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Influence of high-density energetic particles on combustion of solid fuels for Ramjet applications

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Abstract

In solid fuel Ramjet engines, performance are significantly influenced by both fuel heat of reaction and density, which are crucial for achieving optimal specific impulse and density specific impulse. The Density-specific impulse is calculated by multiplying the density of solid fuel compositions with the specific impulse: therefore, it accounts not only for the fuel performance, but also for the volumetric sizes and consequently for the vehicle shape. As well known, the shape of the vehicle has a critical impact on the Lift over Drag, L/D, parameter, and therefore in the vehicle performance. For instance, the specific impulse grows proportionally to the square root of flame temperature or heat release, while the impulse density increases linearly with fuel composition density. Augmenting fuel density can be accomplished by incorporating additives and energetic particles into the fuel matrix, while augmenting of flame temperature can be investigated with the addition of additives such as CUO and PTFE on combustion. Therefore, the goal of this work is to enhance the impulse density of Ramjet solid fuels by integrating high-energy materials like Aluminum (Al), Boron (B), and Magnesium (Mg) into an HTPB-based material, and the specific impulse, by adding CUO and PTFE. The performance characteristics of these solid fuels are evaluated using NASA CEA Code. The paper provides a comprehensive comparison of these solid fuels and their respective characteristics**.**

Keywords: Ramjet engine, Energetic particles, solid Fuels, Additives, and solid fuel combustion

1. Introduction

A Solid fuel ramjet is an air-breathing propulsion system that use subsonic combustion with no moving parts, making it simple in geometry (no fuel control, storage, or feed system is needed), low in cost, and more reliable in design [1]. An SFRJ consists mainly of a hollow cylinder with a cavity containing solid fuel in line with a diffuser. The diffuser intake allows the incoming air to ram and react with the solid fuel surface creating a diffuse flame region [2-3]. In comparison with the traditional rocket engines, these SFRJ offer 3-4 times higher specific impulse, making it more suitable for many applications ranging from tactile long-range missiles to supersonic flights [4]. The most common solid fuels for SRFJ are based on polymeric hydrocarbons, such as hydroxyl-terminated polybutadiene

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(HTPB), polymethyl methacrylate (PMMA), and polyethylene (PE) which provides good regression rate with high mechanical stability and combustion efficiency. Recent studies also indicate paraffin as a superior solid fuel for ramjet applications [5].

The addition of high energetic particles to these hydrocarbon polymers can boost the gravimetric and volumetric heat release of these solid fuels. Additives such as aluminum, beryllium, magnesium, titanium, and zirconium are among the most commonly used additives for solid fuel applications. For several decades Aluminium remained a superior additive for solid fuel matrix. However, recent studies also indicate the high volumetric and gravity metric values of boron as an alternative fuel for the Solid fuel ramjet applications [6].

Despite these advantages of high energetic materials, their applications in SFRJ are limited due to its hindrance in the understanding of their complex burning phenomena, combustion, and the corresponding chemical reaction mechanism. The fuel regression rate is a key factor in the performance of the solid fuel ramjet. The gasification process of the fuel hinges on several factors, notably the airflow rate and the geometry, such as the port diameter, of the combustion chamber. Achieving optimal engine performance necessitates a thorough comprehension of the fuel's regression rate and combustion characteristics under diverse operating conditions. Therefore, the current study aims to understand the innovative solid fuel combinations based on Aluminium, boron, and magnesium as additives with HTPB as a fuel matrix. A detailed comparison and the most suitable materials were proposed for the Ramjet applications.

2. Solid fuel materials and composition

In this work, HTPB (density: 0.916 g/cm^2) loaded with different energetic particles such as Magnesium, Boron, and Aluminium is used as a fuel matrix. Copper oxide (CuO) and Polytetrafluoroethylene (PTFE) were considered as additives for fuel. Table 1 and Table 2, show the characteristics of the fuels and additives used in this study.

Table 1. Properties of fuel matrix

Fuel Matrix	**Chemical Formula**	**Density**(g/cm³)
HTPB-R45	$[-CH_2 - CH = CH - CH_2 -]_n$	0.916
Aluminum	Al	2.7
Boron	B	2.34
Magnesium	Mg	1.738

Table 2. Properties of additives

Properties	**Copper oxide**	**PTFE**
Chemical formula	CuO	$(C_2F_4)_n$
Density (g/cm³)	6.31	2.32
Melting Point (°C)	1326	327
Molecular weight(g/mol)	79.545	100.01

3. Theoretical Analysis

The effect of metal additives and fuel blender combustion performance can be estimated theoretically with the help of NASA Chemical Equilibrium with Applications (CEA). It is noticeable that the theoretical combustion is adiabatic with isentropic expansion in the nozzle and homogenous mixing following ideal gas laws. In fact, performance factors like adiabatic flame temperature, specific impulse, density impulse, and characteristic velocity are good measures to estimate the experimental scenario [9]. The current chemical Equilibrium is considered an Infinite area with equilibrium and a combustion chamber pressure of 1 MPa with fuel–air equivalence ratio, ϕ (phi) varying from 0.6 to 1.1. HTPB with the chemical formula ($C_{10}H_{15.4}O_{0.07}$) is considered a fuel blend loaded with Aluminium, Boron, and Magnesium as metal additives under reaction with atmospheric air at flight test condition at an altitude of 8.3km where the temperature is 511.13 K. However, it is important to emphasize that the ideal calculations did not reflect many factors, such as two-phase flow losses and nozzle erosion. As a result, the actual performance of these fuels with metal additives varies.

3.1. Adiabatic Flame Temperature :

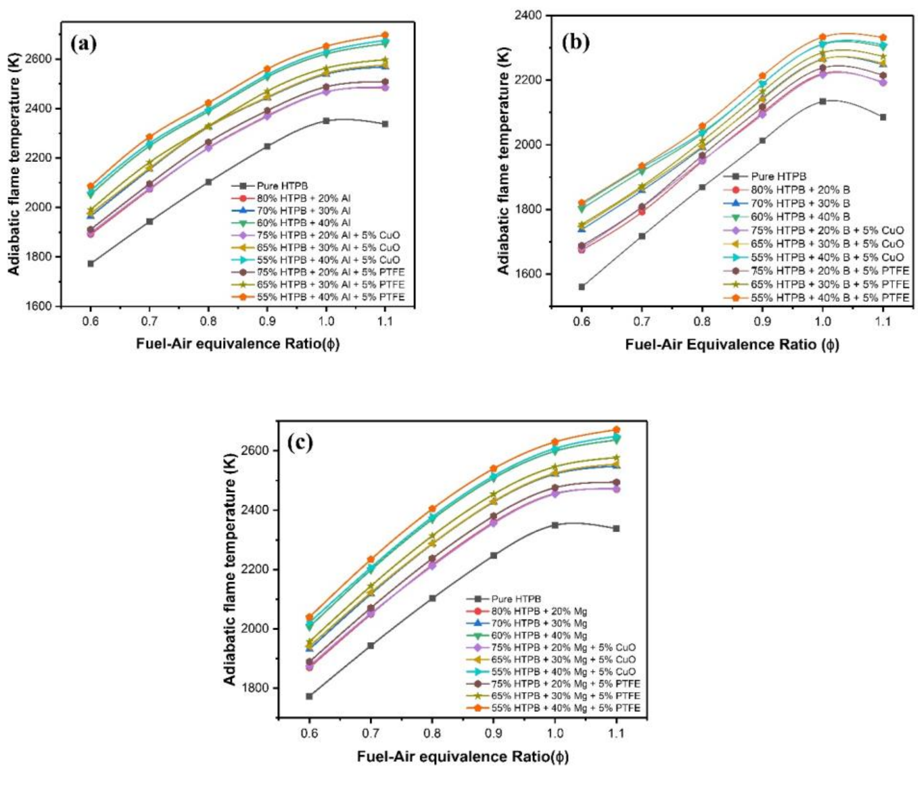


Figure 1. Adiabatic Flame temperature variations as a function of fuel–air equivalence ratio, ϕ for HTPB with varying compositions of (a) Aluminium (b) Boron (c) Magnesium particles at 1 MPa.

The adiabatic flame temperatures for various fuel grain compositions and for different fuel–air equivalence ratio, ϕ (phi); are shown in the figure 1. These figures show that with an increase in the fuel–air equivalence ratio, there is an increase in the Temperature of the combustion chamber until the stoichiometric condition: allowing to predict the stoichiometric fuel/air ratio of the different fuel compositions. Figure 1 demonstrates a significant enhancement in peak flame temperature as the concentration of additives gradually increases within the examined range, from 20% to 40% with a 10% increment. This augmentation results in an enriched fuel mixture through the incorporation of additives. This effect has an important impact on the engine size, since it is related with the mass flow rate of air required with respect to the fuel mass flow rate: lower O/F means also lower frontal area size. Among these configurations, HTPB with Aluminium exhibits the highest temperature in the combustion chamber at fuel–air equivalence ratio, of 1.1. Specifically, HTPB with 40% Aluminium yields a temperature of 2676.1 K, and the addition of 5% PTFE further elevates it to 2697.6 K. Following aluminum, magnesium and boron at 40% concentrations with 5% PTFE result in adiabatic flame temperatures of 2671.4 K and 2562.2 K, respectively. Pure HTPB, on the other hand, yields a temperature of 2337.5 K at this fuel–air equivalence ratio. It can be noted that metal additives contain high heat of combustion. This behaviour contributes to the rise of flame temperatures during combustion. Metal additives increase the gas phase temperature of the base material, which further increases in adiabatic flame temperature and improves the heat of combustion [9].

Commentato [CC1]: Can you add a table where phi=1. It is very useful to know the stoichiometric O/F.

3.2. Oxygen/Fuel Ratio :

Figure 2 shows the Oxygen/Fuel Ratio for various HTPB-based solid fuels loaded with metal additives.

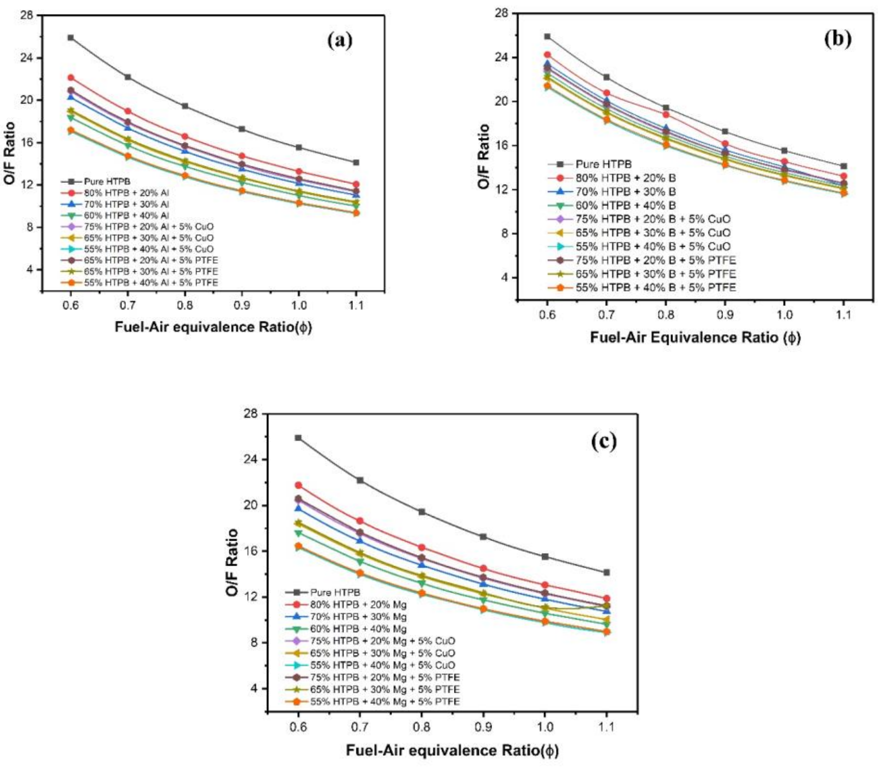


Figure 2. Oxygen/Fuel Ratio variations as a function of fuel–air equivalence ratio, ϕ for HTPB with varying compositions of (a) Aluminium (b) Boron (c) Magnesium particles at 1 MPa.

It is interesting to note that the stoichiometric ratio achieves at low O/F ratios with the effects of additives. At equivalence ratio of 1, Magnesium with 5% of CuO shows a low O/F ratio of 9.8 compared to other HTPB-based fuel formulations. Pure HTPB at this ratio have O/F ratio of 15.54. The addition of CuO and PTFE Lowers O/F ratios in all fuel formulations.

3.3. Characteristic Velocity :

Figure 3 shows the characteristics velocity for various HTPB-based solid fuels loaded with metal additives.

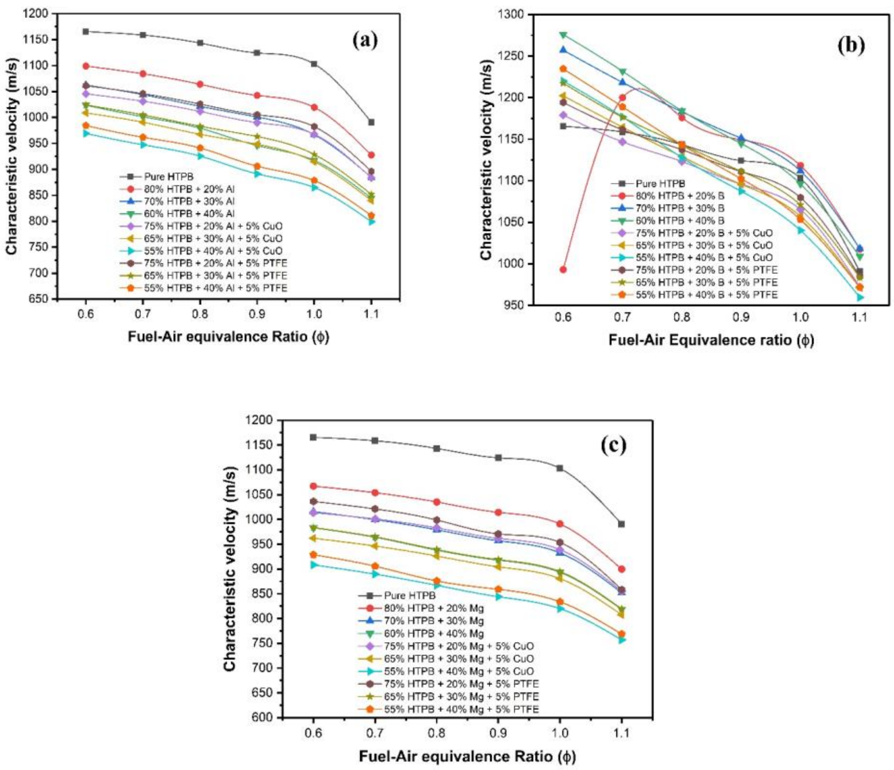


Figure 3. Characteristic Velocity variations as a function of fuel–air equivalence ratio, ϕ for HTPB with varying compositions of (a) Aluminium (b) Boron (c) Magnesium particles at 1 MPa.

The performance of solid fuels can be predicted by evaluating the characteristics velocity (C^*) as a function of the O/F ratio (Davis and Yilmaz 2014). The HTPB loaded with 40% B formulation shows a maximum value of C^* of 1231.75959638051 m/s. The addition of B to HTPB improves the C^* compared to that of Al and magnesium formulation where their effects in the decrease of the Characteristic Velocity. The HTPB/Mg-based composition has a lower value of characteristics velocity (C^*) compared to other HTPB based formulations. It is important to note that the characteristic velocity is a function of the propellent and independent of the rocket geometry, hence, with the improvement in characteristic velocity, higher performance can be achieved due to the improved combustion temperature at a lower O/F ratio allowing for a smaller, lighter oxidizer tank.

3.4. Specific Impulse :

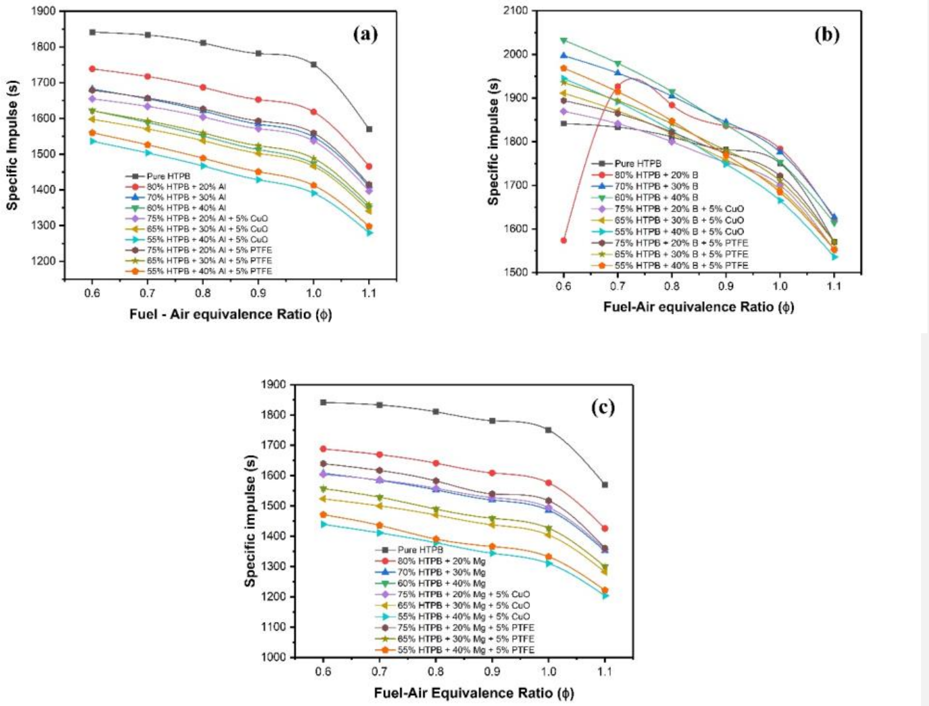


Figure 4. Specific Impulse variations as a function of fuel–air equivalence ratio, ϕ for HTPB with varying compositions of (a) Aluminium (b) Boron (c) Magnesium particles at 1 MPa.

Figure 4, shows the Theoretical Specific Impulse (I_{sp}) for different equivalence ratios. The Isp of the Ramjet is calculated by means of the NASA CEA code using the following formula.

$$\mathbf{ISP}_{Ramjet} = \mathbf{ISP}_{Rocket}\left(\mathbf{1}+\frac{\mathbf{O}}{\mathbf{F}}\right)-\frac{\mathbf{O}}{\mathbf{F}} * \mathbf{M}_{flight} * \sqrt{(\gamma R T)}$$

Among the different fuel combinations, HTPB/B with CuO and PTFE shows an increase in Isp whereas, HTPB based on AL/Mg additive samples shows a decrease in trend below the Pure HTPB. This means that despite the increase in flame temperature with these additives, the contribution of the higher molecular weight balances and outweighs the benefit of adding these additives. In fact, the lower molar weight of boron compared to that of aluminum and magnesium (1.6, 1.4 times lower than AL, Mg), translates into higher performance than pure HTPB regardless of equivalence ratio. It is noticeable that HTPB with 40% Boron shows height value of the specific impulse 2032.58 s. Followed by Pure HTPB at equivalence ratio = 0.6 shows a value of 1841.7 s with decreasing trend with increase in equivalence ratio.

3.5. Density Impulse :

Another performance factor that might be crucial in situations with volume restrictions is the density impulse. In fact, higher density may lead to a reduction of tanks volume. A preliminary analysis may be done considering that for an assigned flight time (mission), one of the most important performance parameters used is the total impulse I_T.

I_t is defined as:

$\mathbf{I_t = F.t = ISP * m_F * g_0 * t}$ (I_{SP} in seconds)

Being the mass of the fuel given by:

m=ρ*V

The total impulse can be written by:

$\mathbf{I_t = ISP * g_0 * \rho * V}$

This equation shows that the total impulse depends on the density impulse. Assuming a constant total impulse, defining:

$$R = \frac{Vol_{HTPB+Additives}}{Vol_{HTPB}} = \frac{(ISP_{HTPB+Additives})(\rho_{HTPB+Additives})}{Isp_{HTPB}\rho_{HTPB}}$$

a real advantage is obtained only if R<1. In fact, this gives a chance to analyse the possibility of a reduction of the tanks volume.

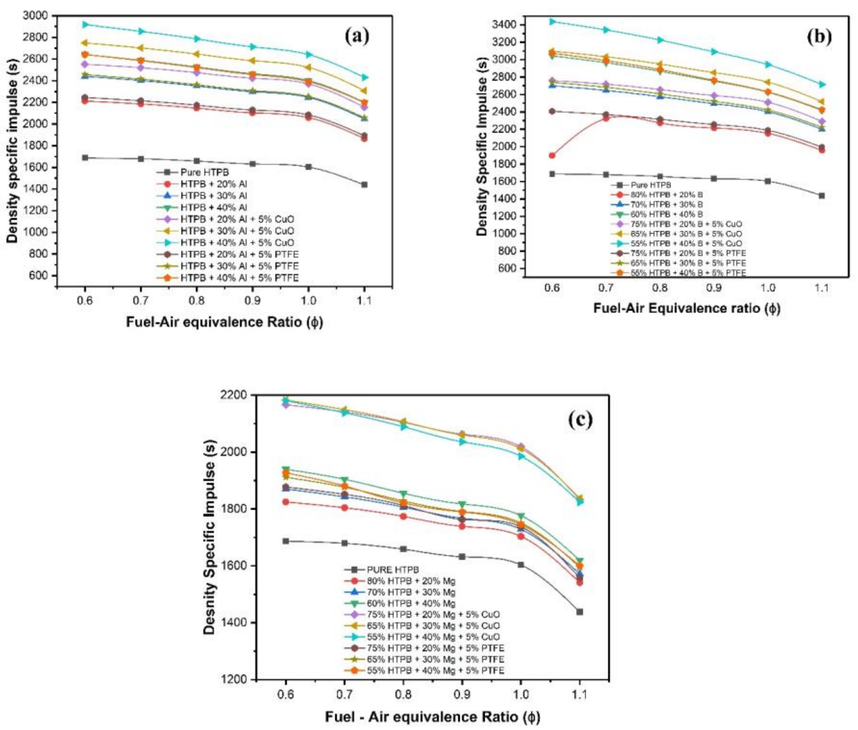
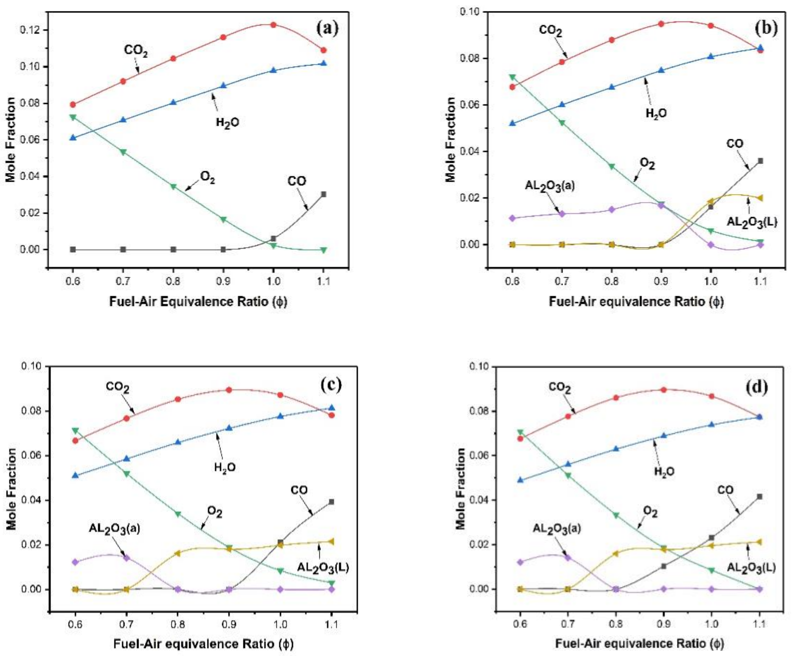


Figure 5. Density Impulse variations as a function of fuel–air equivalence ratio, ϕ for HTPB with varying compositions of (a) Aluminium (b) Boron (c) Magnesium particles at 1 MPa.

As seen in Figure 5, the density impulse for each propellant system has been calculated at its corresponding Isp values. addition of metal additives improves the density impulse for all fuel formulations. At an equivalence ratio of 0.6, Boron-based fuel formulations with 5% CuO shows a density impulse of 3436.86 s. which is 2 times higher than pure HTPB; whereas, for the same equivalence ratio, aluminium and magnesium shows an improvement of 1.73 and 1.29 times respectively.

3.6. Mole Fraction :

Figure 6 (a–j) illustrates the species mole fractions of HTPB base material loaded with Boron, Aluminum, and Magnesium as solid fuel matrix and CuO/PTFE as additives, burning in atmospheric air at a pressure of 1 MPa and the corresponding temperature value of 511.3 K for the flight operating conditions at an altitude of 8.3km. Species with mole fraction values higher than 0.01 were considered in the following plots as a function of O/F ratio. For pure HTPB (5-a), the main combustion products are CO, CO_2, H_2O, ,O_2. It can be noted the there is a visible improvement in the boron combustion with the addition of CuO and PTFE. However, among all fuel species, boron-based composition forms less concentration of H_2O mass fraction and forms HBO isomers that are more stable in combustion [10-11]. This is due to the high flame temperature which disfavours the formation of stable product, but also indicates that this recombination is to be expected in the nozzle due to the expansion of the gases, further increasing the specific impulse compared to the other compositions as shown in Fig. 2.



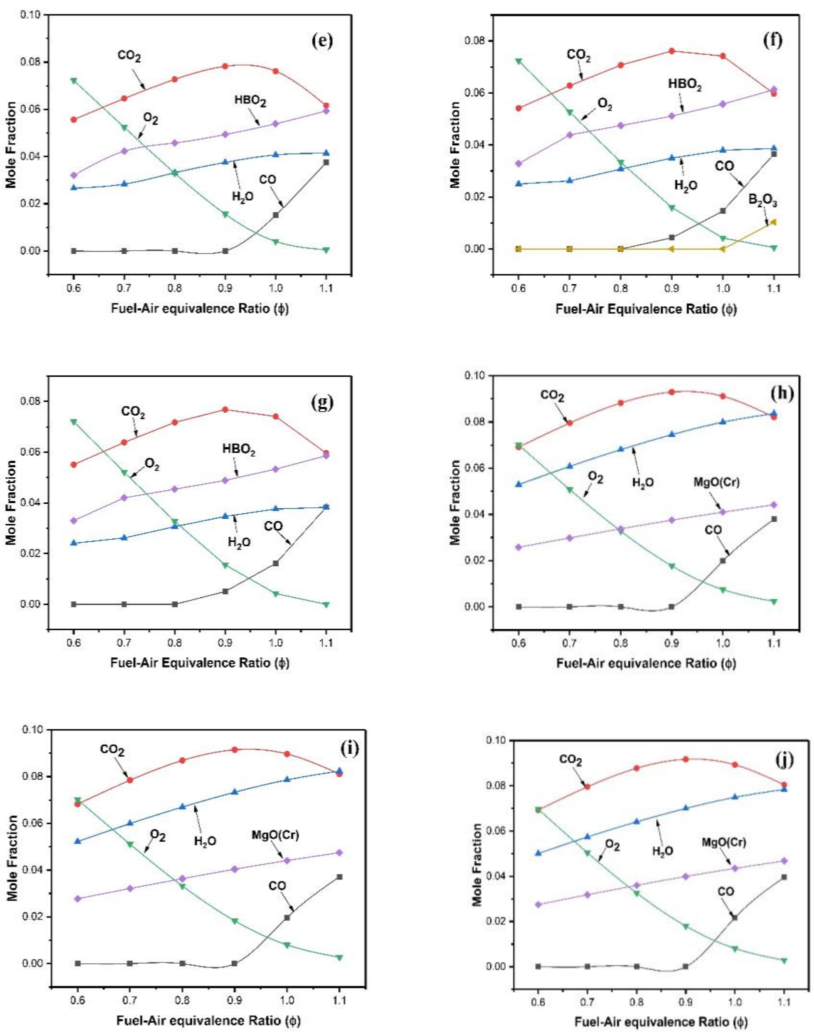


Fig 6. Mole fractions of HTPB-based fuel loaded with **(a)** Pure HTPB **(b)** 40% Aluminium; **(c)** 40% Aluminium; and 5% CUO; **(d)** 40% Aluminium and 5% PTFE **(e)** 40% Boron; **(f)** 40% Boron and 5% CUO; **(g)** 40% Boron and 5% PTFE; **(h)** 40% magnesium; **(i)** 40% magnesium and 5% CUO; **(j)** 40% magnesium and 5% PTFE; additives burning in gaseous oxygen (O2).

4. Conclusion

Solid fuel ramjets are less prevalent than their liquid or gaseous counterparts due to their limited versatility and lack of precise control. Unlike liquid or gaseous fuels, which can be metered and regulated with greater precision, solid fuels are difficult to throttle and tune their performance under varying flight conditions, particularly in supersonic and hypersonic applications. Nonetheless, in specific scenarios where simplicity and reliability are paramount, solid fuel ramjets may find relevance. The potential integration of dual-mode ramjet technology in future small launchers may necessitate higher density impulse to enhance vehicle shape and reduce aerodynamic drag. Therefore, this study aims to demonstrate the viability of solid fuel, incorporating Aluminum (Al), Boron (B), and magnesium (Mg), for ramjet applications. Through a comparative analysis of different solid propellants via theoretical investigation, this work explores the potential of solid fuels in fulfilling the requirements of ramjet propulsion systems.

5. References

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