RESEARCH ARTICLE | FEBRUARY 02 2018

Feasibility study of palm-based fuels for hybrid rocket motor applications FREE

M. Tarmizi Ahmad; Razali Abidin; A. Latif Taha; Anudip; Amzaryi

AIP Conf. Proc. 1930, 020010 (2018)
https://doi.org/10.1063/1.5022904

Feasibility Study of Palm-Based Fuels for Hybrid Rocket Motor Applications

M. Tarmizi Ahmad[1, a)], Razali Abidin[1, b)], A. Latif Taha[1, c)], Anudip[1, d)] and Amzaryi[2, e)]

[1]Department of Mechanical Engineering, Faculty of Engineering, National Defence University of Malaysia, Kem Sg. Besi, Kuala Lumpur, Malaysia
[2]Department of Aerospace Engineering,Universiti Putra Malaysia, Serdang, Selangor, Malaysia

[a)]Corresponding author: m.tarmizi@upnm.edu.my
[b)]razalibidin@upnm.edu.my
[c)]latif@upnm.edu.my
[d)]aniduip@upnm.edu.my
[e)]m.amzaryi@upm.edu.my

Abstract. This paper describes the combined analysis done in pure palm-based wax that can be used as solid fuel in a hybrid rocket engine. The measurement of pure palm wax calorific value was performed using a bomb calorimeter. An experimental rocket engine and static test stand facility were established. After initial measurement and calibration, repeated procedures were performed. Instrumentation supplies carried out allow fuel regression rate measurements, oxidizer mass flow rates and stearic acid rocket motors measurements. Similar tests are also carried out with stearate acid (from palm oil by-products) dissolved with nitrocellulose and bee solution. Calculated data and experiments show that rates and regression thrust can be achieved even in pure-tested palm-based wax. Additionally, palm-based wax is mixed with beeswax characterized by higher nominal melting temperatures to increase moisturizing points to higher temperatures without affecting regression rate values. Calorie measurements and ballistic experiments were performed on this new fuel formulation. This new formulation promises driving applications in a wide range of temperatures.

INTRODUCTION

Large demand for safe and low commercial space applications increases interest in hybrid rocket propulsion systems (HRP). Hence, several government labs, large industrial enterprises, academic research institutes and small bases undertook rocket research and development efforts led during the past decade for significant progress in HRP. Hybrid Rocket Motor (HRM) is a trademark that promotes space applications [1-2]. Many benefits are shown and realized in recent years as green combustion, acceptable performance and reliability, high reliability, reducing capabilities, low cost, high security and available technology.

HRM as a state of the art, requires continuous correction of some weaknesses of variation of performance parameters during testing (regression rate, space pressure, thrust and mass flow rate of fuel), low regression rate and low combustion efficiency [3-4]. In HRM, one of the supporters is solid fuel or solid fuel compound and the other is liquid oxidation or gas.

Different states and separation of fuels and oxidizers are the main reason for being better than solid or liquid propulsion.

This work begins with the usual research stage such as the design, manufacture, and establishing of a small HRM core laboratory. The initial designs produced and parameters verification for real designs can be used in the development of space adoption applications such as launch correction, orbit transfer, orbit correction and de-orbit missions. The objective is to predict variations in operating parameters during testing as space pressure, thrust, fuel mass flow rate, mix ratio and regression rate. It has been found that the most important parameter is convective heat

International Conference on Engineering and Technology (IntCET 2017)
AIP Conf. Proc. 1930, 020010-1–020010-7; https://doi.org/10.1063/1.5022904
Published by AIP Publishing. 978-0-7354-1622-2/$30.00

transfer and the radiation produced by the combustion process, which greatly influences the important regression rate parameters.

Research at Stanford University in late 1990 by [5] led to the identification of solid-burning paraffin fuels at regression rates of 3 to 4 times faster than polymeric fuels. Heat transfer from the combustion zone and gas flow action on the molten fuel surface leads to the formation of an unstable hydro-dynamic liquid film.

In [6], proposing a mechanism of mass transfer involving the penetration of liquid drops from surface liquid layers. The formation of droplets is due to the instability of the liquid layer, which is caused by high velocity gas flow at the port. Due to complex problems, modelling is done in three stages. Initially, the need for the formation of liquid layers on fuel cereals was investigated. In the second stage, the linear stability of thin liquid layers under the strong shear of the gas stream is considered.

Peregrine Sounding Program Rocket [7] is a collaborative effort between NASA Ames Research Center, NASA Wallops, Stanford University, and the Propulsion Group (SPG) in an attempt to test the hybrid liquid fuel to sound a rocket to a height of 100 km. In [8] started the propulsion system composed of liquid nitrous oxides and paraffin-based fuels, which provided a load of 5 kg to the set height. Further development on Paraffin waxes were done by [9].

UPNM researchers have developed a low-cost and efficient stearic acid-based fuel for hybrid rocket engines. Stearic acid is a vital renewable fuel for the future and when derived from palm oil, it can return high percentage in energy invested in its recovery. Stearic acid chemical and physical properties are comparable to paraffin wax which has a history of success as rocket fuel, though hybrid rockets require a fuel with sufficient yield strength, holding its shape during the acceleration of the rocket burn. The low cost of biofuel based on solidified stearic acid, rather than expensive petroleum derivatives, lowers the cost of many rocket launches, lowers the cost of access to orbit and provides safer sounding rocket flights to space. The advantages of biofuels can now be simply and safely apply to hybrid rockets while cutting costs.

The current research in paraffin based and bio-derived fuel has shown that the future space propulsion system shall use wax as the fuel for hybrid rocket motor. In view of the amount of fuel required, it is important to ensure that the fuel is green - less pollution and sustainable. Hence, the timely needs to study and develop palm oil-based wax as the future fuel for hybrid rocket motor.

The stearic acid hybrid fuel is safe to handle before injection of an oxidizer within the hybrid rocket engine. Researchers have chosen components creating exhaust with a high mass percentage of stearic acid and low molecular weight, meaning higher exhaust velocity and consequently an increase in thrust. With this new method of production, solid biofuels are now a low-cost fuel option.

The objective is to study the following combustion characteristics of palm oil based wax and gaseous oxygen hybrid system:

- Study of calorific values of different compositions of palm wax mixtures
- Regression rate and different injection pressures / GOX / N_2O_4 flow rate
- Mass consumption rate and different injection and combustion pressures
- Thrust and Specific impulse of above hybrid system

METHODOLOGY

The heat of combustion studies was carried out using bomb calorimeter and essential components like combustion chamber, injector and nozzle have been designed and fabricated for the purpose of the present studies. Design, fabrication, instrumentation and data acquisition of the static rocket engine test stand was also completed.

The following were works completed as up-to-date:

- Bomb calorimeter testing of pure stearic acid hybrid rocket engines and formulation of different palm fuel composition using certain additives like beeswax and nitrocellulose.
- Study the regression rate in hybrid test motor
- Determination of average rocket motor thrust and specific impulse

Bomb Calorimeter Tests

A Bomb Calorimeter Test facility was set up at the Mechanical Engineering Thermo-Fluid Laboratory. In this experiment, the calorific values of benzoic were found by using the bomb calorimeter. The experiment done by exploding the fuel by a wire in a calorimeter filled by known amount of water then the water temperature was recorded. The value is calculated by the energy balance between water and samples.

In this experiment, the standard enthalpy of combustion of benzoic acid and use its known heat of combustion to determine the heat capacity of a bomb calorimeter. Once the calorimeter has been calibrated, the enthalpy of combustion was measured for stearic acid, paraffin wax and beeswax for comparison purposes

Measurement of Regression Rate

Fuel regression is the rate at which solid fuel is burned over time. There are several theories and tests carried out since the 1930s to investigate the possibility of regression in hybrid rocket motors. The combustion process in the hybrid rocket motors is much more complicated than solid rocket because in hybrids. As solid fuel is burned, both the shape and the mass flux will change. Thus, this will affect the fuel regression and all the thermodynamic properties of combustion products and oxidation to the fuel ratio (O / F).

For the purpose of measuring the regression rate, the test was conducted by the combustion of hybrid rocket motors on static test stand.

Hybrid Rocket Engine Static Test

Rocket Engine

The total motion of the rocket engine is equal to the momentum released by the rocket engine. It is often expressed in units of force units such as Newton-seconds. The amount of rocket motion is equal to its thrust multiplied at the time available thrust. These parameters usually help models and high power rocket to categorize rocket engines according to grade.

$$I = F_{avg} t_b = m_p V_e \tag{1}$$

where I = Impulse, F_{avg} = Average Thrust, t_b = Burn Time, m_p = Mass of Propellant and V_e = Ejection Velocity. By dividing the above equation with burn time, we can obtain the propellant mass flow rate:

$$\dot{m}_p = \frac{m_p}{t_b} \tag{2}$$

where $\dot{m}_p$ = Propellant Mass Flow Rate, m_p = Mass of Propellant and t_b = Burn Time. By dividing the ejection velocity with gravitational acceleration, we can get a parameter called as specific impulse which is important in categorizing a rocket performance.

$$I_{sp} = \frac{V_e}{9.81} \tag{3}$$

where I_{sp} = Specific Impulse and V_e = Ejection Velocity.

Palm Oil Wax

Palm oil Wax or in stearic acid are scientific names derived from palm oil products by several processes. These Wax are in the simplest terms the type of high purity of vegetable fatty acids, especially triglycerides. They are palm oil products after being processed under flux pressure and extreme temperature pressures. From that process, Wax based on vegetables, vegan, 100% wax are produced.

Stearic acid or stearine 〚(C〛_18 H_36 O_2) is widely used in addition to the increase of combustion time, wax sharpener and helps improve the retention of fragrance in the extinguished wax. Stearine is actually derived from unscrupulous oils obtained by a process where oil palm bunches are pressed in the same way as pressed olive oil. It then becomes a bleach-like by absorbent clay, which removes dyes and impurities. Initially, the fruit is in bright orange because it contains a high amount of carotene. The oil is then discarded and sterilized by heating it at high temperatures. Lastly, a process called 'fractionation' is done to separate the fat from the liquid.

The fatty acids contained in palm oil comprise a large number of triglycerides (vegetable fat), each having their own melting point. At high temperatures, triglycerides will crystallize and crystals can be formed by the continuous cooling process around the pipe coil, which separates oil into different fractions. When the temperature is reduced, fat will continue to strengthen that will isolate the oil into liquid fat and vegetables that are present in solid state at room temperature. We can see the result as a palm wax, produced, from fractionation but without any additions or chemical solvents added.

Product Design Specification

Physical description

- Thrust produced: 265-350N
- Combustion chamber pressure: 0.8MPa
- Combustion chamber length: 0.4m
- Combustion chamber diameter: 0.066m
- Combustion chamber thickness: 0.002m
- Nozzle throat diameter: 0.0231m
- Nozzle exit diameter: 0.0467m
- Nozzle expansion ratio: 1.696
- Nozzle converging angle: 31.14°
- Nozzle diverging angle: 6.72°
- Chamber to throat length: 0.02781m
- Throat to nozzle exit length: 0.0989m
- Combustion chamber material: AISI 302 cold rolled stainless steel
- Nozzle material: AISI 1018 low-carbon rolled steel and graphite

Solid Fuel

The solid fuels used in this study are stearic acid 〚C〛 _18 H_36 O_2) derived from oil palm fruit and a combination of stearic acid 〚C〛 (18 ≈ H_36 O_2) and octadecyl octacosanoate (C_15 H_31 COOC_30 H_61).

Both types of solid fuel are made using several processes. For the first type of pure stearic acid fuel, the powder like stearic acid has melted so that it changes the condition into liquid. It is then poured into the mold, which will form the Wax into the certain dimensions required in the design. The mold is then left cool at room temperature.

For stearic acid mixed with the type of bee fuel, there is little difference in the fuel manufacturing process. First, stearic and beeswax acid weighing at the same weight, about 0.6kg, and then mixed together in aluminium bowls. Then, they are diluted together and put into molds to form a wax fuel according to specifications. After that, the mold is left cool at room temperature as well. We can see the process in more detail as follows:

1.2kg powder like stearic acid is filled into an aluminium bowl. The bowl is put in the oven to heat it until it melts. Liquid stearic state acid is poured into the mold. The mold is left cool at room temperature. Fully cooled fuel is extracted from the mold.

FIGURE 1. Hybrid rocket solid fuel

FIGURE 2. Hybrid rocket test

RESULTS AND DISCUSSION

Bomb Calorimeter Test

The adiabatic Bomb Calorimeter supplied by National Defence University of Malaysia (NDUM) Thermodynamic Laboratory is used to evaluate the calorific value of fuel of following three compositions:

TABLE 1. Calorific values of stearic acid mixtures

S/N	Composition-1	Composition-2	Composition-3
Fuel	Palm-based Wax (100%)	Palm-based Wax (50%) Bees Wax (50%)	Palm-based Wax (50%) Nitrocellulose (50%)
Calorific Value	10056 Cal/g	10538 Cal/g	10107 Cal/g

It is found that the calorific value of pure palm-based (stearic acid) wax alone and the sample composed of palm Wax-nitrocellulose are same whereas the sample composed of palm wax- beeswax much higher as compared to pure palm wax.

Regression Rate Measurement Results

It has been observed that the regression rate is highly uneven all along the length of the grain. In all cases, the grain was completely consumed at-least up to 4cm of length at the beginning of the grain. It is also observed that the regression rate increase with higher Oxygen Flow rate for both of the injection pressures.

The average regression rate and average mass consumption rate for all two test at injection pressure 5 bar are presented and for 13 bars were observed higher for the 13 bar and lower for the 5 bar test conditions.

The exhaust flame in all these test firings was highly bright. The appearance of such bright flames indicate that although the fuel grain is regressing it is not combusting properly within the combustion chamber.

TABLE 2. Regression rate, static thrusts and impulse

	Test 1	Test 2	Test 3
Regression Rate mm/s	0.21	0.53	Not recorded
Average Thrust N	324.43	329.22	329.36
Impulse sec	422.78	136.34	Not recorded

Thrust Measurements

The thrust curves are shown in Fig. 3, 4 and 5 and tabulated in Table 2. The average thrust is 327.67N and impulse is 279.56 sec. The specific impulse for hybrid rockets can range from 275-350 sec. Hence, the test results show a representative performance for hybrid rocket. The impulse can be further improving by further development of the palm based hybrid rocket fuel.

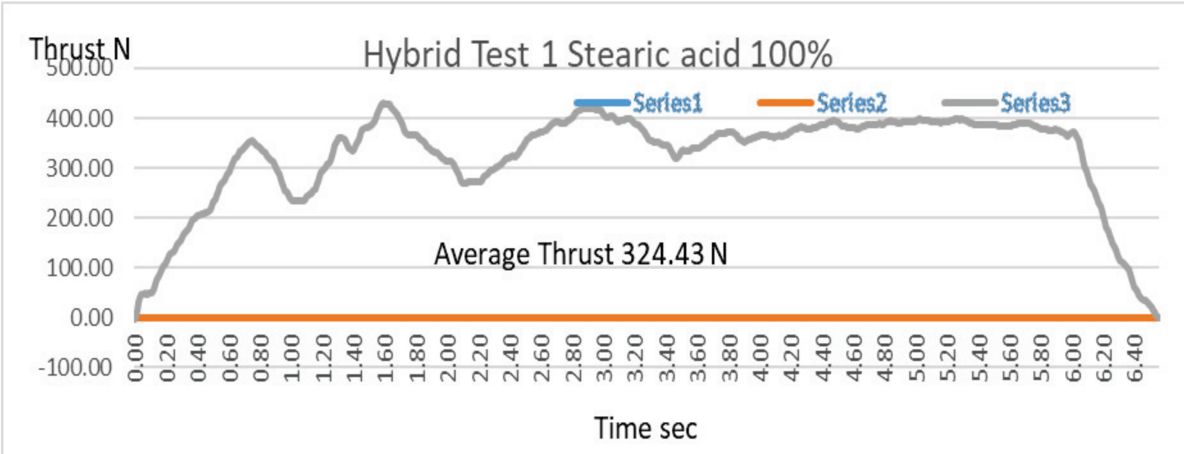

FIGURE 3. Test 1 thrust data

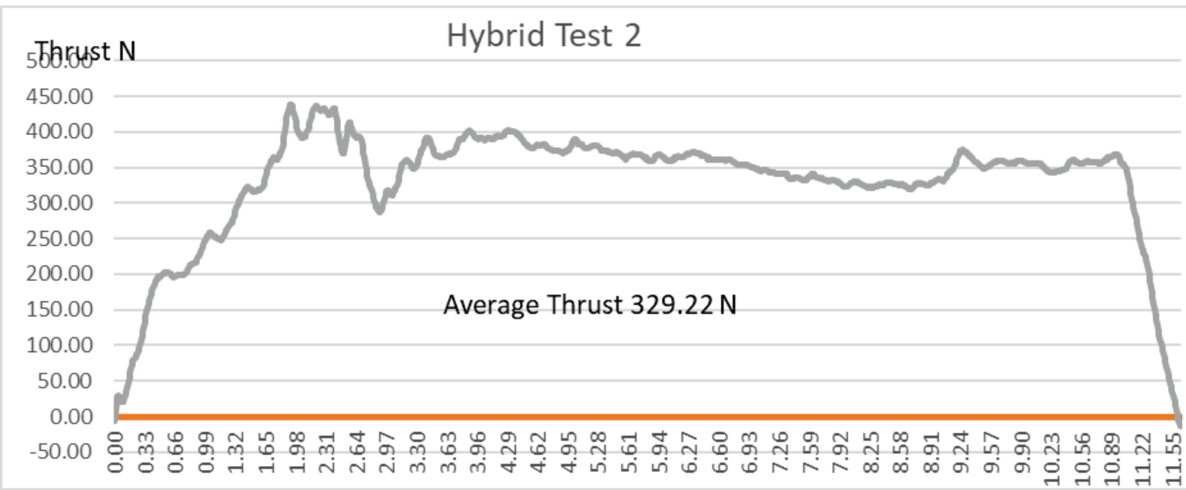

FIGURE 4. Test 2 thrust data

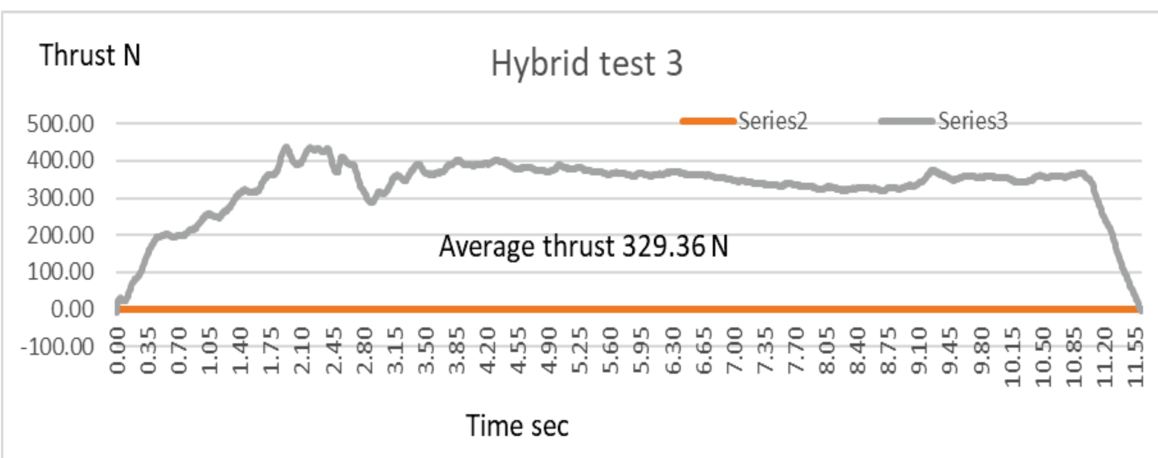

FIGURE 5. Test 3 thrust data

CONCLUSION

Experimental studies were conducted on palm-based fuel that can be used for high regression rate applications in hybrid rocket engines. Regression rates and core data collected are useful for the preparation of hybrid rocket fuel. They provide precise guidance on the temperature range to be controlled to prevent the formation of internal tensile stress during solidification.

It has been found that the caloric value of the sample consisting of Paraffin Wax-Beeswax is higher than 100% paraffin wax. Therefore, it is concluded that the calorific value of palm wax can be improved by adding some additional types. It is also noted that the Stearic Acid / GOX regression rate is slightly lower to HTPB / LOX. It has been seen that all test shots show a very bright look as light flame shows that although fuel cereals retreat but they do not burn properly in the combustion chamber. Exhaust fuel burns externally with atmospheric oxygen contact. It has been observed that all test shots except composition-3 are very smoky appearance such as smoke fires indicating that although fuel cereals retreat but it does not burn properly in the combustion chamber. The impulse of the tested hybrid palm based fuel is within the range of typical hybrid rocket.

FUTURE WORK

Further development of the palm based hybrid rocket fuel shall be carried out shall include the following tasks:

- Increased mechanical strength of paraffin wax without sacrificing regression rates requires extensive research and development work to meet the needs of high thrust engines.
- A study of potential combustion chamber pressure at different locations during testing and analyzing pressure fluctuations for unstable liquid layer combustion will be very helpful in designing hardware components, injectors for hybrid rocket motors.
- Computational analysis of the combustion process using different fuel cereal configurations in combination of different types of oxidation injection systems and different types of motor design will help to further develop the paraffin wax-based hybrid rug platform system.

ACKNOWLEDGMENTS

The authors would like to thank Col. Prof. Ir. Dr. Norazman Mohamad Nor of the National Defence University of Malaysia and his working group for their support, sharing experience and material procurement.

REFERENCES

1. F. Migireanu, “Small launcher enabled by hybrid rocket motor technology,” in 17th International Conference on Applied Mechanics and Mechanical Engineering (2016), pp. 1-20.
2. M. Kanazaki, S. Ito, F. Kanamori, M. Nakamiya, K. Kitagawa and T. Shimada, Journal of Fluid Science and Technology **11**, 1-9 (2016).
3. W. J. Larson, G. N. Henry and R. W. Humble, Space Propulsion Analysis and Design (McGraw-Hill, New York, 1995).
4. G. P. Sutton and O. Biblarz, Rocket Propulsion Elements (John Wiley and Sons, New Jersey, 2017).
5. A. Karabeyoglu, B. J. Cantwell and D. Altman, “Development and testing of paraffin-based hybrid rocket fuels,” in 37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit (American Institute of Aeronautics and Astronautics, Virginia, 2002), pp. 1-25.
6. A. Karabeyoglu, G. Zilliac, B. J. Cantwell, S. DeZilwa and P. Castellucci, Journal of Propulsion and Power **20**, 1037-1045 (2004).
7. A. Karabeyoglu, “Thermal transients in hybrid rocket fuel Grains-Nonlinear effects,” in 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit (2007).
8. J. Dyer, E. Doran, Z. Dunn, K. Lohner, C. Bayart, A. Sadhwani, G. Zilliac, P. B. Cantwell and A. Karabeyoglu, “Design and development of a 100 km nitrous oxide/paran hybrid rocket vehicle," in 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Joint Propulsion Conferences (2007), pp. 1-9.
9. D. B. Larson, E. Boyer, T. Wachs, K. K. Kuo, J. D. Desain, T. J. Curtiss and B. B., Brady, “Characterization of the performance of paraffin/LiAlH4 solid fuels in a hybrid rocket system,” in 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit (2011).