Investigation on solid propellant test and time calibration for complete combustion

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Abstract. A solid propellant is simple and reliable rocket fuel. Once ignited, the propellant cannot be stopped since they burn until they run out. Solid fuel rockets are widely used in military applications such as missiles, model rockets, boosters for satellite launchers and so on because they can be stored for long periods of time without degrading the propellant. The primary objective of this research is to study the burnout mass of solid propellants using various propellants and catalysts. Potassium Nitrate (KNO_3) was chosen as an oxidant in the experiment because of its compatibility with other ingredients and low-cost affordability. KNO_3 was used as an oxidizer in a 65% ratio with 34% of the fuel and 1% of the catalyst. KNO_3, fuel ingredients like Fructose, Glucose and Lactose with catalysts Copper and Aluminum were taken in powdered form. Cylindrical stainless steel with one closed end was taken to fill the cavity, and a concentric hole was made for constant burning. This propellant-filled chamber is fixed strongly in a position so that it does not propel during fuel combustion when thrust is formed. The obtained result shows that the longest burnout mass was secured by burning Glucose with Copper powder and KNO_3 for 136 s when compared to the shortest burnout mass was secured by burning Lactose with Aluminum powder and KNO_3 mixture to 57 s. The highest temperature of the mixture was Lactose with Copper powder and KNO_3 resulted in 518 °C when compared to the lowest temperature of the mixture was Glucose with Copper powder and KNO_3 was 211.75 °C.

1. Introduction

A solid-propellant rocket, also known as a solid rocket, is a rocket powered by SPs (fuel/oxidizer). Solid-fuel rockets propelled by gunpowder were utilized in battle as early as the 13th century by the Arabs, Chinese, Persians, Mongols, and Indians [1]. A sugar propellant rocket is a kind of SP rocket manufactured with sugar as a fuel and an oxidizer. The propellant is made up of two components: the fuel and the oxidizer. Historically, sucrose was the most often utilized fuel. Because of their simplicity of manufacture, modern

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formulations often include fructose, sorbitol, and other sugar kinds [2]. Potassium nitrate is the most often used oxidant. The most typical application of potassium nitrate is as a fertilizer.

The difficulties in creating high-energy rocket propellants are tremendous, hence the availability of low-energy sugar-based propellants in amateur rocketry continues to thrive [3]. Major problems include a lack of resources and the expensive pricing of high-energy chemicals, technology, and tools. The most essential difficulty is also the safety of the ecosystem and property because most high-energy rocket propellants are toxic and dangerous to nature. Sugar-based propellants, sometimes known as rocket candy, are a form of rocket propellant used in model rockets. Its primary fuel is sugar, and its oxidizer is low-energy nitrate. In certain circumstances, the propellant may consist of the fuel, the oxidizer, and the catalysts [4]. Using sucrose as fuel in a sugar propellant is regarded as a great active component; unfortunately, it is hampered by uneven propellant properties due to prolonged caramelization and an abnormally high-pressure index. The burning rate is affected by the value of the pressure exponent. High-pressure index values result in large variations in the burning rate with few changes in combustion chamber pressure, with potentially disastrous results [5].

A few researchers tried to study the thermodynamics and ballistic characteristics of sugar-based propellants. Foltran et.al [6] experimented to study the performance of a cold-manufactured mechanical press with a mixture of 65% Potassium Nitrate and 35% Sucrose. For the propellant grain fabrication, the characteristic properties like density and burning rate and compression pressure were also studied. Yang et.al [7] explained the detailed process of a solid propellant rocket engine, starting with fundamental assumptions based on rocket engines with indistinguishable properties and utilizing modelling tools to calculate the performance of a solid propellant rocket. The experiment simulated the temperature of combustion products and the typical jet velocity or efflux velocity were both verified. The research also indicated that the main byproducts of the Sucrose and Potassium Nitrate burning process are carbon dioxide, carbon monoxide, and water. The addition of a catalyst to the propellant mixture is the most efficient and effective way of boosting the burn rate.

The chemistry of the catalysts improves fuel and oxidizer burning reactions in the combustion chamber and enhances heat transfer at the propellant surface layer. Abhijeet et.al [8] explained in his research the making, limitations and analysis of sugar-based rocket propellant systems. The research also analyzed the safety measures that need to be carried out while preparing the solid propellant. Abbas et.al [10] experimented to study the kinetic parameters and ignition temperatures of Lactose with different oxidisers like Potassium chlorate ($KClO_3$), Potassium Nitrate (KNO_3), Potassium permanganate ($KMnO_4$), Barium nitrate ($Ba(NO_3)_2$) and Potassium perchlorate ($KClO_4$) and Improve safety performance of lactose-fueled binary pyrotechnic systems of smoke dyes. The investigation came to a conclusion stating the lactose and KNO_3 combination can be adopted instead of the well-known lactose and $KClO_3$ blend that is commonly used in smoke dye systems. Iguniwei B.Paul et.al [11] provided various Specific Impulses (Isp) produced by various propellants like Potassium Nitrate /Sugar (KNSU), Gunpowder and APCP–Ammonium perchlorate composite propellant, the literature shows that the specific impulse of KNSU is between 115 °C - 130 °C. Arnold [12] conducted the experiment "Method for collecting Thermocouple data via a secured shell over a wireless local area network in real time" in which he came to a conclusion, about how the k-type TC could be used to calibrate temperature and time inside surface of the metallic cylindrical shell to reach 400 °C.

A. Yu. Krainov et.al [13] studied the slowly varying combustion of solid propellant in the combustion chamber of a controllable solid-propellant rocket motor was designed to simulate using the conjugate physical-mathematical model of the combustion of a ballistic powder with regard to the processes occurring in the condensed and gas phases of the powder at the fourth-kind initial conditions on the edge of its charge. S. A. Bitkin et.al [14] had researched the mathematical model, numerical technique, and parametric study findings for the parameters of a multi-nozzle solid-fuel motor provided with mass flow rate stepper regulators. A. M. Lipanov et.al [15] had researched the highest achievable solid rocket motor pressures calculated using the exponential and real equations of fuel burning rate as a function of pressure. It is demonstrated that for high exponents of the burning rate law, there is a significant difference in the maximum motor pressure achieved by the two approaches. The exponential burning rate law overestimates motor pressure by just 2-3% when the exponent is between 0.3 and 0.4.

O.G. Glotov et.al [16] studied computed statistics on the heat-ejected efficiency of the rocket fuel evaluated. The experimental data gained has been used to construct and validate theoretical models of metalized fuel combustion. Buren Duan et.al tried studying the burning characteristics and combustion wave model of AP/AN-based laser-controlled solid propellant [17]. Chaitanya Vijay et. al researched the estimation of burning characteristics of AP/HTPB composite solid propellant using a sandwich model [18].

V. A. Poryazov et.al [19] studied the boundary conditions on the propellant surface for the equality of heat and mass fluxes of fuel components are established. A numerical solution to the system of equations is used to calculate the dependency of the burning rate of a composite fuel including boron particles on the pressure above the fuel surface. K. Jayaraman et.al [20] studied the effect of nano-aluminum in plateau-burning and catalyzed composite solid propellant combustion.

Ao Wen et.al [26] studied the fuel burning rate, aluminium agglomeration process, CCP size distribution, and combustion characteristics were all investigated in both the forward and backward directions under a range of electric-field voltages (5 to 5 kV). It was discovered that as the electric-field voltage raised, so did the propellant burning rate and combustion efficiency, but the degree of aluminium agglomeration reduced, resulting in smaller CCP particle sizes. The application of an electric field can have significant impacts on particle charge acceleration, Rayleigh crushing, and ion excitation. King Merrill K. [28] worked on aluminium particle tracing a stream-tube via a solid propulsion system port has a model that predicts particle radius and oxide cap size/shape vs time.

Few other researches have been carried out to study the ecofriendly fuel in the areas of renewable energy and biodiesels those are as follows: G. Murali et.al [29] carried out the base test using diesel and various mango seed blended fuels. According to the basis test findings, MSME20 has improved performance criteria. To increase engine efficiency even more, decanol is added to MSME20 at three concentrations: 5%, 10%, and 15% per volume. The findings showed that adding 5% decanol to the MSME20 improves braking thermal efficiency by 3.19% and significantly reduces exhaust emissions such as HC, CO, and smoke. M. Arunkumar [30] the research discusses the usage of castor biodiesel as another fuel for diesel, and it may significantly reduce greenhouse gas emissions while also strengthening castor seed production. According to the study, the use of castor biodiesel as alternate fuel source decreases carbon monoxide to 9% when compared to diesel HC, which reduces oxides of nitrogen by 8.8%. SFC was raised by 4% but thermal efficiency was degraded by 2.2%.

The research gap which was found in this area is the comparison of sucrose, glucose and lactose propellant's burnout time and temperature. Therefore, the main objective of this work is to investigate the burnout time of oxidizers with different fuels like sucrose, glucose and lactose and a rocket propellant that might be utilized in sounding rockets for economically backward nations using the simplest method of manufacturing and widely available components.

2. Materials

2.1 Fuel

Fructose, Glucose and Lactose are used as fuel in this experiment. Minuscule fructose, glucose and lactose particles along with oxidizers catch fire in a flash due to their high proportion of surface area to volume [6,8,10].

2.1.1 Fructose

Fructose, popularly known as fruit sugar, represents the only found naturally ketohexose. Fructose is also known as levulose due to its significant levorotatory optical rotation. [18] Fructose is a monosaccharide (one sugar unit), with a functional group of ketones (R - O - R) in structure. [19] It can be understood from Table 1 the various properties and specification of Fructose which was taken as one of the fuels in this experiment.

Table 1 Properties of Fructose.

Property	Specifications
Chemical Formula	$C_6H_{12}O_6$
Molecular Weight	180.15 g/mol
Density	1.694 g/cm3
Melting Point	103 °C
Chemical Name	Fruit sugar, levulose, d-fructofuranose, dfructose, d-arabino-hexulose

2.1.2 Glucose

The simple sugar glucose has six carbon atoms and one aldehyde group (R - O - H). The molecular formula for this monosaccharide (one sugar unit) is $C_6H_{12}O_6$. [20] It can be understood from Table 2 shows the various properties and specification of Glucose which was taken as one of the fuels in this experiment.

Table 2 Properties of Glucose.

Property	Specifications
Chemical Formula	$C_6H_{12}O_6$
Molecular Weight	180.16 g/mol
Density	1.54 g/cm³
Melting Point	146 °C
Chemical Names	Aldohexose and Dextrose

2.1.3 Lactose

Lactose is a disaccharide that breaks down into two saccharides, i.e., glucose and galactose, when hydrolyzed. Lactose, which is contained in milk in amounts ranging from 2-8%, is the natural type of sugar. [21] It can be understood from Table 3 shows the various properties and specification of Lactose which was taken as one of the fuels in this experiment.

Table 3 Properties of Lactose.

Property	Specifications
Chemical formula	$C_{12}H_{22}O_{11}$
Molecular weight	342.297 g/mol
Density	1.525 g/cm3
Melting point	202.8 °C
Chemical names	Milk sugar, 4-O-β-D-glucopyranosyl-glucose

2.2 Oxidizer

Potassium Nitrate (KNO3) is considered as an oxidizer in this experiment. Potassium nitrate fills the requirement for oxygen and occupies considerably less space, which leaves the blast alone stronger and quicker. It is a fundamental element of explosives. It can be understood from Table 4 shows the various properties and specification of Potassium Nitrate which was taken as oxidizer in this experiment.

Table 4 Properties of Potassium Nitrate.

Property	Specification
Chemical Formula	KNO_3
Molecular Weight	101.1032 g/mol
Density	2.109 g/cm3
Boiling Point	400 °C
Melting Point	334 °C

2.3 Catalyst

Copper and Aluminum Powder were used as catalysts because they are metals having high thermal conductivity and have a tendency to increase the BT [9]. It can be understood from Table 5 shows the various properties and specifications of copper which was taken as one of the catalysts in this experiment. Table 6 shows the various properties and specifications of Aluminum which was taken as one of the catalysts in this experiment.

Table 5 Properties of Copper.

Property	Specification
Chemical Formula	Cu
Molecular Mass	63.546
Density	8.96 g/cm3
Thermal Conductivity	385.0 W/m K

Table 6 Properties of Aluminum.

Property	Specification
Chemical Formula	Al
Molecular Mass	26.981
Density	2.7 g/cm3
Thermal Conductivity	88 - 251 W/m K

3. Measuring instruments used to study the experiment

3.1 K-Type Thermocouple

Thermocouple is a temperature-measuring device that comprises two wires of different metals that are connected at either end. The temperature is monitored at one connection, while the other is held at a steady lower temperature. The temperature difference induces the formation of an electromotive force which is directly proportional to the temperature difference between the two connections. [4] For this experiment, a K-type thermocouple (MAX6675) is a sensor that has the capacity to sense the temperature up to 1260 °C.

There were a total of three thermocouples were used. Each thermocouple was used twice. TC_1, TC_2, TC_3, TC_4, TC_5, and TC_6 are the respective thermocouple test which was used during the combustion. The accuracies and ranges for thermocouples are typically around ± 2.2°C or ± 0.75% and -200°C to 1260°C (-326°F to 2300°F). The thermocouples were placed at the end of the stainless-steel combustion chamber. A brief format of sample tests along with Thermocouples are mentioned below in the tabular column.

Table 7 Thermocouple test with propellant samples

Thermocouple	Thermocouple Test	Sample
T1	TC1	Fructose (Fuel), Potassium Nitrate (Oxidizer) and Copper (Catalyst)
	TC2	Glucose (Fuel), Potassium Nitrate (Oxidizer) and Copper (Catalyst)
T2	TC3	Lactose (Fuel), Potassium Nitrate (Oxidizer) and Copper (Catalyst)
	TC4	Fructose (Fuel), Potassium Nitrate (Oxidizer) and Aluminium (Catalyst)
T3	TC5	Glucose (Fuel), Potassium Nitrate (Oxidizer) and Aluminium (Catalyst)
	TC6	Lactose (Fuel), Potassium Nitrate (Oxidizer) and Aluminium (Catalyst)

3.2 Arduino UNO

The Arduino UNO is a standard Arduino board. In Italian, UNO signifies "one." It is considered to be a powerful board that is used in a variety of tasks. The Arduino UNO board was created by Arduino.cc. In this experiment, the Arduino was used to calibrate the temperature with respect to time through the k-type thermocouple [22].

4. Materials and Methods

4.1 Fabrication of Casing

A stainless-steel cylinder with an outer diameter of 31 mm, an inner diameter of 22 mm, and a length of 90 mm was manufactured in a lathe. An orthographic view with the dimension of the casing is represented in Fig.1

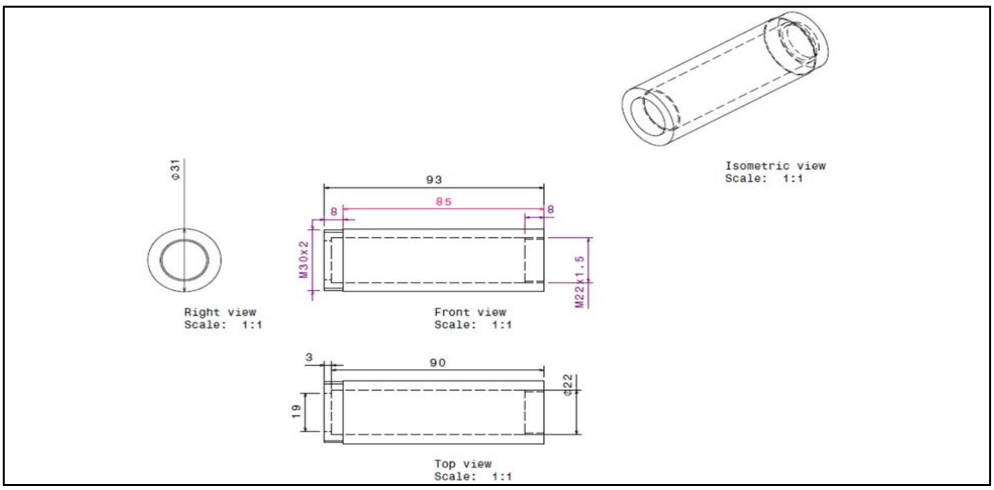

Fig.1 Orthographic view of the casing of stainless-steel cylinder

4.2 Fabrication of Propellant

The total mass of the propellant mixture is 35g out of which 22.75 is of oxidizer that is potassium nitrate (KNO_3), 11.25g is of fuel that is fructose/glucose/lactose (based on test) and 1g of catalyst is used that is copper/aluminum in powdered form (based on test) [6,8]. Six different experiments were conducted with different sugar-based rocket propellant formulations.

The reaction of sample 1 consists of potassium nitrate as an oxidizer, fructose as fuel and copper as a catalyst is given in equation 1

$$C_6H_{12}O_6\ (s) + Cu\ (s) + KNO_3\ (s) \longrightarrow CO_2 + H_2O + K_2CO_3 + N_2 \quad (1)$$

The reaction of sample 2 consists of potassium nitrate as an oxidizer, glucose as a fuel and copper as a catalyst is given in equation 2

$$C_6H_{12}O_6\ (s) + Cu\ (s) + KNO_3\ (s) \longrightarrow CO_2 + H_2O + K_2CO_3 + N_2 \quad (2)$$

The reaction of sample 3 consists of potassium nitrate as an oxidizer, lactose as fuel and copper as a catalyst is given in equation 3

$$C_{12}H_{22}O_{11}\ (s) + Cu\ (s) + KNO_3\ (s) \longrightarrow K_2CO_3 + N_2 + CO_2 + H_2O \quad (3)$$

The reaction of sample 4 consists of potassium nitrate as an oxidizer, fructose as fuel and Aluminum as a catalyst is given in equation 4

$$C_6H_{12}O_6\ (s) + Al\ (s) + KNO_3\ (s) \longrightarrow CO_2 + H_2O + K_2CO_3 + N_2 \quad (4)$$

The reaction of sample 5 consists of potassium nitrate as an oxidizer, glucose as a fuel and Aluminum as a catalyst is given in equation 5

$$C_6H_{12}O_6\ (s) + Al\ (s) + KNO_3\ (s) \longrightarrow CO_2 + H_2O + K_2CO_3 + N_2 \quad (5)$$

The reaction of sample 6 consists of potassium nitrate as an oxidizer, lactose as fuel and Aluminum as a catalyst is given in equation 6

$$C_{12}H_{22}O_{11}\ (s) + Al\ (s) + KNO_3\ (s) \longrightarrow K_2CO_3 + N_2 + CO + H_2O \quad (6)$$

Fig. 2 represents the sample of manufactured propellant of fructose as a fuel, potassium nitrate as an oxidizer and Aluminum as a catalyst. The fuel and oxidizer were blended at a 13:7 ratio. The calibrated burning period was 60 seconds, and the highest temperature obtained was 261.75°C.

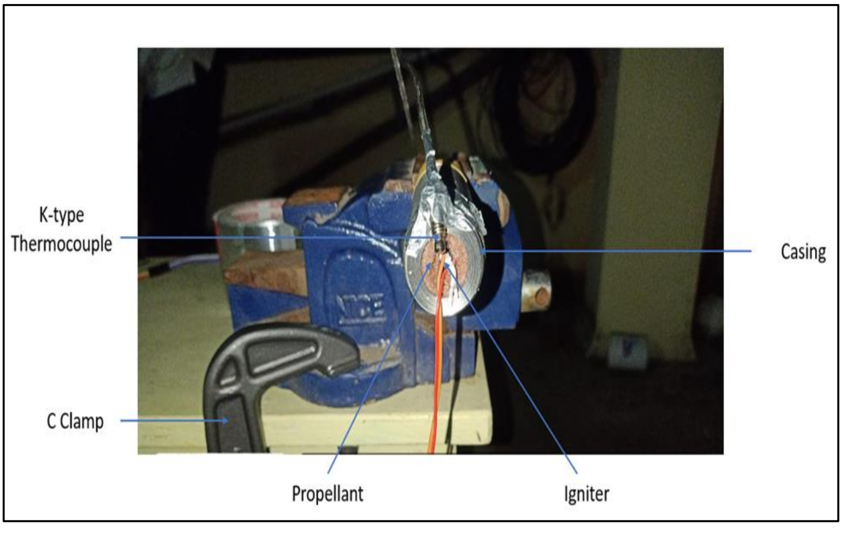

Fig.2 Sample of manufactured propellant (Fuel: Fructose, Oxidizer: Potassium Nitrate and Catalyst: Aluminum)

4.3 Assumptions made for Ideal Conditions

- The combustion products are homogenous.
- The combustion gases are governed by the ideal gas law.

- The specific heat ratio of the combustion gas stays unchanged throughout the engine.
- The flow is adiabatic because no heat is lost through the wall.
- The flow through the nozzle is one-dimensional since temperature and pressure changes are directed axially.
- There is no friction between the rocket motor wall and the exhaust gases, and all boundary layer effects are disregarded.
- The thrust produced is steady throughout the combustion.

5. Setup of Experiment

An ignitor was connected to the exit of the SP. The temperature sensor (K-type thermocouple) is connected to the end of the nozzle. The thermocouple sensor is connected to Arduino UNO which is used to calibrate the input. This UNO Arduino is connected to the laptop where the reading was noted down. A vise was used to hold the stainless-steel cylinder into which the propellant was filled, and a c clamp was used to hold the vise to a table, to prevent the casing from being driven by the propellant's thrust. The same setup was performed for all of the sample studies shown in Fig.3

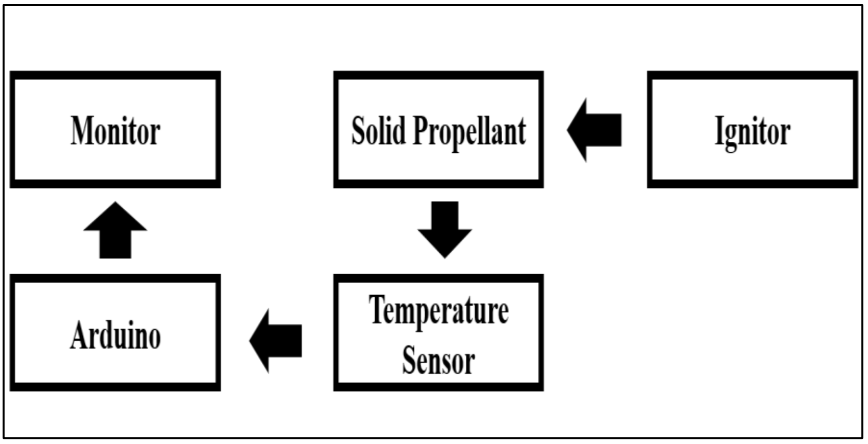

Fig. 3 Schematic Setup of Experiment

6. Experimental Procedure

- The propellant is ignited with the help of an ignitor.
- The propellant starts burning. Since it's a solid propellant, the combustion doesn't stop unless the propellant is burnt completely.
- A thermocouple is connected at the end of the stainless-steel combustion chamber through which the temperature could be calibrated.
- The thermocouple is connected to the Arduino board which transfers the sensor's data into the computer.
- In the computer all the data are stored.

7. Result and Discussion

Considering safety, in this investigation of burnout time of SP with Potassium Nitrate (KNO_3) as the main oxidizer was taken as dry granules and fuel ingredients fructose, glucose, lactose and the catalyst copper and Aluminum mixtures were taken in powdered form. The result shows that the highest burnout time of Glucose with Copper powder and KNO_3 ran out to 136 s when compared to the smallest burnout time of lactose with Aluminum powder and potassium nitrate a mixture of 57 s. The highest temperature of Lactose with Copper powder and Potassium Nitrate went to 518℃ when compared to the lowest temperature of the mixture of Glucose with Aluminum powder and Potassium Nitrate 261.75℃. The combustion time of a solid fuel depends highly on the mode of preparation, particularly the temperature, grain size, catalytic effects, chemical structure, etc. The experiment concludes the simplest way of preparation and with easily available ingredients comparatively, with lesser cost, the burnout time of SPs with different propellant, lactose with copper dominating as a catalyst and Potassium Nitrate combination proved to be the best solution and hence can be used as environmentally friendly even for the economically backward countries can develop solid rocket propellants. Fig. 4 shows the burning of propellant having lactose as a fuel, potassium nitrate as an oxidizer and copper as a catalyst. The fuel and oxidizer were blended at a 13:7 ratio. The calibrated burning period was 68 seconds, and the highest temperature obtained was 518 °C.

Fig.4 Burning of propellant (Fuel: Lactose, Oxidizer: Potassium Nitrate and Catalyst: Copper)

Fig.5 shows the burning of propellant having glucose as a fuel, potassium nitrate as an oxidizer and copper as a catalyst. The fuel and oxidizer were blended at a 13:7 ratio. The calibrated burning period was 136 seconds, and the highest temperature obtained was 211.75℃.

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Fig.5 After the burning of propellant (Fuel: Glucose, Oxidizer: Potassium Nitrate and Catalyst: Copper)

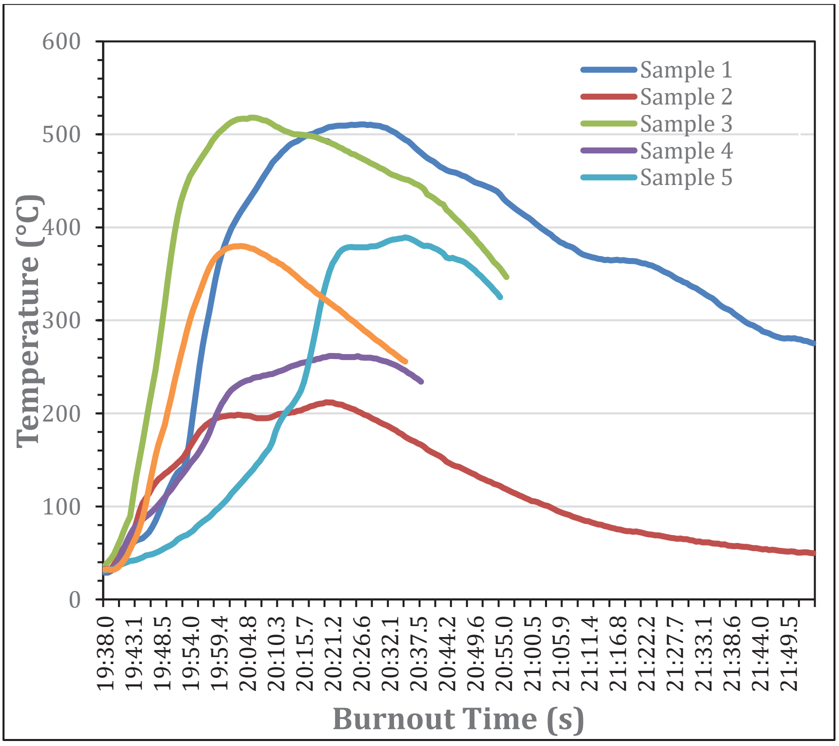

Fig.6 Burnout profile with respect to temperature for all the test samples

In sample 1, the cavity was filled with a mixture of Fructose as a fuel, Potassium Nitrate as an oxidizer and Copper powder as a catalyst used to increase the speed of BT of the propellant. The maximum temperature calibrated was 510.75°C and the BT calibrated was 137 s.

In sample 2, the cavity was filled with a mixture of Glucose as a fuel, Potassium Nitrate as an oxidizer and Copper powder as a catalyst used to increase the speed of the BT of the propellant. The maximum temperature calibrated was 211.75°C and the BT calibrated was 136 s.

In sample 3, the cavity was filled with a mixture of Lactose as a fuel, Potassium Nitrate as an oxidizer and Copper powder as a catalyst used to increase the speed of the BT of the propellant. The maximum temperature calibrated was 518°C and the BT calibrated was 68 s.

In sample 4, the cavity was filled with a mixture of Fructose as a fuel, Potassium Nitrate as an oxidizer and Aluminum powder as a catalyst used to increase the speed of the BT of the propellant. The maximum temperature calibrated was 261°C and the BT calibrated was 60 s.

In sample 5, the cavity was filled with a mixture of Glucose as a fuel, Potassium Nitrate as an oxidizer and Aluminum powder as a catalyst used to increase the speed of the BT of the propellant. The maximum temperature calibrated was 388.75°C and the BT calibrated was 76 s.

In sample 6, the cavity was filled with a mixture of Lactose as a fuel, Potassium Nitrate as an oxidizer and Aluminum powder as a catalyst used to increase the speed of the BT of the propellant. The maximum temperature calibrated was 379.5°C and the BT calibrated was 57 s.

8. Conclusions

The longest burnout mass was obtained by burning Glucose with Copper powder and KNO_3 for 136 seconds. The second longest burnout mass was obtained by burning Fructose with Copper powder and KNO_3 for 132 seconds. The third longest burnout mass was obtained by burning Glucose with Aluminium powder and KNO_3 for 76 seconds. The fourth, longest burnout mass was obtained by burning Lactose with Copper powder and KNO_3 for 68 seconds. The fifth, longest burnout mass was obtained by burning Fructose with Aluminium powder and KNO_3 for 60 seconds. While the shortest burnout mass was obtained by burning Lactose with Aluminium powder and KNO_3 for 57 seconds. The highest temperature reached by the mixture was Lactose with Copper powder and KNO_3 was 518 °C. The second, highest temperature reached by the mixture was Fructose with Copper powder and KNO_3 was 510.75 °C. The third, highest temperature reached by the mixture was Glucose with Aluminium powder and KNO_3 was 388.75 °C. The fourth, highest temperature reached by the mixture was Lactose with Aluminium powder and KNO_3 was 379.75 °C. The fifth highest temperature reached by the mixture was Fructose with Aluminium powder and KNO_3 was 261.75 °C. While the lowest temperature reached by the mixture was Glucose with Copper powder and KNO_3 was 211.75 °C.

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