Acta Astronautica 141 (2017) 196–208

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

A review of the performance and structural considerations of paraffin wax hybrid rocket fuels with additives

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ARTICLE INFO

Keywords:
Hybrid rocket
Regression rate
Paraffin wax
Additives

ABSTRACT

Paraffin wax as a hybrid rocket fuel has not been comprehensively characterised, especially regarding the structural feasibility of the material in launch applications. Preliminary structural testing has shown paraffin wax to be a brittle, low strength material, and at risk of failure under launch loading conditions. Structural enhancing additives have been identified, but their effect on motor performance has not always been considered, nor has any standard method of testing been identified between research institutes. A review of existing regression rate measurement techniques on paraffin wax based fuels and the results obtained with various additives are collated and discussed in this paper. The review includes 2D slab motors that enable visualisation of liquefying fuel droplet entrainment and the effect of an increased viscosity on the droplet entrainment mechanism, which can occur with the addition of structural enhancing polymers. An increased viscosity has been shown to reduce the regression rate of liquefying fuels. Viscosity increasing additives that have been tested include EVA and LDPE. Both these additives increase the structural properties of paraffin wax, where the elongation and UTS are improved. Other additives, such as metal hydrides, aluminium and boron generally offer improvements on the regression rate. However, very little consideration has been given to the structural effects these additives have on the wax grain. A 40% aluminised grain, for example, offers a slight increase in the UTS but reduces the elongation of paraffin wax. Geometrically accurate lab-scale motors have also been used to determine the regression rate properties of various additives in paraffin wax. A concise review of all available regression rate testing techniques and results on paraffin wax based hybrid propellants, as well as existing structural testing data, is presented in this paper.

1. Introduction

Hybrid rocket technology has advanced since the discovery of liquefying fuels, also referred to as non-classical fuels. Hybrid rockets are named as such due to their propellants, which often comprise a solid fuel and a liquid or gaseous oxidiser. The physical and state separation of the fuel and oxidiser offer an increased safety aspect to rocket design and fuel handling. However, there is compromised performance due to the limiting boundary layer combustion method. The measure of regression rate of the solid fuel is a good indicator of the combustion performance of a propellant combination, which defines how quickly the solid fuel burns, however, the density of the propellant should also be considered. Hybrid fuels, particularly traditional variants such as hydroxyl-terminated polybutadiene (HTPB) are known to have very low regression rates. The regression rate is often improved through the use of performance-enhancing additives, such as high-energy metal particles. The degree to which these additives improve the combustion performance and the effect they have on the structural performance on a solid fuel grain has not been comprehensively determined and is dependent on factors such as particle size and density, as well as the original binder material. Although we can consider the propellant performance independently, the performance of the rocket itself is dependent on various design parameters, such as vehicle size, design thrust, mass and fuel density. In this paper, we review the current state of paraffin wax fueled hybrid rocket motor performance testing with specific reference to the role of additives in improving metrics such as specific impulse and density impulse. The purpose of this review is to create a link between existing regression testing results, with various additives, in comparison to the available structural characterization data on those fuel mixtures of paraffin wax based hybrid fuels to determine their feasibility in launch applications.

2. Hybrid combustion models

Combustion within a hybrid rocket motor (HRM) differs from that

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https://doi.org/10.1016/j.actaastro.2017.10.012
Received 12 August 2017; Received in revised form 27 September 2017; Accepted 6 October 2017

Nomenclature

a	regression rate coefficient
A_b	combustion area (m^2)
G_o	oxidiser mass flux (kg/m^2s)
ID	inner diameter
I_{sp}	specific impulse
m	mass (kg)
n	flux exponent
OD	outer diameter
O/F	oxidiser to fuel ratio
$\dot{r}$	regression rate (mm/s)
r_f	regression rate (mm/s)
t_b	combustion time (s)
ρ_f	fuel density (kg/m^3)
HTPB	hydroxyl-terminated polybutadiene
HRM	hybrid rocket motor
SRM	solid rocket motor
LRM	liquid rocket motor
PMMA	polymethyl methacrylate
GOX	gaseous oxygen

within a solid rocket motor (SRM) with the separation of the oxidiser from the solid fuel grain, which resides in the combustion chamber. Combustion initiates when the oxidiser is either pumped or allowed to flow under pressure past the fuel grain surface, through either a single port or multiple ports. The number of ports is determined by the regression rate of the fuel material, and the required thrust. This combustion mechanism allows for the development of a flame zone above the exposed fuel surface and varies along the length of the port due to the changing O/F ratio. Classical fuels such as HTPB have very low regression rates as a result of the dominant boundary layer combustion mechanism. Non-classical fuels, such as paraffin wax have a mechanical combustion mechanism referred to as droplet entrainment in addition to the boundary layer mechanism, which promotes faster regression of the fuel. The focus of this review is the effect of additives on the non-classical combustion mechanism of paraffin wax through empirical means. However, a brief overview of both mechanisms is included for reference.

2.1. Classical hybrid combustion

Boundary layer combustion is a result of fuel vaporisation. The primary combustion region is shown to be within a relatively narrow flame zone located within the boundary layer [1], depicted in Fig. 1. The various forms of heat transfer allowing for fuel vaporisation include convection and radiation from the flame zone. Vaporised fuel is transferred away from the heated fuel surface towards the flame zone. Un-combusted oxidiser is moved from the main oxidiser stream to the flame by turbulent diffusion. The stoichiometric conditions of the reaction define the position of the flame within the boundary layer. The rate of the combustion reaction, which is dependent on pressure and temperature, determines the flame thickness. Other factors which affect the development of the boundary layer include chamber pressure, gas temperature, gas composition, mass flow rate, port length, and port diameter [2]. Classical combustion is limited by the diffusive heat transfer to the fuel surface, resulting in slow regression rates. There has been significant work conducted in the diffusion limited classical combustion mechanism defining the regression rate of these types of fuels and the reliance on the position of the flame zone within the boundary layer as well as the heat of gasification. This problem is highly complex and is beyond the scope of this review, however detailed work on the heat and mass transfer between chemically reacting liquids has been conducted by numerous researchers leading to adequate regression rate laws [3,4].

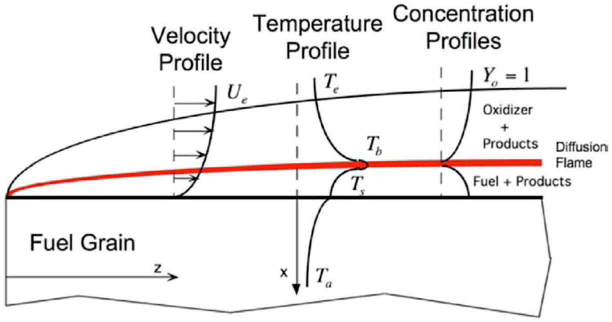

Fig. 1. Schematic of the classical hybrid fuel combustion mechanism [5].

There have been some methods discussed for testing and enhancing the regression rate of classical hybrid fuels. To name a few, authors such as Gariana et al. developed a 2D HTPB/GOX slab motor to compare combustion results to a numerical simulation developed [6]. Li et al. investigated the increase in the average regression rate when using swirl injectors. The impinging injectors and oxidiser swirl resulted in an uneven burn [7]. Pei et al. considered the effect of altering the combustion chamber port geometry on the regression rate and combustion efficiency of the motor [8]. These modifying techniques indicated an increase in performance measures, but the effects did not result in a performance enhancement similar to that of high regression rate fuels which do not rely primarily of diffusive heat transfer.

2.2. Non-classical hybrid combustion

The identification of higher regression rate fuels has allowed hybrid rocket motor technology to develop further, addressing more practical requirements. The fundamental difference between the classical and non-classical combustion mechanisms is the formation of a low viscosity liquid layer on the regressing surface. These fuels, known as liquefying fuels, produce a thin, low viscosity, low surface tension liquid layer on the fuel surface during combustion. Instability of this liquid layer caused by the flow of oxidiser over the liquid surface results in the formation of waves, which promote the entrainment of droplets into the gas stream, increasing the overall mass transfer rate and combusting surface area. A schematic of this combustion mechanism can be seen in Fig. 2 [5].

The droplet entrainment significantly enhances the speed of regression, and thus addresses some of the classical hybrid performance concerns. The increased regression rate of these fuels reduces the need for multi-port designs, and thus overly complex geometries and manufacturing techniques. This fuel diffusion invention was patented by Karabeyoglu et al. [9,10] in which they developed a method of identifying hydrocarbon fuels that are solid at room temperature, have a mean carbon number between 15 and 80, and have a low molecular weight

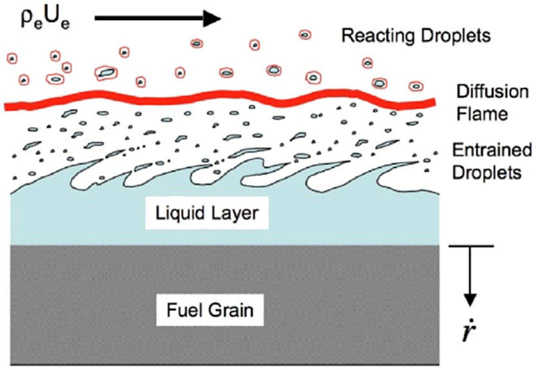

Fig. 2. Liquefying fuel entrainment mechanism [5].