COMBUSTION CHARACTERISTICS OF AMMONIUM PERCHLORATE BASED SOLID ROCKET PROPELLANT

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A thesis submitted in fulfillment of the
requirement for the award of the degree of
Master of Mechanical Engineering

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

April 2011

Dengan nama Allah yang Maha Pengasih lagi Maha Penyayang..

Teristimewa buat ibu dan ayah yang tersayang, Ramlah Binti Jusoh dan Aziz Bin Othman. Begitu juga kepada Rokiah, Zaiton, Zainun, Razali, Razman, Zawiah, Abdul Razak serta Nur Zulika ...

Terima kasih atas sokongan dan berkat doa kalian sehingga aku mampu mencapai hingga ke tahap ini. Pengorbanan kalian semua tidak akan aku sia-siakan...

Amin..

Motivator terbaik adalah diri sendiri…

ACKNOWLEDGEMENT

All praises to Allah S.W.T, the Almighty God and the Lord of the Universe, the Merciful and Gracious. Salam to our beloved prophet, Nabi Muhammad s.a.w for His mercy has given me the strength, blessing and time to complete this project.

Words cannot express my thankfulness to my supervisor Prof. Ir. Dr. Wan Khairuddin Wan Ali who relentlessly providing me guidance throughout the study with his knowledge and great patience. Both his dedications and passions toward science have inspired me a lot. His encouragement is always with me all through my study years. Without his endless support and guidance, I certainly will not be able to accomplish this thesis and presented.

Thank you to Malaysia Space Agency (ANGKASA) and Ministry of Science, Technology and Innovation (MOSTI) for funding my research and scholarship. I extend my gratitude to Prof. Dr. Subramaniam Krishnan, Mr. Yaheyia Aldreany and Mr. Wan Zaidi, who wealthily shared their experience and knowledge on the rocket propellant and combustion analysis. I express my deep sense of gratitude and indebtedness to our research officers and team members, Miss Zuriana, Mrs. Intan, Mr. Rozi, Mrs. Norazila and all staffs of Aeronautic laboratory for their guidance, advices and motivation while completing this project.

Last but not least, the biggest appreciation to my parent and family and also to everyone for their precious contribution and a warm thank for all the support given.

Thank you…

ABSTRACT

There were many studies on ammonium perchlorate (AP) based solid rocket propellant (SRP) and some data already exist. However, there is no complete data available in Malaysia especially the information on the combustion characteristics of baseline data of AP based SRP. This thesis discusses on the combustion characteristics of AP based SRP including the methods of the propellant selection and fabrication, burning rate test and static thrust test. Together with literature study and theoretical performance, thirteen sets of different propellant mixture were finalized with consideration of the mechanical and processability factors. The propellant was a mixture of AP as an oxidizer, Aluminum (Al) as fuel and Hydroxy-Terminated Polybutadiene (HTPB) as binder/fuel. For each mixture, HTPB binder was fixed at 15% and cured with Isophorone isocyanate (IPDI) (9.33% per mass of HTPB). The percentage of the solid materials was set at a constant value of 85%. By varying the AP and Al, the effect of oxidizer-fuel (O/F) ratio on the whole propellant can be determined. The propellant strands were manufactured using press-molding method and burnt in the strand burner at ambient pressure to obtain the initial burning characteristics. Then four propellant compositions were selected, namely p60, p66, p74 and p80 for further evaluation over a range of pressure from 6 atm to 31 atm. The results show that the increasing of O/F ratio and combustion pressure lead to the increase in burning rate. The fastest burning rate achieved was 12 $mmsec^{-1}$ at combustion pressure of 31 atm for propellant p80 which has O/F ratio of 4.0. It was found that, the formulated propellant in this study have the normal burning characteristics with pressure exponent lies within the range of 0.501 to 0.561. Based on theoretical evaluation, formulation for p66 gives highest specific impulse, I_{sp}. Thus, p66 has been selected to be evaluated in static thrust testing to obtain its performance characteristics. The results showed that the maximum thrust obtained is 162 N with generating I_{sp} of 143.92 sec.

ABSTRAK

Kajian mengenai bahan dorong yang berasaskan ammonium perchlorate (AP) telah banyak dijalankan dan sebahagian data telah diperoleh. Walaubagaimanapun, tiada maklumat lengkap mengenai data-data asas bagi cirian pembakaran bahan dorong yang berasaskan AP di Malaysia. Tesis ini merupakan kajian mengenai cirian pembakaran bahan dorong berasaskan AP yang meliputi kaedah pemilihan dan penyediaan bahan dorong, ujian kadar pembakaran dan ujian daya tujah statik. Berdasarkan kajian literatur dan prestasi andaian ini, tigabelas set campuran bahan dorong telah dipilih selepas mengambil kira faktor mekanikal dan kebolehsediaan. Bahan dorong ini mengandungi AP yang bertindak sebagai bahan pengoksida, aluminum (Al) sebagai bahan bakar dan hydroxy-terminated polybutadiene (HTPB) sebagai bahan pengikat/bahan bakar. Bagi setiap campuran, HTPB telah ditetapkan sebanyak 15%. Manakala bahan silangrantainya adalah isophorone diisocyanate (IPDI) (9.33% daripada berat HTPB). Peratusan bahan pepejal pula telah dimalarkan pada nilai 85%. Kesan nisbah bahan pengoksida-bahan bakar, O/F untuk keseluruhan bahan dorong boleh diperoleh dengan mengubah kandungan AP dan Al. Jalur bahan dorong disediakan dengan menggunakan kaedah acuan mampat dan dibakar di dalam pembakar jalur pada tekanan atmosfera bagi memperoleh cirian pembakaran awal. Kemudian, empat komposisi bahan dorong iaitu p60, p66, p74 dan p80 telah dipilih bagi kajian lanjutan di bawah tekanan antara 6 atm hingga 31 atm. Keputusan ujikaji menunjukkan bahawa peningkatan nisbah O/F dan tekanan kebuk merupakan faktor kepada peningkatan kadar pembakaran. Kadar pembakaran terpantas yang diperoleh adalah 12 $mmsec^{-1}$ pada tekanan kebuk 31 atm untuk bahan dorong p80 yang mempunyai nisbah O/F 4.0. Kajian mendapati keempat-empat formulasi bahan dorong dalam kajian ini mempunyai cirian pembakaran normal dengan nilai pekali tekanan, n antara 0.501 hingga 0.561. Berdasarkan kepada prestasi andaian, formulasi p66 menunjukkan nilai denyut tentu, I_{sp} yang tertinggi. Dengan itu, p66 telah dipilih untuk diuji dalam ujian daya tujah statik bagi memperoleh cirian prestasi. Nilai daya tujah tertinggi yang diperoleh adalah 162 N dengan nilai denyut tentu 143.92 saat.

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LIST OF SYMBOLS

A	-	Cross sectional surface area for the propellant strand
a	-	Empirical constant
AFT	-	Adiabatic flame temperature
AN	-	Ammonium nitrate
Al	-	Aluminum
Al_2O_3	-	Aluminum oxide
AO	-	Ammonium oxalate
AP	-	Ammonium perchlorate
atm	-	Atmosphere
a_{ij}	-	Number of atoms element *i* on the molecular formula
$AlOHCl_2$	-	Gidroksoalyuminiya chloride
BEM	-	Ballistic evaluation motor
BE	-	Beryllium
CEA	-	Chemical equilibrium application
CRV7	-	Canadian Rocket Vehicles 7
C17	-	Canadian 17
CTPB	-	Carboxyl terminated polybutadiene
CO	-	Carbon monoxide
CO_2	-	Carbon dioxide
C	-	Carbon
Cl	-	Chlorine
C_s	-	Specific heat solid, $\text{J mol}^{-1}\text{K}^{-1}$
C_p	-	Specific heat gas, $\text{J mol}^{-1}\text{K}^{-1}$
$C_{p_{gas}}$	-	Specific heat of gaseous, $\text{J mol}^{-1}\text{K}^{-1}$
$C_{p_{mix}}$	-	Specific heat of mixture, $\text{J mol}^{-1}\text{K}^{-1}$
c^*	-	Characteristic exhaust velocity, m s^{-1}

C_F	-	Thrust coefficient
DAE	-	Department of Atomic Energy
DAQ	-	Data acquisition system
DDI	-	Dimeryl-diisocyanate
DOA	-	Dioctyl adipate
DOP	-	Dioctyl phatalate
etc.	-	et cetera
FE_2O_3	-	Ferum oxide
g	-	Gas or a vapor
g_o	-	Gravity, (9.81 m s^{-2})
HTPB	-	Hydroxyl terminated polybutadiene
HTPS	-	Hydroxy-terminated polyester
HTPE	-	Hydroxy-terminated polyether
HTPA	-	Hydroxy-terminated polyacetylene
H_2	-	Hydrogen
H_2O	-	Water
HCl	-	Hydrogen Chloride
H	-	Hydrogen (atom)
HC	-	Hydrocarbon
ISRO	-	India Space Research Organization
IPDI	-	Isophorone diisocyanate
I_{sp}	-	Specific impulse, sec
IDP	-	Isodecyl pelargonate
JANAF	-	Join Army-Navy- Air Force
KNO_3	-	Potassium nitrate
$KClO_4$	-	Potassium perchlorate
K	-	Kelvin
k_{mix}	-	Specific heats ratio of mixture
kg	-	Kilogram
$LiClO_4$	-	Lithium perchlorate
log	-	Logarithm to the base 10
L_p	-	Measured propellant length (mm)
l	-	Liquid

MDI	-	Methylene diphenyl diisocyanate
Mg	-	Magnesium
MSDS	-	Material safety data sheet
mol_s	-	Mole of species
m_s	-	Mass of species
$\overline{M}_s$	-	Molecular weight species
$\overline{M}$	-	Effective molecular weight
M	-	Mach number
m_{strand}	-	Mass of strand
m_t	-	Total mass
MAPO	-	Tris[l-(2-methyl) aziridinyl] phosphine oxide
NASA	-	National Aeronautics and Space Administration
NG	-	Nitroglycerin
NC	-	Nitrocellulose
NA	-	Not available
NH_4ClO_4	-	Ammonium perchlorate
N_2	-	Nitrogen
N	-	Nitrogen
n	-	Number of species
n_j	-	Mol of molecule in the balance chemical equation
n_i	-	Number of moles of gas components
n_s	-	Number of moles of condensed component
n	-	Total number of moles gas
$NaNO_3$	-	Sodium nitrate
O/F	-	Oxidizer to fuel mixture ratio
ODI	-	Octadecylisocyanate
O	-	Oxygen
OH	-	Hydroxide
P	-	Absolute pressure
P_a	-	Atmospheric pressure
P_c	-	Chamber pressure, bar
PBAN	-	Polybutadiene acrylonitrile

PU	-	Polybuatadiene
Psi	-	Pound per square inch
P_f	-	Final pressure
r	-	Burning rate, mm sec^{-1}
R_o	-	Universal gas constant, 8.314 $\text{J mol}^{-1}\text{K}^{-1}$
$R_{specific}$	-	Specific gas constant, $\text{J mol}^{-1}\text{K}^{-1}$
RTV	-	Room-temperature vulcanizing
SRP	-	Solid rocket propellant
S.E.M	-	Scanning electron microscope
S.W.G	-	Standard wire grade
TDI	-	Toluene-2,4 diisocyanate
TiO_2	-	Titanium Oxide
TPB	-	Triphenyl bismuth
T_e	-	Temperature at exit condition, K
t_b	-	Burning time, sec
T_f	-	Final temperature, K
UFAL	-	Ultra Fine Aluminum
$V_{s.b}$	-	Volume of strand burner, m^3
Zr	-	Zirconium
ΔU	-	Change in internal energy, kJ mol^{-1}
ΔH	-	Change in enthalpy, $H=U+PV$, kJ mol^{-1}
ΔH	-	Heat of combustion, kJ mol^{-1}
Δ	-	The increment in a given property for a given process or reaction, taken as the value for the final state (or sum for the products) less that for the initial state (or sum for the reactant)
ΔH_f^o	-	Standard enthalpy of formation, in which is the increment in enthalpy associated with the reaction of forming the given compound from its elements in their reference states, with each substance in its thermodynamic standard state at the given temperature, kJ mol^{-1}

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CHAPTER 1

INTRODUCTION

Ammonium perchlorate (AP) has been used as a major propellant ingredient for decades in ballistic missiles, military attack missiles, space applications, etc. It is known for its advantages as an oxidizer for solid propellant. Two main advantages of AP are, its stability, resulting in safe munitions, and its ability to control a propellant's burning rate.

There were a lot of studies from those who used AP based propellant and some of the data are already existed. However, there is no complete information on the characteristic of the baseline data of AP based solid rocket propellant as well as the device and technique used to get the data. Knowing the limited data and technique used is not enough since other parameters such as the size and type of device used to generate the baseline data is not fully taken into account, then the data cannot be correctly interpreted and errors due to the scale up may result.

Fundamental study had been conducted to obtain the data of characteristic for AP based solid propellant by using facilities available in UTM. The current study was based on a typical and established heterogeneous or sometimes called composite propellant composed of ammonium perchlorate (AP) as an oxidizer, aluminium (Al) as a metal fuel, hydroxyl terminated polybutadiene (HTPB) as a binder and isophorone diisocyanate (IPDI) as a curative agent. In this study, by varying the oxidizer-fuel mixture ratio it is possible to achieve different propellant burning rates. The burning characteristics of propellant were obtained by using a strand burner.

The performance characteristics of AP base solid rocket propellant (SRP) was evaluated using a ballistic evaluation motor (BEM) or also known as static thrust testing to obtain another important parameter, which is the specific impulse. Although both measuring technique and devises used will introduce errors, accurate prediction is possible by establishing a correlation between subscale test motor and strand burner test.

1.1 Objective of the Study

To determine the combustion characteristics data of the developed ammonium perchlorate based solid rocket propellant (SRP).

1.2 Scope of Study

I. Literature review on applications of AP in solid rocket.
II. Theoretical study on the performance of AP based SRP using NASA CEC71 program.
III. Evaluate the burning rate of AP based SRP at different O/F ratio and at different operating pressure using strand burner.
IV. Conduct the static thrust testing.

1.3 Research Methodology

The research was started with literature studies on rocket propellants, especially solid rocket propellants. The study focused on the history and development of rocket technology in the world. Then, the methods that could be used to measure and analyze the burning rate of propellant had been studied and understood in order to find the most appropriate method to be used with the facilities available in UTM.

Lastly, the basic ingredients that commonly used in composite solid propellants were reviewed.

After that, theoretical study on the performance of AP based SRP were conducted by using NASA CEC71 program. Based on the literature reviewed, previous experience and the theoretical performance, thirteen sets of propellant formulation were fabricated with a different oxidizer-fuel mixture ratio.

Initially, the burning characteristic of all propellant formulations were evaluated at an atmospheric condition by using the strand burner. From that, four main formulations were selected and tested at the elevated pressure range of 6 atm to 31 atm. Finally based from the theoretical evaluation by NASA CEC71 program, one optimum mixture namely p66 had been chosen for static thrust testing to obtain the performance characteristics. All the documentation of the work done and literature review related to this study were continuously carried out throughout this research study.

1.4 Outline of Report

The report on this study is divided into six chapters. Chapter 1 provides the general introduction on the study and it include the objectives, scopes, research methodology and outline report of the study was briefly explained.

Chapter 2 presents literature reviews on solid rocket propellants. The reviews start with the history and development of rocket technology around the world. Then, discussion on basic ingredients that commonly used in composite solid propellants is presented. At the end of this chapter is a brief explanation on the methods that could be used to measure and analyze the performance characteristics of a propellant.

Chapter 3 starts with the basic assumptions that must be made in order to simplify the analysis of a rocket motor. Then an example of a propellant analysis of a given propellant formulation is presented. After that, several theoretical approaches to determine the thermochemical properties for a given propellant formulation such as chamber pressure, nozzle dimensions, and nozzle exit pressure are briefly discussed. Finally, it discussed the method utilized to determine the main performance parameter such as theoretical specific impulse, characteristic exhaust velocity, thrust coefficient and *etc*.

Chapter 4 discussed the three main contributors that significantly influence the selection of a propellant formulation and they are the literature review data, NASA CEC71 program and type of the fabrication method to be used. Then, the methods of preparing the ingredients were shown and explained which later followed by the mixing procedure. Finally the method that is used to prepare the propellant mixture and fabrication of the propellants strand for burning rate test is briefly explained.

Chapter 5 explained the methods and facilities employed for burning rate test. Firstly, the propellants were tested in the strand burner at the ambient pressure by using wire technique to obtain the initial burning characteristics. Then, four propellant compositions which are the p60, p66, p74 and p80 were selected for further evaluation over a range of pressures from 6atm to 31atm. The results obtained were analyzed to find the effect of oxidizer-fuel mixture ratio and chamber pressure to the burning characteristics of the propellant.

Chapter 6 discussed the static thrust testing that was conducted to obtain the thrust time curve characteristics in order to obtain the actual performance of a solid propellant. Final chapter summarized several conclusions and recommendations that could be considered for the next researcher to improve and advancing further the research on ammonium perchlorate based solid propellant.

1.5 Limitation of Study

1. The fabrication of the propellant only utilized press molding method without detailed study on other methods such as casting and extrusion. There was also no study on the effects of varying compression pressure to the burning rate and mechanical properties of the propellant.

2. The purpose of utilizing SEM was to study the structure of the solid loading such as aluminum and ammonium perchlorate in the propellant grain. There was no detailed study on eliminating bubbles in the propellant.

3. The purpose of static thrust test was to obtain the thrust and some performance characteristics. Due to the limitation of scope, there was only two static thrust testing were conducted.

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