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Chemical Composition of Igniter for Ignition System in Solid Rocket Motor

Z. Salleh[1], A. H. A. Hamid[1*], W. M. W. Mohamed[2], A. Tamimi[3], M. J. Sujana[3], K. A. Ahmad[4]

[1] School of Mechanical Engineering, College of Engineering, Universiti Teknologi MARA (UiTM), 40450 Shah Alam, Selangor, MALAYSIA.

[2] Malaysia Institute of Transport (MITRANS), Universiti Teknologi MARA (UiTM), Selangor, MALAYSIA.

[3] MTC Engineering Sdn. Bhd., No. 2, Jalan Astaka U8/88B, 40150 Shah Alam, Selangor, MALAYSIA.

[4] Faculty of Engineering, National Defense University of Malaysia, 57000 Kuala Lumpur, MALAYSIA.

**Corresponding Author (Tel: +60-3-5543 6284, Email: hussein@uitm.edu.my).*

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Abstract

The ability of the black powder to ignite the propellant grain of the rocket motor is not powerful enough to provide the combustion stability of the propellant grain that delays the ignition lag interval during the transient phase. This project studies the heat combustion of spitfire powder, develops and improves this chemical composition for solid rocket motor, and analyses the spitfire powder performance to pressurize the rocket chamber. The selection of the percentage composition is identified through Graphical User Interface Propellant Evaluation Program (GUIPEP) Program. Results showed the chemical composition of spitfire powder with the higher percentage of thermite (30%) obtained the highest burning temperature (2255.2°C). A bomb calorimeter was used to obtain the value of enthalpy gain which recorded the highest value (7.92 kJ/g) at the highest percentage of thermite. The mixture of KNO_3/Charcoal with 15% of thermite gave a higher value of burning temperature (1551.9°C) than the mixture of KNO_3/Charcoal with 15% of Sulphur (1486.4°C). The highest burning temperature of chemical composition spitfire igniter (55% KNO_3, 15% C, 20% Al, 10% Fe_2O_3) was used to calculate the critical pressure (591.6 atm). The appropriate igniter weight (20.6 grams) obtained from the selected volume of the igniter, V_i (9.0 cm^3) was able to achieve the optimum igniter pressure (607.31 atm) higher than the critical pressure. Thus, the use of thermite in the spitfire igniter will give a higher burning temperature compared to black powder that uses Sulphur. The appropriate igniter weight will be able to achieve optimum igniter pressure higher than critical pressure.

Disciplinary: Mechanical Engineering (Thermal & Combustion Engineering), Materials Engineering.

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1 Introduction

MTC Engineering Sdn Bhd, under the Defense Solution Department, is a company that has a research collaboration with UiTM Shah Alam under the Micro Industrial Hub program. One of the objectives of the program is to develop a cloud seeding rocket. There are four (4) main structural activities for this cloud seeding rocket development which are the development of solid rocket motor, development of hydroscopic flare system, development of parachute deployment system, and development of launcher system. Under the development of a solid rocket motor, the igniter system was introduced to enhance the ignition of the rocket motor propellant. It is well known that an igniter charge is used as a booster to ignite propellant powder charges for projectiles of all types, including rocket propellant charges.

Igniter charge contains the chemical composition that can generate a specific level of heat and gas in order to ignite the propellant grain for initiating a larger combustion reaction to create full force trust. During combustion of the ignitable material, hot gases, flame, and pressure are generated within the housing. According to Bornsten [1], the energy release system of the igniter provides the heat necessary to pressurize the free volume of the rocket chamber as to ignite motor propellant and raise it to self-sustaining combustion [1].

In general, the igniter composition charge consists of finely divided metallic fuels and oxidizers. The oldest propellant known to man such as black powder is a mixture of salt-peter (potassium nitrate), charcoal, and Sulphur. According to Tenney, potassium nitrate is an oxidizer, carbon, and Sulphur composed of a fuel that is deflagrant or low explosive, the classification of which differs from the detonation of high explosives devices [2]. The black powder comprises a mixture of 75% potassium nitrate, 15 % charcoal, and 10% Sulphur. Although black powder has been in use for many centuries, the temperature, transient chemical species, and mechanism of combustion are still not clear, and conflicting results have been reported.

The main challenge in studying the igniter charge combustion performance is the requirement of stable and reliable ignition in order to pressurize the rocket chamber to ignite the propellant grain. If the igniter charge performance is not good enough, some grain surfaces may burn for a short time that causes the flame spreading to be extinguished. This can lead to serious abnormalities such as over-pressure, combustion oscillation, hang fire (delayed ignition) and chuffing [3]. It increases delay ignition time to build up pressure from the combustion of the igniter charge that is not reliable and effectively ignites the propellant; hence, downgrading the overall thrust performance. This is because the chemical composition charge that is generated has no uniform effective heat transmission in order to simultaneously pressurize inside the rocket motor chamber due to the temperature dependency of the deflagration properties within the range of use.

In this research of the chemical composition for the igniter charge in a solid rocket motor, the effectiveness, and reliability of the igniter charge combustion performance are observed to simultaneously pressurize the rocket motor propellant grain to ignite the propellant [4]. The spitfire powder has been dedicated as the new igniter charge for extended research of solid rocket motor ignition systems. The composition of the spitfire powder is tested to analyse the heat combustion of charge reaction and the performance of the igniter to build the pressure in the motor chamber to ignite the solid rocket motor propellant to create rocket thrust for references in future work.

2 Methodology

This section discusses the whole process flow of the project which includes all the necessary procedures and steps involved in the design, preparation igniter charge, and analysis on the heat combustion of igniter charge reaction to build up pressure chamber in solid rocket motor based on the optimum pressure obtained by using appropriate igniter volume and igniter weight.

2.1 Structure of Solid Rocket Motor Model

The molar mass is used to find the value of the effective force, λ in order to find the pressure in the rocket chamber. The effective force, λ is the result of the division of impetus value and molar mass. The pressure in the rocket chamber can be estimated as long as the value of igniter charge mass density and impetus is known whereby impetus is represented in terms of Universal gas constant, R and adiabatic combustion temperature, T from the ideal gas equation. Table 1 shows the value molar mass of each chemical composition of spitfire igniter obtained from the GUIPEP Program.

Table 1: Molar mass of the chemical composition of Spitfire igniter

Species	Molar mass (g/mol)
Potassium Nitrate, $KNO3$	101.1032
Carbon, C	12.011
Aluminium powder, Al	26.982
Iron Oxide, $Fe3O2$	159.69
The total molar mass of Spitfire	299.786

A propellant composition that is used for cloud seeding rockets is AP/AL/HTPB type. The solid type propellant is attached at the motor casing wall with appropriate web thickness, b based on the performance and functionality of the rocket used.

The material for the motor case in this cloud seeding rocket project should be able to withstand high pressure during the burning of the propellant that creates the pressure inside the chamber to create thrust. Table 2 shows the specification of the rocket motor chamber.

Table 2: Specification of rocket motor chamber

Material	Polyvinyl chloride (PVC)
Diameter	45.25 mm
Length	225 mm
Maximum temperature	> 2562.54°C

2.2 Bomb Calorimeter Experimental Test

The combustion of the sample releases the energy which is absorbed in the calorimeter that results in temperature change. The test was conducted with seven samples of Spitfire powder with different ratios of composition percentage as shown in Table 3.

Table 3: Ratio design of Spitfire composition percentage

Composition (Wt %)			
Oxidizer	Fuel	Thermite	
KNO_3	C	Al	Fe_2O_3
87.5	12.5	0	0
77	13	5	5
72	23	3	2
70	10	5	15
68	15	10	7
65	20	10	5
55	15	20	10
87.5	12.5	0	0
77	13	5	5

The procedure for the bomb calorimeter test is listed as shown:

i Prepare the chemical composition sample in the bomb. The crucible is placed on the analytic balance and the reset button is pressed in order to make it into origin reading.

ii The sample is put in the crucible and weighed (0.5g – 1.0g).

iii The crucible is then placed together with a piece of cotton thread. Make sure the cotton thread that is connected to the ignition wire touches the sample and attaches both ends of the wire to the 2 electrodes of the decomposition vessel.

iv Be careful when closing the decomposition vessel to prevent disturbing the sample when the decomposition vessel is moving. Moisten the decomposition vessel with a bit of water in order to lower the pressure inside the decomposition vessel and check the sealing ring to ensure it is in good condition.

v Put decomposition vessel into IKAC200 Bomb Calorimeter machine.

vi The weight of the sample is set at the controller and press the button "Okay" to run the test.

vii Before measuring any data, let the stirrer run for 5 minutes to achieve an equilibrium condition. Read and record the data of the calorific value or known as heat combustion (kJ/g).

3 Results and Discussion

The results of heat combustion of the igniter charge reaction are determined by the GUIPEP Program for the value of temperature and the Bomb Calorimeter test for the value of enthalpy. The results obtained are analysed and discussed in detail according to the various proportions of the thermite with KNO_3/Charcoal mixture. Then, the calculated igniter pressure is used to observe whether the igniter pressure with the use of appropriate igniter weight can generate hot gases higher than the critical pressure.

3.1 Spitfire Igniter Charge with Various Proportions of Thermite

The combustion of the KNO_3/Charcoal mixture with the various proportions of the thermite, which is the mixture of Al/Fe_3O_2, is observed based on the temperature and enthalpy of the chemical composition reactions. Previously, the use of the black powder with the chemical composition of Sulphur with KNO_3/Charcoal mixture by the company needs to be enhanced on its performance to pressurize the motor chamber due to the ignition delay time to ignite the propellant which takes about 4 to 6 seconds. To generate more reliable and effective hot gases towards the grain surface, the spitfire powder was dedicated.

From Table 4, a steady increase in the burning temperature was observed to reach the maximum temperature of 2255.19°C at approximately 31% of thermite with 20% of Al and 10% Fe_3O_2. This can be shown based on Figure 1 in which the burning temperature increases with the increasing of thermite content in the 12.5% charcoal/87.5% KNO_3 and reacts in a directly proportional manner.

This can be proven based on the result of enthalpies plotted in the graph of Figure 2 in which the maximum value of ΔH occurs at approximately 59% KNO_3, 10% charcoal, and 30% thermite, similar to the burning temperature of the mixture. This is because as the temperature increases, the amount of molecular interactions also increases. If the number of interaction increases, then the system's internal energy increases which lead to the increase of the enthalpy. Moreover, the result from the previous study showed the increase of the enthalpy value, ΔH from 2.753 kJ/g to 3.212 kJ/g with the increase of Sulphur content from 0% to 10% in the KNO_3/Charcoal mixture [5].

Table 4: The effect of increasing thermite content on the burning temperature of KNO_3/Charcoal mixture

Thermite (%)	$Tmax$ (°C)	Enthalpy of reaction, ΔH (Bomb Calorimetry) (kJ/g)	Oxidiser KNO_3 (%)	Fuel C (%)
0%	945	2.753	87.5	12.5
5%	1065.10	3.355	72	23
10%	1395.06	3.717	77	13
15%	1551.95	6.014	65	20
17%	1820.59	6.374	68	15
20%	2201.52	7.804	70	10
30%	2255.19	7.924	55	15

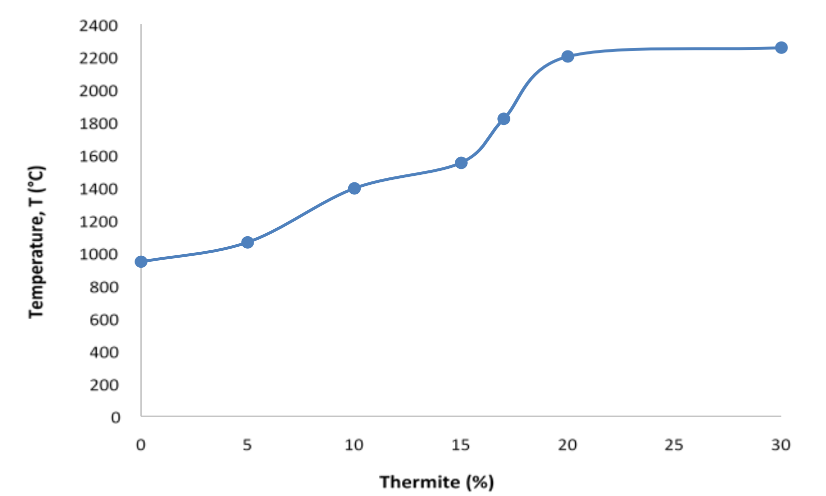

Figure 1: Burning temperature of KNO_3/Charcoal mixtures containing various proportions of thermite

Both thermite and Sulphur are able to enhance the performance of the igniter charge burn to be more efficient and reliable in order to pressurize the rocket chamber at the optimum pressure during ignition of the propellant grain when mixed with KNO_3/Charcoal mixture. But thermite will give a higher burning temperature compared to Sulphur. This is stated in a previous study in which the temperature of hot jet flow for the KNO_3/Charcoal mixture with thermite is higher than the KNO_3/Charcoal mixture with sulphur. This can be proven from the use of 15% thermite which obtained about 1551.95°C with KNO_3/Charcoal mixture while the previous study showed about 1300°C with the use of 15% of Sulphur with KNO_3/Charcoal mixture [5].

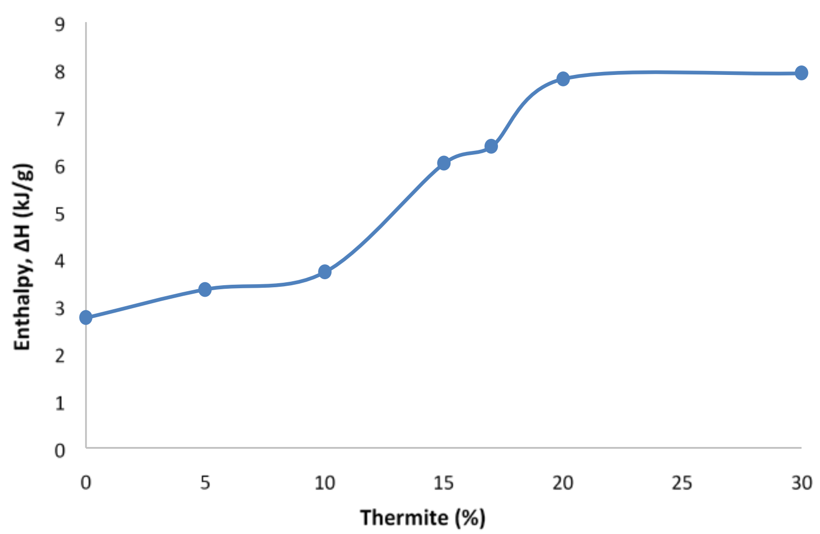

Figure 2: Enthalpy of reaction against percentage thermite for KNO_3/Charcoal mixture containing various proportions of thermite.

3.2 Comparison of Thermite and Sulphur in KNO_3/Charcoal mixture

Based on Table 5, the use of thermite with KNO_3/Charcoal mixture showed a high burning temperature compared to the use of Sulphur with KNO_3/Charcoal mixture with a small percentage difference between both materials that bring the average percentage difference of about 0.048%. The temperature of combustion is important as the increase of temperature will lead to the increase of the igniter pressure that is used to pressurize the rocket chamber in order to ignite the propellant grain.

Table 5: The combustion temperature of thermite and Sulphur based on the GUIPEP Program.

Thermite and Sulphur (%)	KNO_3 (%)	C (%)	Temperature with thermite (°C)	Temperature with Sulphur (°C)	Percentage different (%)
0%	87.5	12.5	945.00	898.91	0.049
5%	72	23	1065.10	987.42	0.073
10%	77	13	1395.06	1335.46	0.043
15%	65	20	1551.95	1486.38	0.042
17%	68	15	1820.59	1810.47	0.006
20%	70	10	2201.52	2082.97	0.054
30%	55	15	2255.19	2098.05	0.070

Based on the high burning temperature produced by the thermite with KNO_3/Charcoal mixture, it can be said that the use of thermite, which is the mixture of aluminum and iron oxide, can react violently when ignited and it quickly releases energy without external oxygen with the temperature that can reach about 3000°C [6]. The aluminium material inside the mixture of thermite that has the reaction with oxygen from the iron oxide, Fe_3O_2 is able to improve the performance during the combustion of the igniter charge in order to ignite the propellant grain compared to the Sulphur with KNO_3/Charcoal mixture as shown in Figure 3.

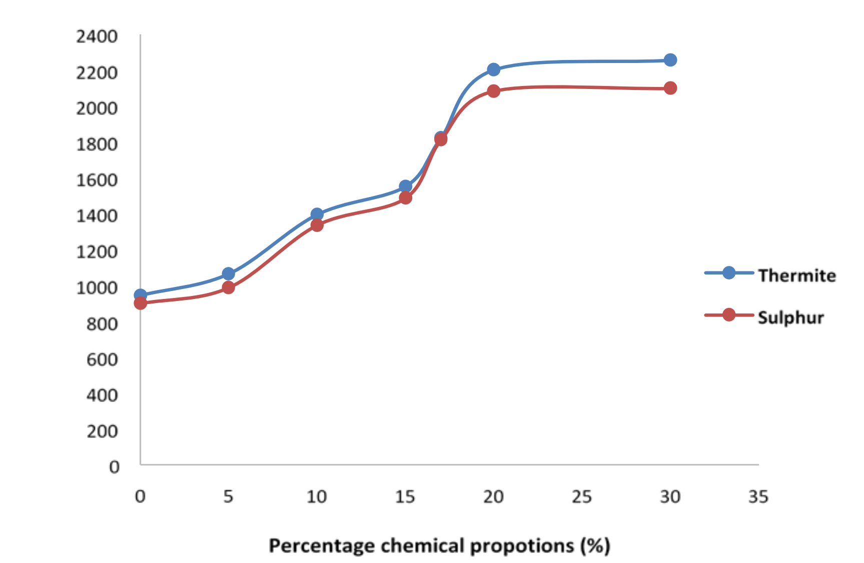

Figure 3: The combustion performance of thermite and Sulphur with KNO_3/Charcoal mixture

3.3 The Effect of Igniter Volume and Igniter Charge Weight on Igniter Pressure

An accurate design by selecting the correct igniter dimension will have the accurate volume of the igniter to meet the optimum igniter pressure. The dimension of the volume of igniter charge measurement is based on the company's requirements. The decision on the various dimension of igniter needs to be always less than one percent of the propellant mass [3]. Based on the propellant used in this cloud seeding rocket which is AP/AL/HTPB type, the mass of the propellant is about 306.63 grams. Based on Table 6, the decision on the measurement of igniter to obtain the volume of igniter was accurate as the percentage of the igniter was less than one percent of the propellant mass.

Table 6: Percentage of igniter mass with various dimension measurement

Volume igniter charge, Vi (cm^3)	Igniter charge mass (%)
5.79	0.981
6.44	0.979
7.08	0.977
7.73	0.975
8.36	0.938
9.01	0.933
9.65	0.927

A proper volume of the spitfire igniter is used to achieve the optimum igniter pressure that is able to reach the critical pressure, 591.61 atm inside the rocket motor chamber. Based on Table 7, the least volume of the igniter, V_i which is 5.79cm^3 obtained about 369.89 atm of the igniter pressure. Meanwhile, the highest volume of the igniter, V_i which is 9.65cm^3 obtained about 658.68 atm of the igniter pressure. Both minimum and maximum igniter volumes failed to meet the requirement of the optimum pressure as the minimum was not powerful enough to reach the critical pressure while the maximum was too high for the igniter pressure and this will lead to the over-pressurized of the rocket chamber. Therefore, the volume of igniter at about 9.01cm^3 with 607.31 atm of igniter pressure is the most appropriate igniter volume as the pressure is sufficient enough to ignite the propellant as shown in Figure 4.

Table 7: Various igniter volumes to obtain the igniter pressure based on the highest burning temperature of spitfire igniter, 2528.19 K

Volume igniter charge, Vi (cm^3)	Igniter pressure, P_i (atm)
5.79	369.89
6.44	416.10
7.08	462.1
7.73	509.05
8.36	558.25
9.01	607.31
9.65	658.68

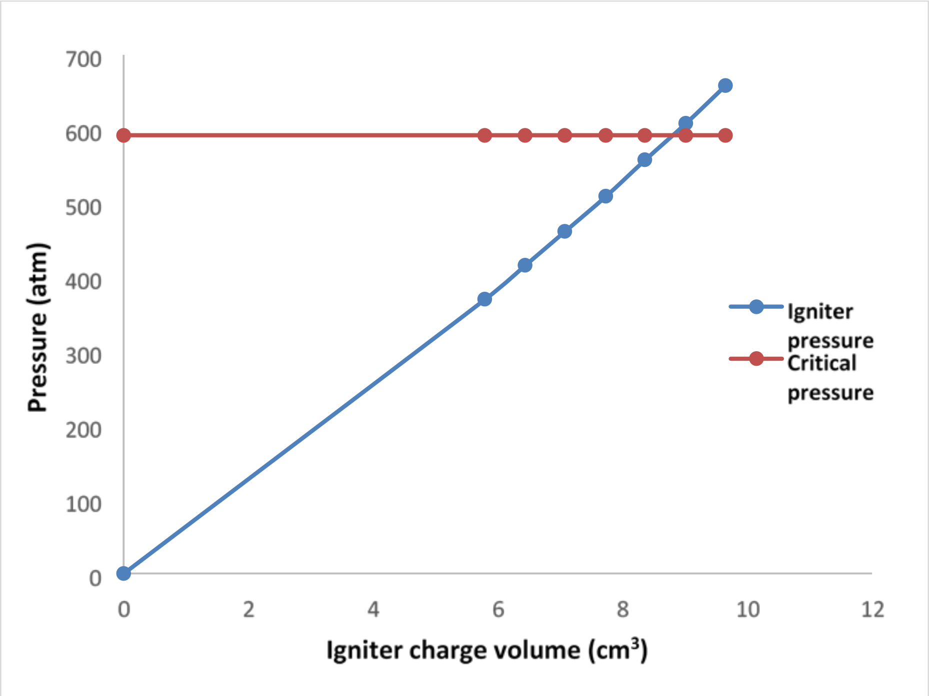

Figure 4: The igniter pressure against igniter charge volume

Based on Table 8, the appropriate igniter weight, C obtained from Igniter Chamber Pressure Excel Program prepared by Richard Nakka [4] was used to achieve the optimum igniter pressure that is able to reach the critical pressure, 591.61 atm inside the rocket motor chamber. Optimum pressure of the igniter charges was able to pressurize the chamber in stable combustion.

Table 8: Various igniter weights to obtain igniter pressure based on the highest temperature, 2528.19 K

Igniter weight (gram)	Igniter pressure, P_i (atm)	Percentage different (%)
13.2	369.89	0.375
14.69	416.10	0.297
16.2	462.10	0.219
17.6	509.05	0.139
19.1	558.25	0.056
20.6	607.31	0.026
22.1	658.68	0.102

Based on Table 8, the igniter weight of about 13.2 grams obtained about 369.89 *atm* of the igniter pressure. This shows that the percentage difference between the critical pressure is about 0.375%. Meanwhile, the value of the igniter weight at about 20.6 grams with igniter pressure of about 607.31 atm showed the percentage difference of about 0.026% between the critical pressure. Therefore, the igniter weight of 20.6 gram was the most appropriate igniter weight to achieve the optimum igniter pressure as it obtained the least percentage difference between the critical pressure, P* which was 591.61 *atm*.

Based on the plotted graph of the igniter pressure against igniter weight as shown in Figure 5, all values of the igniter pressure are below the critical pressure (red line), indicating insufficient power to properly ignite the rocket propellant at the first ignition as it generates fewer hot gases to the cool grain propellant surface. A previous study had reported that with less quantity of igniter charge, it is still able to raise the pressure inside the chamber but it is not enough to raise an appropriate pressure to trigger the propellant grain to be higher than the critical pressure. On the other hand, an appropriate amount of igniter weight is able to increase the pressure of the igniter to pressurize the free volume of the igniter chamber in order to ignite the propellant grain [7].

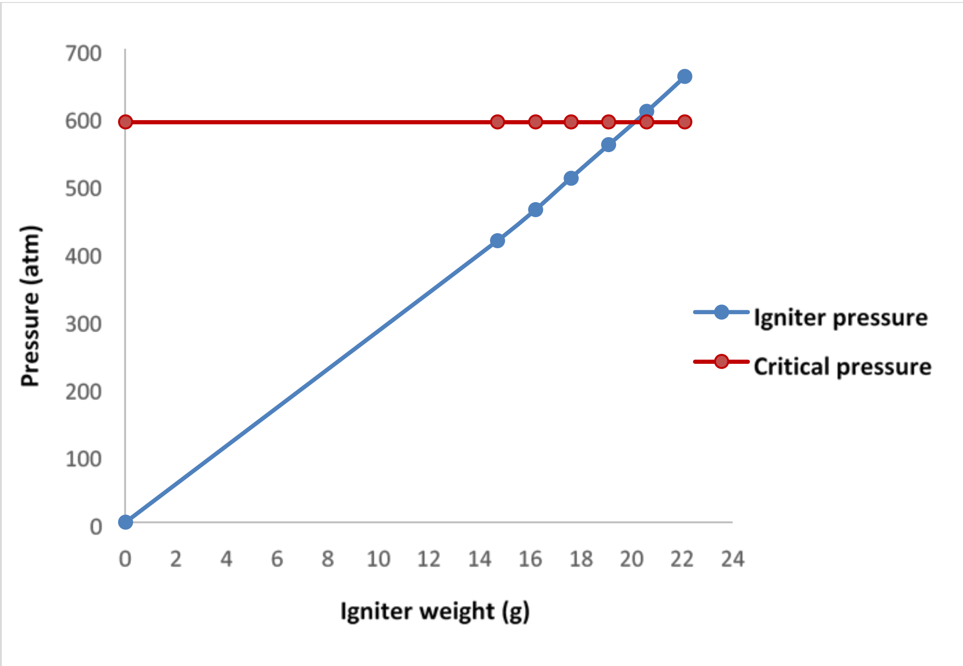

Figure 5: The igniter pressure against the igniter weight

Moreover, the use of appropriate igniter weight can also help to meet the requirement of the ignition time. By referring to a previous study, the use of the lowest igniter weight of about 59 grams with the critical pressure of about 27.7 atm showed that the ignition pressure was low than the critical pressure, and the ignition of the rocket motor was delayed for 0.294 seconds. Meanwhile, the igniter weight with 175 grams at 27.7 atm critical pressure was successful to ignite the rocket motor in 0.036 seconds. It can be concluded that the higher the use of the igniter weight, the faster the ignition of the rocket motor [2].

4 Conclusion

Various chemical compositions were analysed from the fundamental understanding of previous studies on black powder composition. Based on the results obtained, spitfire powder with 30% of thermite produces the highest temperature of about 2255.19°C and enthalpy value, ΔH of about 7.924 kJ/g compared to black powder with about 2098.05°C and 2.595 kJ/g. This can be concluded that the use of the thermite with KNO_3/Charcoal mixture as the composition of the igniter charge combustion performance is more efficient and reliable.

The critical pressure is the minimum reference pressure needed to ignite the solid propellant and produce stable combustion. The highest temperature of the spitfire powder with 55% KNO_3, 15% C, 20% Al, 10% Fe_2O_3 was used to calculate the critical pressure built by the combustion of the spitfire igniter charge which successfully obtained about 591.61 atm. The volume of the igniter, V_i with 9.01cm^2 obtained the appropriate igniter weight of about 20.6 grams. It can be observed that the appropriate igniter weight is able to gain the optimum value of igniter charge pressure with 607.31atm higher than the value of critical pressure with the percentage difference of about 0.026%.

For future research, the static test must be done to obtain the most suitable and optimum temperature, especially for the temperature selection to calculate the pressure of the igniter during the flame spreading phase when observing the performance of the igniter charge combustion. The chemical material specifications list that can be used to design the igniter charge also needs to be provided to standardize the output of the igniter charge combustion performance every time the testing is made.

5 Acknowledgement

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Dr. Zuraidah Salleh is an Associate Professor at School of Mechanical Engineering, Universiti Teknologi MARA, Malaysia. She received her Bachelor Degree in Mechanical Engineering from Universiti Teknologi MARA and her MSc. from Universiti Sains Malaysia (USM). Her research interests include Composites, Coatings, Welding and Rocketry.

Dr. Ahmad Hussein Abd Hamid is an academic staff in School of Mechanical Engineering, Universiti Teknologi MARA, Malaysia. He received his M.Sc. degree in 2008 from the same university. In 2016, he obtained his PhD in Mechanical Engineering from Monash University, Melbourne, focusing on Magnetohydrodynamics and Heat Transfer. His research interests include Wake Flow of a Bluff Body, Magnetohydrodynamic Flow, Heat transfer, liquid atomization and renewable energy.

Dr. Wan Mazlina Wan Mohammad is Head of the Training & Continual Professional Development (CPD) at Malaysia Institute of Transport (MITRANS), and a Senior Lecturer at School of Mechanical Engineering, Universiti Teknologi MARA (UiTM), Malaysia. She received her double degrees, a B.Sc. in Aerospace Engineering & a B.Sc. in Aircraft Maintenance Engineering from St. Louis University, USA, and obtained an MSc in Air Transport Management from Cranfield University, UK. She was awarded a PhD by UiTM, Malaysia. She actively involves in Aviation and Land Transport Research and Consultancy Projects. She was involved in the development of Malaysia Transport Policy (Aviation Sector) and has been appointed as Technical Working Group (TWG) member for Department of Standard, Malaysia in developing Vehicle Sales Standards.

Ahmad Tamimi Ahmad Termizi is an engineer at MTC Defence Sdn. Bhd and works as principal researcher at High Energy Material Research Laboratory (HEMREL), a joint venture of MTC Engineering Sdn. Bhd. and Universiti Teknologi MARA. He received his B.Eng. from University Malaysia Pahang focusing on R&D of Solid Propulsion Technology. He has vast experience in amateur rocketry and founded Kedah Rocketry Group, a Special Interest Group (SIG) to propel the vision of promoting rocketry activity in Malaysia.

Lt Col RMAF (Rtd) Ir. Mohamed Juani Sujana graduated from Universiti Teknologi Malaysia in Electrical Engineering Bachelor Degree. He is a fully qualified and professional Military Aircraft Engineer and Advanced Weapon System Engineer. He is certified as Professional Engineer from Board of Engineer Malaysia and licensed to perform aircraft and component maintenance, modification and repair on a wide variety of aircraft and engine types (Russian/ UK/ American). He served in Royal Malaysian Air Force for 24 years and currently a Techno-pruner in Rocket Technology Development, collaborating with Universiti Teknologi MARA under the High Energy Material Research Lab (HEMREL).

Col (Rtd) Assoc. Prof. Dr. Khairol Amali Ahmad obtained a BSc in Electrical Engineering from the United States Military Academy, West Point and MSc in Military Electronic Systems Engineering from Cranfield University. While serving the Malaysian Army, he was positioned in various posts and units including those dealing with engineering maintenance and procurement consultation of equipment. He then joined the National Defence University of Malaysia (NDUM) and completed his PhD from ISAE-SUPAERO, France. Currently, he is Dean of the Engineering Faculty and an associate to Centre for Tropicalization (CENTROP) and Centre of Defence Research and Technology (CODRAT) in NDUM. His research interests include signal processing related to signal propagation and radar performance in Tropical area, mesh networks for IoT applications, Machine Learning and Delay\Disruption Tolerant Network (DTN).