INVESTIGATION OF END-BURNING TYPE HYBRID ROCKET MOTOR DOPED WITH HIGH ENTROPY ALLOY

BY

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A thesis submitted in fulfilment of the requirement for the degree of Master of Science in Engineering

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OCTOBER 2023

ABSTRACT

Hybrid rocket motors (HRMs) have become an attractive propulsion system due to their advantages over solid and liquid rockets, such as safety, environmental friendliness, low cost, and typically not containing toxic additives. However, low regression rate and poor combustion efficiency are critical weaknesses that affects the performance. To address this issue, extensive investigations have been conducted on the end-burning hybrid rocket (EBHR) doped with high entropy alloys (HEAs) to improve the regression rate and increase combustion efficiency. Static firings were conducted to obtain the thrust, regression rate and specific impulse. Simulations were also performed using NASA CEA software to assess HEAs' performance in HRMs. The characteristic velocity, specific impulse, and adiabatic flame temperature were the propulsive parameters analyzed. The present investigation focuses on a single port EBHR utilizing paraffin wax doped with HEAs as the fuel. Experimental results showed that the inclusion of 5% HEAs contributed to a 45.4% increase in the regression rate, 28.03% increase in thrust, and 25.89% increase in specific impulse compared to pure paraffin wax. The EBHR demonstrated an overall lower performance compared to the conventional HRM due to unstable combustion throughout the firings. According to the simulations, the higher the HEAs' concentration, the better it performs at an oxidiser-to-fuel ratio (O/F) of 1.0-1.3. Gaseous oxygen (GOX) as the oxidiser provides the best performance overall but hydrogen peroxide (H_2O_2) performs better at O/F greater than 4. The experiments and simulations demonstrate the potential of HEAs to enhance the regression rate, thrust, and specific impulse of HRMs. End-burning has also shown no fluctuations of O/F and chamber pressure during steady-state, which might be helpful in some applications. The findings also highlight the influence of initial fuel mass, mass flux, and HEAs' concentration on the hybrid rocket's performance. These improvements can expand the range of applications for hybrid rockets and contribute to the growth of commercial space activities, scientific research, and space exploration efforts.

ملخص البحث

أصبحت محركات الصواريخ الهجينة نظام دفع جذابًا نظرًا لمزاياها على الصواريخ الصلبة والسائلة ، مثل السلامة والود البيئي والتكلفة المنخفضة ، وعادة لا تحتوي على إضافات سامة .ومع ذلك ، فإن انخفاض معدل الانحدار وضعف كفاءة الاحتراق هي نقاط ضعف حرجة تؤثر على الأداء .لمعالجة هذه المشكلة ، تم إجراء تحقيقات مكثفة على الصاروخ الهجين المحترق النهائي المطعم بسبائك إنتروبيا عالية لتحسين معدل الانحدار وزيادة كفاءة الاحتراق .تم إجراء عمليات إطلاق ثابتة للحصول على الدفع ومعدل الانحدار والاندفاع المحدد .كما تم إجراء عمليات المحاكاة باستخدام برنامج لتقييم أداء سبائك الإنتروبيا العالية في محركات الصواريخ الهجينة .كانت السرعة المميزة ، والاندفاع المحدد ، ودرجة حرارة اللهب الأديباتية هي المعلمات الدافعة التي تم تحليلها .يركز التحقيق الحالي على صاروخ هجين مشتعل من طرف واحد يستخدم شمع البارافين المطعم بسبائك إنتروبيا عالية كوقود .أظهرت النتائج التجريبية أن إدراج سبائك الإنتروبيا المرتفعة بنسبة 5٪ ساهم في زيادة معدل الانحدار بنسبة 45.4٪ وزيادة 28.03٪ في الدفع و 25.89 %زيادة في الاندفاع النوعي مقارنة بشمع البارافين النقي .أظهر الصاروخ الهجين المحترق النهائي أداءً أقل بشكل عام مقارنة بمحرك الصواريخ الهجين التقليدي بسبب الاحتراق غير المستقر في جميع أنحاء عمليات إطلاق النار .وفقًا للمحاكاة ، كلما زاد تركيز سبائك الإنتروبيا العالية ، كان أداؤها أفضل بنسبة مؤكسد إلى وقود 1.0-1.3 .يوفر الأكسجين الغازي كمؤكسد أفضل أداء بشكل عام .ولكن بيروكسيد الهيدروجين يعمل بشكل أفضل في المؤكسد إلى الوقود أكبر من 4 توضح التجارب والمحاكاة إمكانات سبائك الإنتروبيا العالية لتعزيز معدل الانحدار ، والدفع ، والاندفاع المحدد لمحركات الصواريخ الهجينة .لم يظهر الحرق النهائي أيضًا أي تقلبات في ضغط المؤكسد إلى الوقود وضغط الغرفة أثناء الحالة المستقرة ، مما قد يكون مفيدًا في بعض التطبيقات . تسلط النتائج الضوء أيضًا على تأثير كتلة الوقود الأولية ، وتدفق الكتلة ، وسبائك الإنتروبيا العالية على أداء الصاروخ الهجين .يمكن لهذه التحسينات توسيع نطاق تطبيقات الصواريخ الهجينة والمساهمة في نمو أنشطة الفضاء التجارية والبحث العلمي وجهود استكشاف الفضاء.

APPROVAL PAGE

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DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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ACKNOWLEDGEMENTS

In the Name of Allah, the Most Gracious, the Most Merciful. All praise is given to Allah for granting the power and abundance of benefits necessary to complete this report.

My supervisor, Asst. Prof. Dr. Muhammad Hanafi Azami, deserves special recognition for his patience, enthusiasm, insightful remarks, essential insights, helpful information, practical guidance, and never-ending ideas, all of which have greatly aided me in my study and preparation of this report. His extensive knowledge, profound experience, and professional expertise in Aerospace Propulsion, particularly hybrid rockets, as well as his invaluable assistance with constructive comments and suggestions throughout the progress of my Masters in Semester I 2022/2023 and Semester II 2022/2023, have all contributed to the success of this research.

In addition, I am grateful to all lecturers in the Department of Mechanical Engineering for their generosity, hospitality, and technical support, as well as their permission to use the required equipment and materials after my project was completed. My heartfelt thanks to my loving parents, Sabri Mohd Arif and Rusna Md Zain, for their unending love, prayers, and encouraging words. I'd express my gratitude to all of my friends for their generosity and moral support throughout my studies. Your generosity means a lot to me, especially to those who contributed indirectly to my research. Thank you so much for everything.

Once more, we praise Allah for His unending generosity toward us, one of which has allowed us to successfully complete the composition of this thesis. Alhamdulillah.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

α	Regression rate coefficient
A_f	Fuel area
A_p	Port area
A_t	Nozzle throat area
A_e	Nozzle exit area
C_p	Specific heat
c^*	Characteristic exhaust velocity
$c_{ave}*$	Time-averaged characteristic exhaust velocity
$c_{th}*$	Theoretical characteristic exhaust velocity
ε	Nozzle expansion ratio
F	Thrust force
γ	Specific heat ratio
G_f	Fuel mass flux
G_o	Oxidiser mass flux
g_o	Gravitational constant
I_{sp}	Specific impulse
K	Thermal conductivity
λ	Nozzle efficiency
L_p	Port length
M	Molar mass
M	Mass
M_e	Exit mach number
$\dot{m}_f$	Fuel mass flow rate
$\dot{m}_o$	Oxidiser mass flow rate
n	Mass flux exponent
η_{c^*}	Characteristic exhaust velocity efficiency
O/F	Oxidiser-to-fuel ratio
P_a	Ambient pressure

P_c	Chamber pressure
P_e	Exit pressure
ρ_f	Fuel density
ρ_o	Oxidiser density
$\dot{r}$	Regression rate
R	Gas constant
R_o	Fuel grain outside radius
T_f	Flame temperature
V	Volume
V_i	Chamber inlet velocity
X	Amount of substances

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

Rocket propulsion can be classified based on the type of rocket engine and propellant employed. The three main categories are liquid, solid, and hybrid rockets. In a liquid rocket, the fuel and oxidiser are stored separately and combined in the combustion chamber. On the other hand, solid rocket propellants are pre-mixed and enclosed in a sturdy container.

This study specifically focuses on hybrid rocket motors (HRMs), which combine either a liquid or gaseous oxidiser with solid fuel. HRMs offer numerous advantages over traditional liquid or solid rocket propulsion systems, including enhanced safety, simplified fuel management, throttling capability, and environmental benefits. These factors have led to increased research and application of HRMs. Due to their ability to easily control the oxidiser mass flow rate, HRMs are well-suited for applications requiring variable thrust rockets in diverse scenarios.

However, conventional hybrid rockets have multiple disadvantages related to propulsion efficiency when compared with solid and liquid propellant rockets, which are low regression rate, combustion inefficiency, and fluctuating oxidiser-to-fuel ratio (O/F) throughout firing and throttling operations. End-burning combustion, where the combustion occurs at the end of the fuel surface, was reported to solve the O/F fluctuations problem. Using metallic additives have also proven to increase the performance of HRMs.

In this research, fuel doped with high entropy alloys (HEAs) and end-burning combustion are studied for their impact on the performance of the HRMs. HEAs are metallic additives that studies claimed to have better catalytic performance than conventional alloys due to their high surface area and vital adsorption energy. The context of the research significance, problem statement, research philosophy, research objectives, research methodology, research scope, and thesis structure are all discussed in this chapter.

1.2 RESEARCH SIGNIFICANCE

There is currently a growing emphasis on enhancing propulsion safety, reducing costs, using environmentally friendly fuels and oxidisers, and achieving high functionality in propulsion systems. As a result, there has been an increased interest in hybrid propulsion systems. This interest is reflected in the involvement of various entities such as government agencies, large corporations, academic research institutions, and small enterprises in the research and development of hybrid rocket technology. These collective efforts have led to notable advancements in hybrid rocket propulsion, as documented by Chiaverini and Kuo (2007). In recent times, hybrid propulsion systems have gained significant attention as a viable option for launching satellites and other spacecraft.

The hybrid rocket propulsion system is being investigated in many areas of space transportation since it is relatively safe and has a higher capability for environmentally friendly technology compared to some other rocket propulsion technologies. On the other hand, the low regression rate is a significant drawback that prevents the widespread application of HRM. The limitations that continually occur in the hybrid propulsion system can be solved by conducting research and analytical investigation on the end-burning mode of the hybrid rocket, which is projected to increase the regression rate, and reduce O/F shift. The utilization of HEAs, which is reported to exhibit remarkable qualities such as improved mechanical and chemical properties, enhanced hardness, high fracture strength, yield stress, and plastic strain compared to conventional alloys, should also be investigated (Dada et al., 2019).

1.3 PROBLEM STATEMENT

The lower regression rate of HRMs compared to solid and liquid rocket motors is one of the main problems. A low regression rate limits the rate at which the solid fuel grain is consumed, resulting in lower thrust levels and propulsion effieciency. The correlation between the regression rate and the combined mass flux of the fuel and oxidiser is directly proportional. Several variables, including the viscosity of the propellant, flame zone and the wall’s enthalpy difference, blowing factor, fuel’s density, solid fuel’s vaporization, and gas’ velocity at the boundary layer and down the flame zone, affect the rate of fuel mass flux on the surface. Thermochemical characteristics primarily influence these parameters. The O/F shift in conventional HRM contributes to the combustion efficiency, influencing the regression rate.

Therefore, end-burning combustion will be used in this study as it is stated that there is no O/F shift in this mode. The thermochemical reaction of fuel can be altered by changing the fuel compositions. HEAs are viewed as a promising energetic metal additives compared to conventional alloys because of their high surface area and crucial adsorption energy. The nanosized HEAs catalyst is anticipated to boost regression rate and hence improve combustion efficiency of the propulsion system. The necessity for complex geometry to produce the necessary thrust will be eliminated by the significant increase in regression rate that is achieved. The focus of this study will be on the use of HEAs in HRM.

1.4 RESEARCH PHILOSOPHY

One of the innovative ideas for chemical rocket propulsion is the HRM. Due to its distinctive interior ballistic architecture, it stimulates in-depth propulsion studies. Although these investigations were conducted decades ago, most of them focused on improving the regression rate using vortex injectors, metal additives, fuel grain geometric modifications, and surface layer fuels that have been liquefied. There is, however, limited research on end-burning combustion and the effects of HEAs doping on liquefying fuels from the surface layer, such as paraffin wax (PW). Therefore, this research project aims to examine the functionality of a HEAs-doped end-burning lab-scaled HRM.

1.5 RESEARCH AIM AND OBJECTIVES

The aim of this project is to investigate the performance of the end-burning HRM using PW fuel doped with HEAs. To achieve this aim, the following objectives are highlighted:

1. To investigate the performance of end-burning HRM in terms of thrust, regression rate and specific impulse analytically.

2. To study the properties of HEAs as metallic additives in HRM in terms of characteristic velocity, specific impulse and adiabatic flame temperature.
3. To formulate and compare new empirical regression rate correlation utilizing the experimentally designed fuel.

1.6 RESEARCH METHODOLOGY

Analytical analysis and experimental data provide the foundation of this study. Following is the research approach used:

1. Analytical calculations and preliminary design are developed. The design and analysis were based on previous works.
2. Fabricate PW fuel doped with HEAs.
3. Conduct static firing of HRMs in a lab-scaled testing facility.
4. Evaluate the experimental performance with the analytical calculations.

1.7 RESEARCH SCOPE

The proposed hybrid rocket fuel doped with HEA and end-burning combustion might be able to increase the regression rate and boost combustion efficiency; however, this research is constrained by several restrictions. The HRM was studied at the lab scale with static firing because the primary goal of this research is to find ways to enhance the regression rate. For static firing, a sequence of circular port fuel is utilized. The essential parts are the feeding system, combustion chamber, nozzle, and data-collecting system. This research did not focus on the characterization of the mixture between HEAs and PW fuel.

The study did not consider the effects of aerodynamics or fuel structure for simplicity and early research. The equilibrium chemical reaction was thought to occur very slowly and be fully reacted in a frozen flow. In the analytical investigation, some parameters and ideal conditions were also assumed. The HRM’s performance was assessed by evaluating the thrust, inlet and chamber pressure, and chamber temperature at various HEAs compositions.

1.8 THESIS STRUCTURE

There are five chapters in this thesis. The overview of this research is briefly discussed in Chapter 1. Along with the problem statement, research significance, research objectives, research methodology, and research scope are also included.

A review of related literature is included in Chapter 2 to highlight and explain the parallels and differences between this research and earlier studies, particularly regarding the lab-scale end-burning hybrid rocket (EBHR) design and additives used.

The preliminary design and the analytical approach used to analyze the performance of HRMs are covered in Chapter 3. Additionally, this chapter has the explanation on the design and construction of a lab-scale HRM. The lab-scale HRM's parts are exhaustively detailed.

The outcomes of the analytical and experimental work are thoroughly analyzed and evaluated in Chapter 4. This chapter explored the evaluation and analysis of the HRMs' performance using different design characteristics. The results were compared to demonstrate the dependability and precision of the analytical computations.

The research projects discussed in the earlier chapters are summed up and concluded in Chapter 5. Additionally, recommendations and potential future projects are also included.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The goal of improvements in rocket propulsion is always to achieve higher performance, improved dependability, and lower production costs. Hybrid rocket technologies will be the main topic of this literature review. The regression rate is a metric used in assessing the HRM's performance. The rate of fuel surface regression during a burn is known as the regression rate; the higher the regression rate, the better the performance. Conducting the combustion in end-burning mode is one of many investigations and tests to improve the rockets' regression rate. For end-burning, the combustion occurs at the fuel end towards the rear of the chamber. This literature review will concentrate on the end-burning mode's potential in hybrid rocket propulsion.

Comprehension of the rocket systems' structure, internal ballistic, theoretical knowledge, and prior research is needed to understand the significance of end burning on the regression rate in an HRM. The relevant background information on rocket propulsion is explained in this literature study for a better understanding of the HRM. The classifications and descriptions of various rocket systems will be covered in this chapter, focusing on the hybrid rocket, which will be the subject of the entire study. The development of the rocket system from its inception to the established and current initiatives of the twenty-first century is depicted in the history of the hybrid rocket system, which will also be covered. A hybrid rocket's benefits, drawbacks, and mitigations to each issue are covered in detail. The two chapters' final section will discuss the concept of end burning, its effect on the HRM, and high entropy alloy.

HRM uses liquid and solid propellants, which are kept in separate tanks. In addition to the traditional design, hybrid propellant systems can come in mixed hybrid or tribrid configurations. The most typical arrangement, known as the "classical configuration," uses solid fuel in conjunction with a liquid or gaseous oxidiser. Inverse hybrid vehicles run on liquid fuel and solid oxidisers. Because solid oxidiser is challenging to manufacture, it is not as feasible as the preceding version.

In a tribrid configuration, a mixture of solid oxidiser combined with solid fuel undergoes combustion with a separate liquid oxidiser. The various configurations were created to increase the regression rate, a critical problem with hybrid rockets. The fuel regression rate determines the total mass flow rate and total oxidiser-to-fuel mixture ratio, which regulate the specific impulse and thrust for a specific chamber pressure.

The essential parts of an HRM are depicted in Figure 2.1. The oxidiser is delivered to the combustion chamber by a single fluid feed system managed by the main run valve. The liquid oxidiser typically converts into gas when it enters the chamber, and when the gas oxidiser travels over the solid fuel, it heats it. The solid fuel will pyrolyze into gas fuel at that point. As a result of the reaction involving the fuel and oxidiser in proximity to the solid fuel surface, a turbulent and reactive boundary layer is formed. The combustion process in the chamber of the hybrid rocket follows standard diffusion combustion principles. The most crucial element in measuring the effectiveness of the HRM is the regression rate, which represents the rate of solid fuel pyrolysis. It depends on the circumstances surrounding gasification and the amount of thermal energy used during gasification (Zhao et al., 2018).

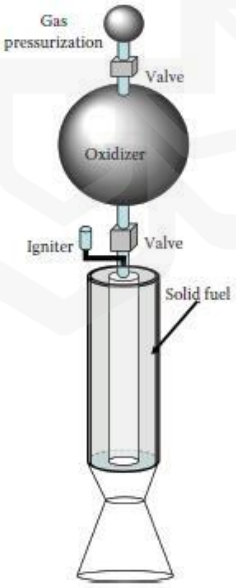

Figure 2.1 Schematic of a hybrid rocket (Travis, 2017)

2.2 INTERIOR HYBRID MOTOR BALLISTICS

The conventional hybrid configuration, where there is no oxidiser present in the fuel grain, leads to combustion occurring only in the gaseous phase. This causes notable differences in fuel surface regression rates compared to solid rocket engines. Sutton and Biblarz (2017) stated that the regression rate of the fuel surface is closely connected to the fluid dynamics of the combustion port and the transfer of heat to the surface of the fuel. The solid fuel needs to evaporate before combustion can take place.

The formation and expansion of a boundary layer over the fuel grain surface is believed to contain the primary combustion region. The surfaces of the fuel grain receive heat through radiation and convection. The specific characteristics of a hybrid motor are heavily dependent on the propellant used, as well as the size and arrangement of the combustion chamber, which are typically determined through empirical research. Figure 2.2 provides an illustration of the HRM combustion operation for a non-metallized fuel system (Sutton & Biblarz, 2017).

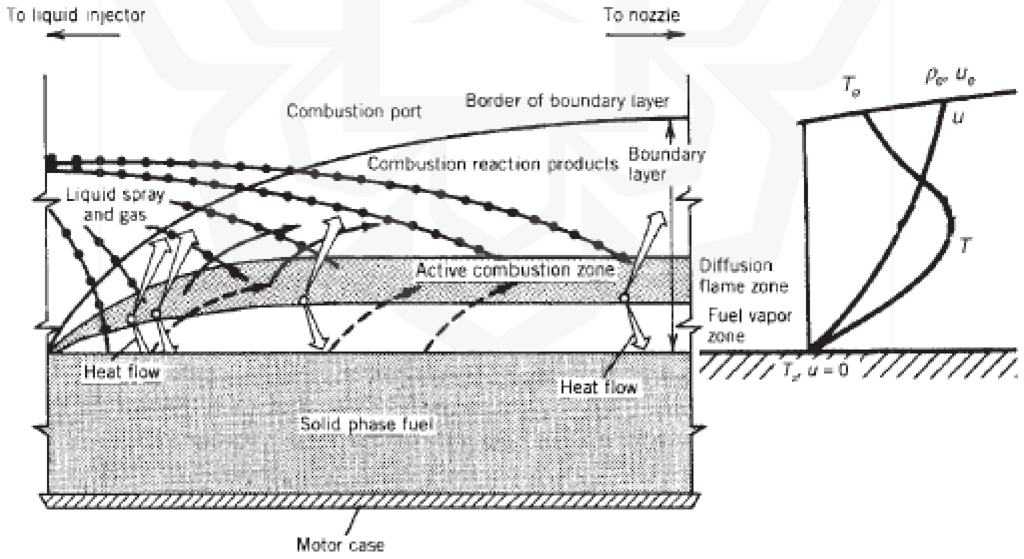

Figure 2.2 Illustration of a diffusion-controlled HRM combustion operation (Sutton & Biblarz, 2017)

According to Sutton and Biblarz (2017), fuel that has evaporated due to the heating of the flame zone flows away from the surface and into the flame region while oxidiser convects by turbulent diffusion from the free stream to the flame zone. The boundary layer location where the flame first appears is solely dictated by the stoichiometry necessary for combustion. The rate of oxidation reactions plays a significant role in determining how thick this flame zone is. These rates often follow an exponential relationship with temperature and are heavily influenced by local pressures.

In addition to pressure and gas temperature, other variables that influence the formation of the fuel-grain boundary layer and, consequently, the features of fuel regression include grain design, oxidiser mass flow rate, port length, and cross-sectional area. Convection is thought to transfer heat much more effectively than gas-phase radiation or radiation from soot particles in the flow with non-metallised fuel grains. As a result, investigations of convective heat transfer in a turbulent boundary layer can be used to investigate the fundamental properties of fuel grain regression. For the fuel regression rate, $\dot{r}$, the following equation may be used:

$$\dot{r} = a(G_o)^n \tag{1}$$

G_o is the oxidiser mass velocity, which is calculated by dividing the oxidiser mass flow rate by the cross-sectional area of the combustion port. Additionally, the constants a and n are determined via empirical fitting. This equation suggested that HRM’s fuel regression rates are strongly dependent on G_o.

2.3 ADVANTAGES OF HYBRID ROCKET

HRMs offer distinct advantages over both liquid and solid-fueled rockets, with a combination of evident and subtle benefits. One of the primary advantages of HRMs is their safety. HRMs typically utilize inert solid fuel grains, and their burn rate is determined by the mass flux rate of the oxidizer. This design makes the propellant grain more forgiving of manufacturing flaws, such as cracks, reducing the risk of catastrophic failures. Moreover, since the fuel and oxidizer are stored separately until combustion, HRMs have fewer potential failure modes.

Consequently, the risk of explosions is greatly diminished. Handling precautions are also less stringent compared to solid-propellant rockets, which require extensive inspections due to the non-explosive nature of propellants during the mixing phase in the combustion chamber. Additionally, the propellant grain is highly resistant