter, S is the length of the jet's first cell and p_e/p_a is the ratio between jet pressure in the nozzle exit and ambient pressure around the jet. Experimental results of tests perfomed by R. A. Marchan [14] demontrated that the empirical formulas (1), (2) and (3) can be used to define the limits of the adjustment range. Palme suggested that cavity diameter should equal the widest diameter attained by the under-expanded cell structure [15]. The geometry of the cavity is given by [16] in terms of operative ranges. Dimensionless igniter design characteristics selected for this study are $d_r = 1.2 \cdot d_n$, $d_c = 0.316 \cdot d_r$, $l_c = 4 \cdot d_r$, $\Delta = 1.92 \cdot d_n$, $p_e/p_a = 2.9$. The nozzle throat diameter (d_n) is 0.01 m.

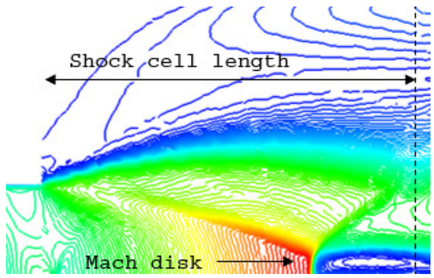
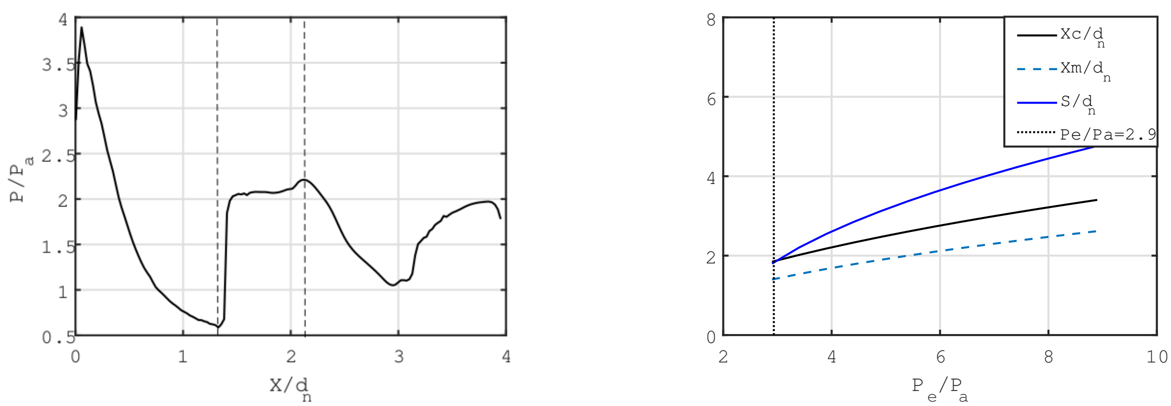


FIGURE 2. Under-expanded jet's first cell.



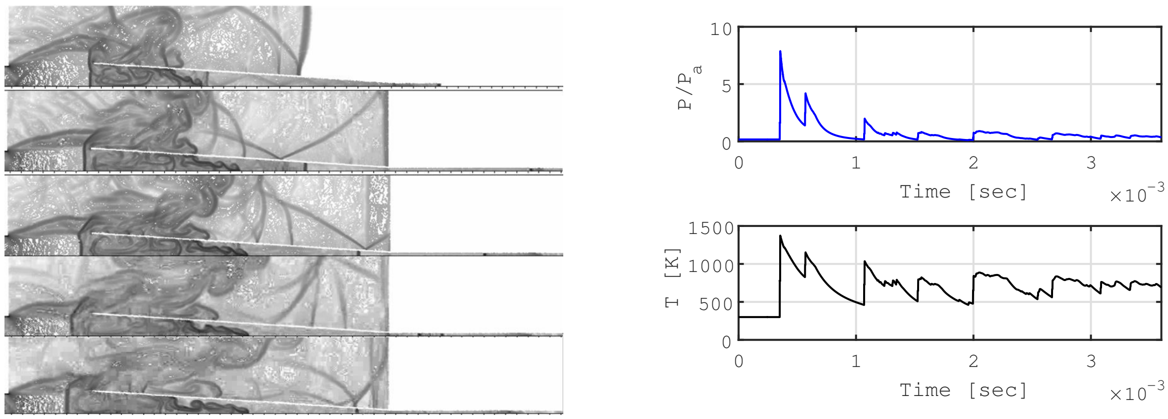
(a) (b)

FIGURE 3. (a) Dimensionless pressure at the jet centerline as a function of dimensionless axial distance. Compression region between dash lines. (b) Distance to the Mach disk (X_m) and length of the jet's first cell (X_c [12], S [1]) as a function of the ratio between jet pressure in the nozzle exit and ambient pressure around the jet. Dot line for $p_e/p_a = 2.9$.

RESULTS AND CONCLUSIONS

Computational fluid dynamic analysis were conducted to analyze the oscillatory behavior inside the resonance cavity. A preliminary study was performed with an ideal gas, adiabatic wall condition and $p_e/p_a = 2.9$. This value was later increased to $p_e/p_a = 7$, to analyze the impact of the pressure ratio on the resonant behavior. Experimental studies demonstrated that increasing the pressure ratio with fixed geometry lead to a higher heating [14]. Numerical Schlieren during an oscillatory cycle at startup and dimensionless pressure and temperature trends as a function of time in a point at the end of the cavity are reported in Figure 4 for $p_e/p_a = 7$. In this case, the temperature peaks exceed 1000 K during the initial transient phase and the average temperature after a few cycles is ~780 K. This value is significantly larger than the gas total temperature inside the nozzle (300 K).

Future work will be devoted to more accurate studies, in which Unsteady Reynolds Averaged Navier-Stokes models or Large Eddy Simulations approaches will be considered to properly describe the turbulence phenomena which characterize the flow field.



(a) (b)

FIGURE 4. (a) Numerical Schlieren during an oscillatory cycle at startup. (b) Dimensionless pressure and temperature trends in a point at the bottom of the cavity.

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