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Experimental studies on combustion performance of beeswax-paraffin blended solid fuels in a hybrid rocket

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The study intends to investigate the physical, chemical and thermal characteristics of paraffin blended fuels to determine their suitability as a solid fuel in a hybrid rocket. Wax fuels are a viable and efficient alternative to conventional rocket fuels, having excellent structural strength and thermal and mechanical properties. By utilizing both axial and swirl injection technique, the combustion performance of paraffin – beeswax blended fuels have been tested with a fabricated cylindrical grain in a laboratory-scale rocket setting along with oxygen. The test outcomes revealed solid fuel compositions of more beeswax content in paraffin wax on an oxygenated gaseous environment with a swirl-flow injection method has the highest average regression rate of 1.649 mm/sec at 181 kg/m^{2}s mass flux. Axially injected oxygen with pure paraffin wax has the lowest value of 0.85 mm/sec at 96 kg/m^{2}s. The regression rate comparisons revealed that oxygen injection by a swirl injector increased the regression rates by 40% for mass fluxes greater than 80 kg/m^{2}s. Compared to other studies, the combustion efficiencies have been obtained in this study are good. Blended fuels can manage and increase combustion efficiencies for axial and swirl flow conditions. Swirl injectors outperform axial injectors for oxygen injection and allow for a higher proportion of Beeswax combined with paraffin. This study exclusively designed and manufactured an axial injector and swirl injector, according to the required dimensions of a lab-scale hybrid rocket's combustion chamber, injector, and exhaust nozzle, and their performances have been evaluated.

Keywords: Blended solid wax fuels, Combustion, Hybrid rocket, Axial flow, Swirl flow, Regression rate, Characteristic velocity

A hybrid rocket has an oxidizer in the form of a fluid and the fuel in the form of a solid, making it less prone to explosion than solid rocket motors. Solid fuel is loaded into the rocket combustor *via* a structure having a hollowed-out port running the length of its axis. On igniting the fuel, there occurs a flame of diffusion on the surface of the fuel down the length of the port. The long-term viability of combustion through transfer of heat transfer tends to result in fuel vaporization that will continue until the flow of oxidizer is interrupted. Paraffin is a non-renewable resource that is unaffected by most of the chemical substances and burns cleanly and Paraffin is not a particularly allergic fuel. Honeybee wax is a renewable natural wax that provides a clean-burning and brilliant fuel source[1, 2] that is been explored by the hybrid rocket performance with a paraffin fuel to improve the regression rate, which is a viable option for higher-thrust rocket applications. Because of its low melting point, liquefiable fuel burns at the fastest pace, and paraffin fuel has 3 to 5 times faster regression rate than other fuels[3]. From his experiments on a lab-scale hybrid rocket, Karabeyoglu discovered that paraffin-based fuels have a three-fold higher regression rate than standard hybrid fuels[4]. Rajiv Kumar estimated that the hybrid fuel's performance in regression rate is of 30% of paraffin wax, and 70% microcrystalline wax, along with the gaseous oxygen utilizing combustion chamber pressure. In this method, the estimation of mass of fuel burned and regression rate was done using the rocket's nozzle throat choked flow condition. For fuel and oxidizer combinations, the algorithms of regression rate, O/F ratio, and combustion efficiencies were compared to experimental findings obtained using the weight loss approach[5]. The regression rate studies of three compositions of paraffin wax-HTPB hybrid fuel grains in a gaseous oxygen stream using two swirl injectors at a fixed injection condition of pressure were performed[6].The swirl injector SW2 increased 6%, 7%, and 12% in average regression rates for 35P, 50P, and 65P fuels, respectively. Then, the thermal stability and thermal degradation behaviour of the hybrid fuels with SW1 injector were investigated by DTA/TGA techniques. The flame behaviour of a swirl-type oxidizer injection combustor in a rocket engine with a large quartz glass window was observed. In the combustion of both PP and PMMA, the disturbed swirling flames were developed closer to the grain surface than those without swirl, increasing fuel regression rates[7]. The performance evaluation of paraffin wax and polyvinyl chloride (PVC) with gaseous oxygen on injection patterns were done. Combustion efficiency increases of 38% and 14% were also observed using a multi-angle diverging injector for PVC and paraffin wax fuel grains, respectively[8]. The effect of head-end swirl injection under high geometric swirl numbers by numerical method was performed. Head-end swirl injection under high geometric swirl number improved the hybrid rocket motor's fuel regression rate and combustion efficiency. Using head-end swirl injection, the parameters, including oxidizer mass flux, geometric swirl number, and injection velocity component ratio, significantly influenced the hybrid rocket[9]. Martino et al. proposed an optimized injector design that included both the axial and radial orifices to combine their characteristics. The effects of the re-circulation zone over the hybrid rocket's regression rate and combustion efficiency for both non-liquefying and liquefying fuels at various port diameters were observed. Mass flux dependence on the fuel regression rate was also analyzed[10.11]. A series of experimental investigations were performed to optimize the conditions for oxidizer swirl flow and grain configuration to enhance the regression rate of solid fuel. PMMA with gaseous oxygen was the solid fuel used. The test results revealed that, with helical grain configuration, the regression rate increased up to 50 percent[12]. Numerical simulations showed that a helical grain configuration induces swirl flow and increases the turbulence level along the helical grain. Regression rates and burning performance upon the combustion of paraffin/polyethylene were studied[13.] Tarmizi *et al*. investigated the performance of pure palm-based wax as a solid fuel in a hybrid rocket. When burned with oxygen, found that paraffin, lard, Beeswax, a paraffin-lard mixture, and combinations of aluminum and beeswax outperformed normal propellants. A rigorous review of the literature on beeswax hybrid rocket fuels revealed many works by various authors over time[14]. A series of investigations was undertaken at the University of Tennessee[8,9] Knoxville that culminated to a postgraduate thesis[15-17]. And there was another series of annual senior design projects executed at the Central Connecticut State University[18-26] and a peer-reviewed article in the field of beeswax propulsion published by the Egyptian Space Technology Centre[27]. Most of these studies looked into a broader range of bio-derived hybrid rocket fuels. However, beeswax has consistently proven to be the most practicable one. Beyond the original work[16], Scholes added a significant contribution; that is, he did experimental data on beeswax combustion, resulting in regression rates for beeswax[17] that were higher than those reported for paraffin, at all tested oxidizer fluxes[4, 17, 23]. The combustion of bio-derived advanced fuels Beeswax and aluminium to determine regression rates and other operating performances and 2 grain port design losses[23, 25] were analyzed. Naoumov *et al.* analyzed six-year data on bio-mass fuels with oxygen enhanced by aluminium[21]. The swirl injection of oxidizer oxygen is a suitable approach to improve a particular fuel's regression rates. Swirl oxygen gas injection resulted in a three-fold higher regression rate than axial PMMA injection. Compared to longer grains, the swirl is superior at average regression rate improvement for short grains (L/D =5) with big diameters[28, 29]. The injector's impact on the solid fuel regression rate was studied using a pressure swirl atomizer and nitrous oxide injection on paraffin fuel. When compared to direct showerhead injection methods, there is a 20% reduction in the rate of regression[30]. The performance of a fuel HTPB hybrid rocket with whirling oxidizer nitrous oxide, about the internal ballistics characteristics, fuel regression rate, particular impulse, and swirl flow hybrid engine characteristics velocity and combustion efficiency. The result revealed an improved rate of fuel grain regression by using tangential oxidizer injection at the motor head. Swirl flow was 10% more than the axial flow. In this present work, based on the literature findings, a concept is been devised to increase the combustion performance of the oxidizer gaseous oxygen flow by introducing a hybrid motor design incorporated with swirl and axial injection to the beeswax and paraffin wax blended fuel. The present work confers the comparable regression rate improvements using a swirl injector and the axial injector. The average regression rate, local regression rate, and characteristic velocity were been studied as performance measures[31].

Experimental Section

Propellant selection

Paraffin wax and beeswax fuels with oxygen gas as the oxidizer were chosen for combustion in a hybrid rock-et combustion chamber. Paraffin wax ($C_{20}H_{42}$) has a molecular weight of 282 g/mol and beeswax has a molecular weight of ($C_{46}H_{92}O$) 676 g/mol. The melting points of paraffin and beeswax were 47-65 °C and 61-65°C, respectively. The theoretical densities of paraffin and beeswax were approximately 900 kg/m^3 and 950 Kg/m^3[34]

Manufacturing of fuel grain

For our analysis, paraffin and beeswax were blended in various weighting ratios such as 100B, 70B, 60B, 50B, 40B, 30B, and 0B where 70B denotes 70% beeswax & 30% paraffin and so on. Using the casting method, cylindrical fuel grains was produced with inner and outer diameters of 21 mm and 59 mm respectively and a length of 220 mm as shown in Fig. 1.

For each formulation, calculated quantities of paraffin wax and beeswax were melted and stirred for 15 to 20 minutes in a nonstick pan. To keep the liquid from solidifying, the blending container was placed in a water shower at a temperature of 350 K. The mixed wax sludge was projected on a die made of metal comprising a mold and a mandrel. It was then cured under atmospheric conditions for three days before being baked in a hot air oven at 350 K. Because wax shrinks on cooling, the dimensions during casting must be slightly larger than those of the final wax cast. This can be achieved by adding extra wax to the mold to fill the gaps created by the shrinkage, resulting in a propellant grain geometry that fits the hybrid rocket combustion chamber.

Hybrid rocket motor design

The settling chamber of the setup was 76 mm in height and outer and inner diameters were 107 mm and 92 mm, respectively. The injectors were an axial injector with 9 ports and a swirl injector with 12 ports. The injectors were 40 mm in height with 59 mm outer diameter and 21mm inner diameter. The swirl injector ports were 3 mm in circumference and each was held at an angle of 30 degrees horizontally and 5 degrees vertically. The swirl injector was designed for a swirl number 0.339 with respect to the outer and inner diameters and the injector's swirl angle. The combustor had an outer diameter of 74 mm, an inner diameter of 59 mm and a chamber length of 240 mm with a throat-diameter of 32.02 mm and an exit-diameter of 60 mm. The nozzle was a convergent-divergent nozzle. (Fig. 2)

Axial injector

Axial injection is extensively employed in hybrid rocket motors; nevertheless, the motor's combustion efficiency may alter at different times due to the regression of the burning surface. As a result, injector patterns for hybrid rocket motors must be designed in such a way that the overall combustion efficiency can be increased. The rocket injector is the component that introduces the fluid propellant (s) into the thrust chamber at a predetermined mass flow rate (s). It atomizes, distributes, and mixes the propellant in such a way that the fuel-to-oxidizer-to-fuel ratio, mass flow rate, and combustion are all uniform. Turbulence and breakup of axial streams downstream of the injector face are primarily responsible for mixing and atomization. The average combustion efficiency rises as the oxidizer mass flow rate rises. The designed injector is shown in Fig. 3. The axial injector dimensions are as follows.

- The Injector is 40 mm in height.
- Outer and Inner Diameter being- 59 and 41 mm respectively.
- 12 holes each of 3mm dimensions are given around it circumferentially.

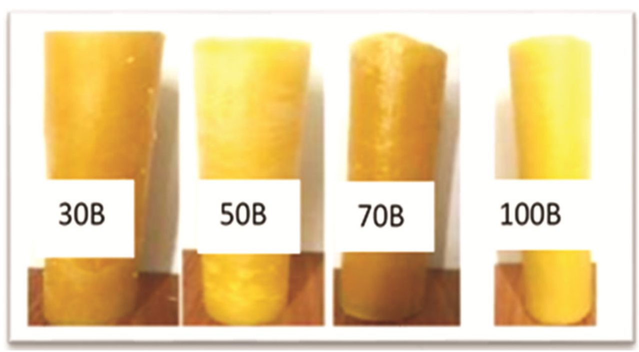

Fig. 1 — Propellant fuel grain.

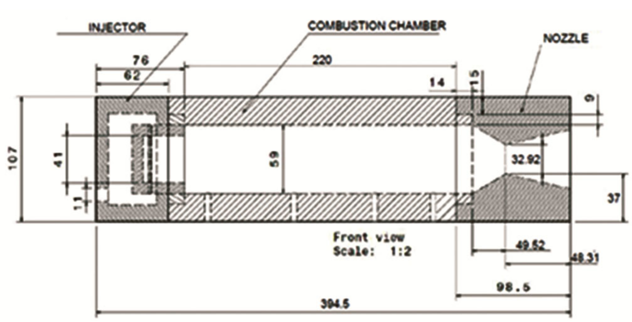

Fig. 2 — Hybrid rocket motor design.

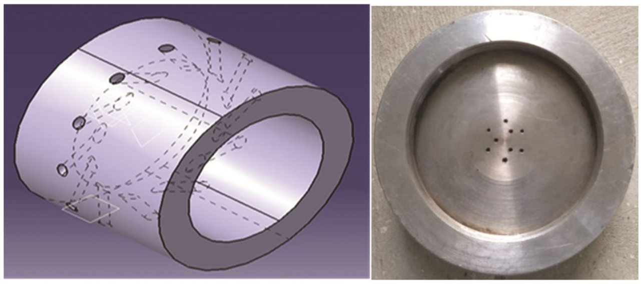

Fig. 3 — Axial injector.

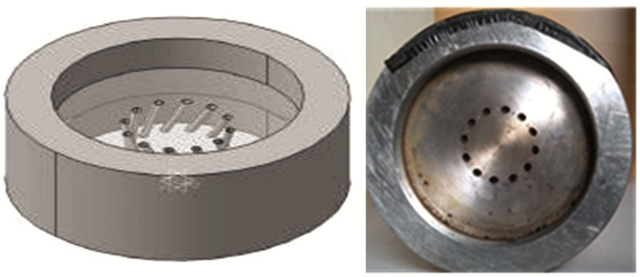

Fig. 4 — Swirl injector.

- Each hole given an angle of 30 degrees.
- The material used is stainless steel.

Swirl injector

In the hybrid rocket motor, the swirl injector generates an additional tangential velocity component in addition to the axial component created by traditional showerhead injectors. When oxidizer streams travel over the fuel surface with this increased velocity in the swirl injector, the thickness of the boundary layer is effectively reduced. In hybrid rockets, research has shown that oxidizer swirl injection and liquefiable fuels like paraffin wax can boost regression rates. Swirl injection increased regression rates by up to 2.4 times compared to axial injection, while also offering smoother operating conditions.

The results show that thrust density of a hybrid rocket can be increased simultaneously by the use of a liquefying fuel and swirl injection. The results show that using a liquefying fuel and swirl injection, the thrust density of a hybrid rocket may be boosted concurrently. The findings of regression rate comparisons revealed that swirl injection enhanced regression rates by 50% for mass fluxes greater than 45 kgs–1m–2. The swirl injector produced better results than the axial one, which is consistent with the literature[32,33]. The fabricated swirl injector dimension used for the testing (shown in Fig. 4) is as follows.

The Injector is 40 mm in height.

- 12 holes each of 3mm dimensions are given around it circumferentially.
- Each hole given an angle of 30 degrees with the horizontal.
- Each hole given an angle of 5 degrees with the vertical.
- The material used is stainless steel304.

Experimental Procedure

A lab-scale hybrid motor was built to conduct static fire testing using a cylindrical grain structure. It was built to investigate the combustion characteristics such as regression rate and characteristic velocity of the blended solid fuels. A settling chamber was attached to the injectors (axial and swirl), followed by a combustion chamber and an exhaust nozzle. A pressure regulating system, an oxygen supply system, an igniting system, and a data collection system were part of the test equipment. The oxidizing mass flow rate was determined using an orifice plate and two pressure transducers.

The average pressure difference was coupled with the upstream pressure data to compute the oxygen flow rate. Fuel grains were fed into the combustion chamber with various fuel compositions. The schematic layout of setup is shown in Fig. 5. A pyrogenic igniter was present at the fuel grain port at the head which was made of potassium nitrate, KNO3 (40% by wt.), and sucrose C12H22O11 (60% by weight). Nichrome wires wound over the igniters were connect-ed to the jumper wire terminals for conductivity. A digital thermocouple present at the nozzle was connected to Arduino Uno over a Max 6675 coupler to measure the temperature conditions at the nozzle during exit. A power supply with a current of 40A and a voltage of 220V was induced from the electrical source. A pressure regulator was used to regulate oxygen gas at a pressure of 1.5 MPa and make it flow through the injector. As the oxidizer flow reached a steady flow in the chamber, the combustion was initiated by the igniter. The static firing test was then carried out for about 0-20 seconds and hot gases were allowed to flow from the combustion chamber through the nozzle and exit with high velocity. A pressure transducer was used to gauge the pressure inside the combustor. The mean fuel flow rate was calculated by dividing the fuel mass lost during the burning process by the burn duration. After a predetermined amount of time, the combustion was terminated by turning off the oxidizer

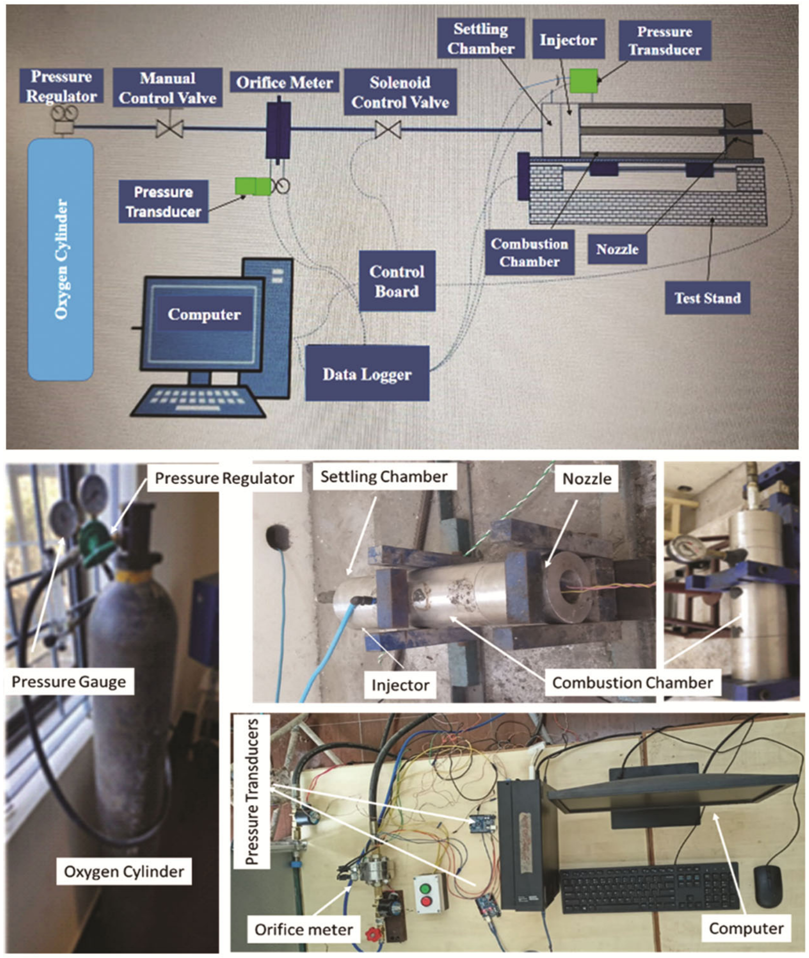

Fig. 5 — Schematic diagram of hybrid rocket setup.

flow. Gaseous oxygen was injected through the axial and swirl flow injectors during the fire tests for blending wax fuels.

Results and Discussion

A series of experiments was carried out using an oxidizer supply pressure of 1.5 MPa set by the regulator. Oxygen injection pressure was the primary variable in the experimental setting that could be controlled; the oxidizer supply pressure was chosen as the study's independent variable. Various mass fluxes were achieved throughout the firing by running various tests at varied mass flow rates.

Uncertainty analysis in instrumentation and measurements

Before and after each test, the mass of the fuel grains was measured on a digital scale (1-gram resolution). The instrumentation errors were 1% (set scale) for timers and 0.3% (full scale) for pressure transducers. An uncertainty study of oxygen mass flow rate for a test, for example, found that the range of uncertainties in mass flow rate measurement lay between the two worst-case scenarios at 16–24%. A test run where only the oxidizer was allowed to flow through the system for 15-20 seconds at an average upstream pressure of 1.5 MPa showed a change in the oxidizer tank mass of 2.1 kg ± 0.2 kg, resulting in an average mass flow rate of 0.07 kg/s ± 0.0067 kg/s and a difference of 11.2 % ± 4.5 % in pressure transducer mass flow rate of 0.042 kg/s .The results were tabulated in Table 1.The uncertainties in determining the regression rate include burn time, initial port dimension, initial fuel mass, and fuel mass burnt in trials. The findings of the initial port combustion radius, burn time, and initial and final fuel grain mass showed uncertainty in regression rate.

The uncertainties were ±0.0015 m, ±0.004 s, ±0.0015 kg, and ±0.075 kg respectively. The other source, the spallation of unburned solid particles or liquid droplets of fuel leaving the nozzle, raised the computed regression rate value without considerably contributing

Table 1 — Oxygen mass flow rate uncertainty for a sample test.

Case	Down Stream pressure (MPa)	Upstream pressure (MPa)	Pressure difference (MPa)	Oxidizer mass flow rate (kg/s)
Low case	1.51	2.31	0.8	0.024
Experimental value	1.56	2.96	1.4	0.035
High case	1.61	1.82	2.1	0.042

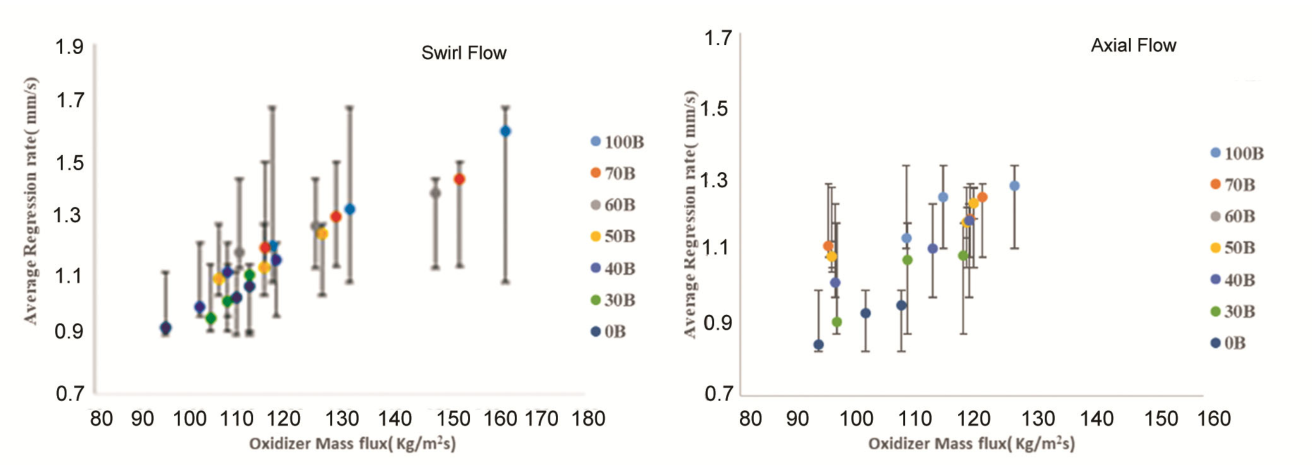

Fig. 6 — Regression rate versus oxidizer mass flux (a) Axial flow and (b) Swirl flow (Repeatability test results).

to the thrust produced. The unburnt fuel uncertainty was estimated as 4% of the fuel grain final mass.

Fuel regression rate

Fuel regression rate is an important performance parameter that influences a hybrid rocket motor's ballistics. The parameters that influence combustion are propellant combination, propellant mass flow rates, fuel choice, and fuel components. Radioactive and convective heat transfer, as well as the entrainment of microscopic droplets from the layers of fluid on the solid surface to the combustion zone, promote combustion and cause mass transfer mechanisms, resulting in faster fuel burning.

The Marxman (1963) gives the average regression rate of a rocket system,

$$\dot{r} = a_0 \bar{G}_{ox}{}^{n} \qquad \ldots (1)$$

Where a_0- regression rate coefficient, n- regression rate exponent, and $\bar{G}_{ox}$- Oxidizer mass flux rate

Oxidizer mass flux for a cylindrical grain is given by,

$$\bar{G}_{ox} = \frac{\dot{m}_{ox}}{\pi\left(\frac{D_i + D_f}{2}\right)^2} \qquad \ldots (2)$$

Where $\dot{m}_{ox}$ – Oxidizer mass flow rate

The diameter averaged approach can be used to compute the regression rate from experiment findings

$$r = \frac{D_f - D_i}{\Delta t} \qquad \ldots (3)$$

D_i-initial port diameter; D_f- final port diameter (average value of the diameters of 3 cross-sections), Δt- burn time

A combustion test of the Hybrid rocket was carried out for a 0-15 second burn duration with solid fuel compositions containing beeswax and paraffin wax in various ratios, in a cylindrical grain design. Gaseous oxygen was allowed to flow through the swirl flow and axial flow injectors for combustion. As the solid fuel grain distance increased, the focused injected gaseous oxidizer through the injector ports decreased, and the reaction between gaseous oxygen and fuel vapors decreased. The combustion performance behavior for different fuel compositions was recorded by static fire testing. Figure 6 indicates that the regression rate for beeswax with swirl injection was the fastest at 1.649 mm/sec with an oxidizing mass flux of 181 Kg/m^{2}sec, compared to 0.93 mm/s for pure paraffin at 89 Kg/m^{2}s. At a mass flux of 96 kg/m^{2}s, paraffin with axial injection oxygen

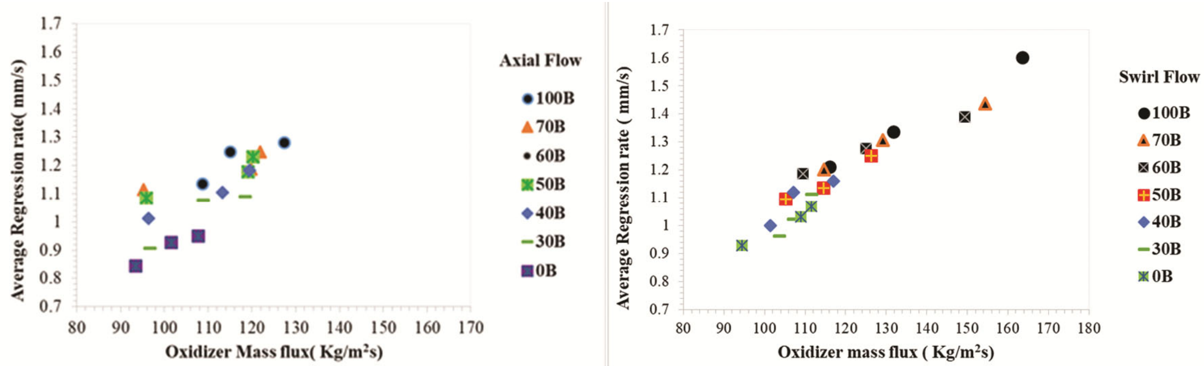

Fig. 7 — Average regression rates for different fuel compositions (Axial flow & Swirl flow).

achieved 0.85 mm/sec, while pure beeswax achieves a maximum of 1.43 mm/s at 129 kg/m^{2}s flux. Blended fuel had a higher regression rate than 100% paraffin. The performance of a swirl injector was substantially higher than that of an axial injector.

The outcomes were found to be consistent with results reported in earlier work. The regression rate of paraffin wax/oxygen was earlier reported by Putnam to be 1.2 mm/s, and that of beeswax/oxygen was 1.8 ± 0.33 mm/s.[15]. The regression rate of paraffin-based fuel was reported [35] to be 1-3 mm/s at 40-110 kg/m^{2}s oxidizer mass flux. Karabeyoglu found a regression rate in the range of 0.5 mm/s–2 mm/s with an oxidizer mass flux of 50-150 Kg/m^{2}s using paraffin/oxygen[4].

Naoumov showed the performance of palm-based paraffin to lie in the range of 0.5 mm/s to 1 mm/s at an oxidizer flux of 70 -140 Kg/m2s and that of beeswax to lie between 0.6 mm/s to 1.4 mm/s at 45-145 Kg/m2s oxidizer flux 23. (Fig. 7). The performance on axial and swirl flow injection were tabulated in Table 2. In our work, it was seen that increasing the content of beeswax in the blend resulted in a faster rate of regression than pure paraffin. Furthermore, since the beeswax had a wider scope for regression rates, it was hard to quantify the enhancement of regression rate over paraffin. The difficulties in calculating the regression lay in the accurate assessment of the fuel initial mass and the fuel mass burnt in experiments. Despite of the vulnerability in the regression rate estimation, the differences were prominent and noteworthy. The overall mass flux rate accounted for both the fuel and the oxidizer, and was calculated using the fuel's average flow rate across the burn duration.

Table 2 — Beeswax-paraffin-blend fuel composition test results (Swirl & Axial flow).

Fuel composition	Regression rate coefficient(a)	Regression rate exponent(n)	Rate law
100B	0.089	0.56	$\dot{r} = 0.025\ G_{ox}^{0.82}$
70B	0.096	0.54	$\dot{r} = 0.07\ G_{ox}^{0.6}$
60B	0.137	0.47	$\dot{r} = 0.11\ G_{ox}^{0.50}$
50B	0.243	0.34	$\dot{r} = 0.04\ G_{ox}^{0.74}$
40B	0.139	0.44	$\dot{r} = 0.012\ G_{ox}^{0.97}$
30B	0.147	0.42	$\dot{r} = 0.014\ G_{ox}^{0.42}$
0B	0.154	0.41	$\dot{r} = 0.024\ G_{ox}^{0.80}$
Fuel composition	Regression rate coefficient(a)	Regression rate exponent(n)	Rate law
100B	0.024	0.82	$\dot{r} = 0.044\ G_{ox}^{0.72}$
70B	0.049	0.67	$\dot{r} = 0.22\ G_{ox}^{0.35}$
60B	0.051	0.64	$\dot{r} = 0.045\ G_{ox}^{0.68}$
50B	0.066	0.58	$\dot{r} = 0.123\ G_{ox}^{0.46}$
40B	0.103	0.48	$\dot{r} = 0.045\ G_{ox}^{0.68}$
30B	0.097	0.49	$\dot{r} = 0.013\ G_{ox}^{0.93}$
0B	0.07	0.55	$\dot{r} = 0.02\ G_{ox}^{0.86}$

Local regression rate

The purpose of estimating local regression rates is to look at how solid fuels burn along the grain's length. Following the completion of the test, the cooled solid fuel grain was removed from the casing. The local regression rate was calculated by measuring the un-burned fuel grain thickness at each 20 mm distance. Figure 8 shows that pure paraffin wax fuel had the lowest rate of local regression, which varied between 0.92 and 0.95 mm/s for swirl flow and 0.9875–1.024 mm/s for an axial flow injection of oxygen gas. Because of the zone of flame, which is significantly closer at the end of igniter, the local regression rate for all compositions of beeswax and paraffin wax showed larger rates at the start of the fuel grain length, almost constant rates in the middle, and reduced rates towards the end of exhaust nozzle.

When there is an increase in the size of the boundary layer during combustion. The heat flow along the fuel surface reduced as the zone of flame advanced away from the fuel.

The increased regression performance during the first phase of combustion might be attributed to complete reactions due to good vapor mixing. The oxidizer mass flow concentration dropped as the fuel grain neared the nozzle's end. The flow parameters that balance heat transfer remained constant in the middle of the grain. As the proportion of beeswax in the composition grew, the rate of local regression enhanced at all points in line with the grain. For an axial flow, the local regression rates of fuel samples 0B,30B, 40B, 50B, 60B, 70B, and 100B were 1.02–1.05, 1.09–1.13, 1.2–1.258, 1.325–1., 1.385–1.428 & 1.48–1.52 mm/s and for a swirl flow, the rates were 0.9875–1.024, 1.0275–1.049, 1.1375–1.116, 1.25–1.29, 1.35–1.408, 1.46–1.512, & 1.625–1.649 mm/s respectively.

Chamber pressure variation with time

The pressure readings in the combustion chamber were recorded and plotted between 0 to 15 seconds of fuel burn. The most critical phases of the motor test firing were the ramp-up, steady state, and cut-off phases. Figure 9 shows this for the 100B and 30B samples. There was a rise in average pressure with grain burning radially outward for a cylindrical grain, and HRE profiles were moderately regressive and slightly ramped down close to neutral burning. The chamber pressure dropped slightly from the start of the firing, but when the oxidizer mass flow rates increased, a greater pressure decrease was seen from the start to the end of the combustion. A sharp pressure rise was observed upon engine ignition, which was attributed to primer charge ignition. The igniter burned and produced significant amounts of heat and combustion fumes when it was turned on. The pressure-time profile for the cylindrical grain at 0.9 MPa showed that as the oxidizer mass flow increased, chamber pressure also increased, and thereby there was an increase in the burning rate. The pressure level increased due to the expansion of the combustion gases, and the ramp-up phase was reached. The chamber pressure decreased towards the conclusion of the burn during steady-state operation, which can be attributed to a change in the fuel mass flow rate pressure pattern. A blended 30B fuel sample showed a similar chamber pressure pattern. A drop in chamber pressure was seen after the combustion of

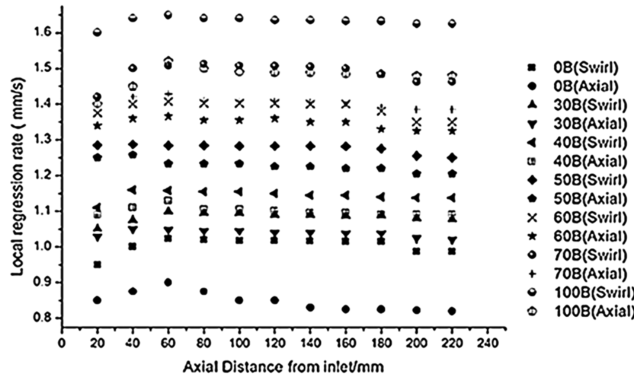

Fig. 8 — Local regression rates for blended fuel (Axial flow & Swirl flow).

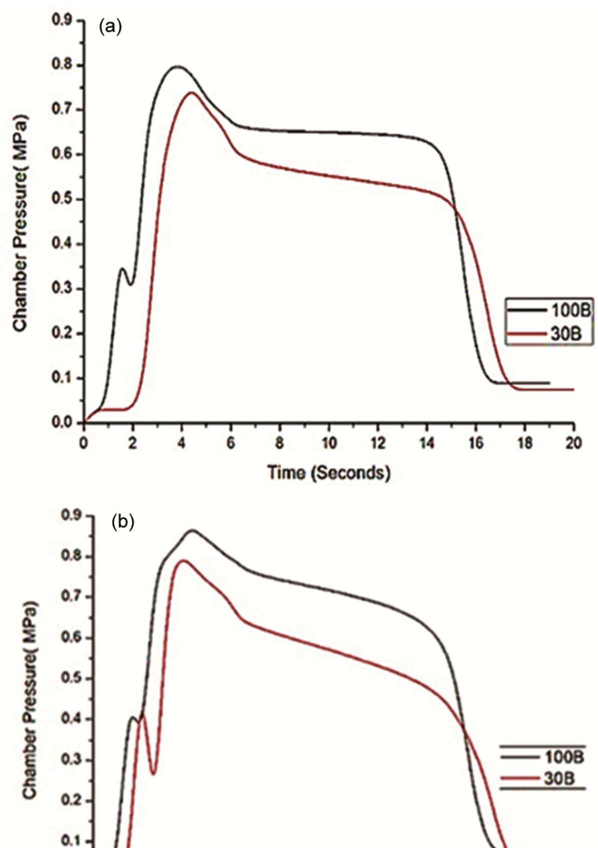

Fig. 9 — Chamber pressure- Time trace (a) Axial flow and (b) Swirl flow.

the fuel grain during the initial phase of the burn produced by the widening of the fuel port.

The above observations may be because the combustion chamber pressurization rate is influenced by the turbulent flame propagation speed. A sufficient amount of paraffin fuel vapors was produced during the igniting phase, allowing the flame to spread. Due to the presence of turbulent mixing within the engine, the flame propagation was extremely fast. A more intriguing finding is that pure beeswax fuel exhibits significant pressure instability in the chamber.

Characteristic velocity

Characteristic velocity is a function of the pairs of propellants selected and combustion efficiency. It is a performance parameter that is been frequently used to compare various combinations of fuels, as each pair has a different adiabatic flame temperature and different specific heat. The ideal characteristic velocity is for the same specific heat ratios, and the maximum characteristic velocity is obtained on maximizing the T/M ratio (Fig. 10) . The ideal values of characteristic velocity are obtained in the thermochemical reaction for all propellants. In our work, the characteristic velocity was calculated from the mass flow rate of propellant during the fire testing corresponding to the chamber pressure condition and nozzle geometry, and the experimental results were compared with ideal results in terms of efficiency. By dividing the estimated characteristic velocity by the ideal characteristic velocity, the combustion efficiency of the beeswax-paraffin blended fuel was calculated.

Characteristic velocity is generally used to describe the quantity of energy released during the process of fuel burning. In our work, the NASA CEA algorithm was used to calculate the theoretical characteristics velocity, and the experimental characteristic velocity (C*exp) was calculated by

$$\dot{m} = \frac{P_c A_t}{C^*} \quad \ldots (4)$$

Where,

$\dot{m}$-Average propellant flow rate, A_t- throat area of the nozzle, and P_c - average chamber pressure.

The efficiency of characteristic velocity was assessed by

$$\eta = \frac{C^*_{exp}}{C^*_{theo}} \quad \ldots (5)$$

Figure 10 shows theoretical, experimental, and characteristic velocities for all mixed fuels in terms of O/F ratio. It is worth noting that all fuel compositions had high characteristic velocities when the Oxidizer-Fuel ratio (max) was in the range of 1.5 to 2, whereas the stoichiometric O/F ratio was in the range of 2.18 to 2.95. The ideal O/F ratio determines the characteristic velocity C*. The characteristic velocity efficiency ranged from 61.9 to 87 percent for all fuel compositions (Fig. 11). Beeswax and paraffin were used together to boost the typical characteristic velocity efficiency.

The stoichiometric ratio, oxidizer mass flux, and the rocket engine characteristic length, all influence combustion efficiency based on characteristics velocity[4]. The characteristic velocity was enhanced by increasing the mass flux and scale of the motor. Based on the data, it is concluded that blending paraffin fuel with beeswax has an impact on the hybrid rocket's combustion efficiency and performance of the engine. The experimental results differ from the theoretical calculation due to some uncertainty in the mass flow rates of fuel and oxidizer (stoichiometric conditions), and due to the temperature and pressure settings of the combustor and the instrumental errors in the test measurements.

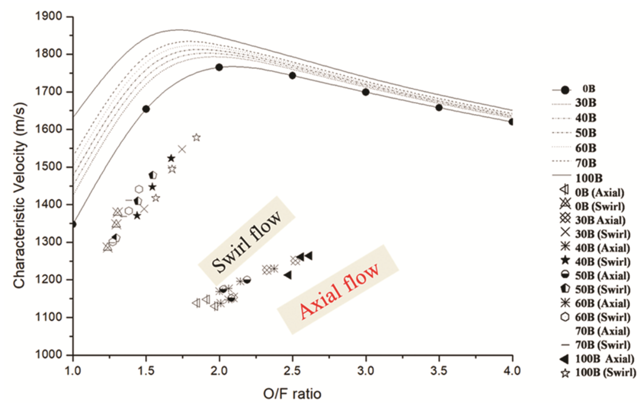

Fig. 10 — Characteristic velocity variations for blended fuel (Axial flow & Swirl flow).

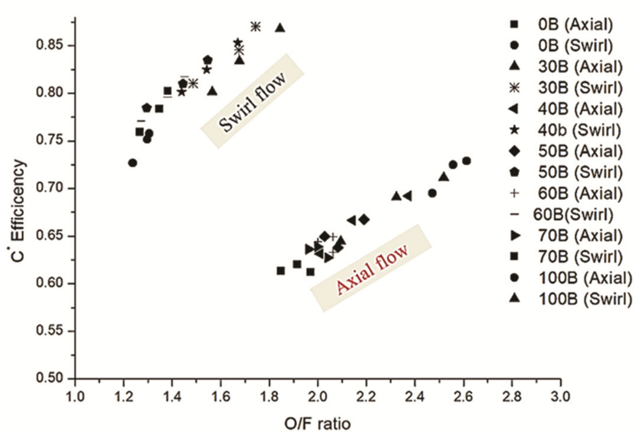

Fig. 11 — Efficiency versus O/F ratio for blended fuel (Axial flow & Swirl flow).

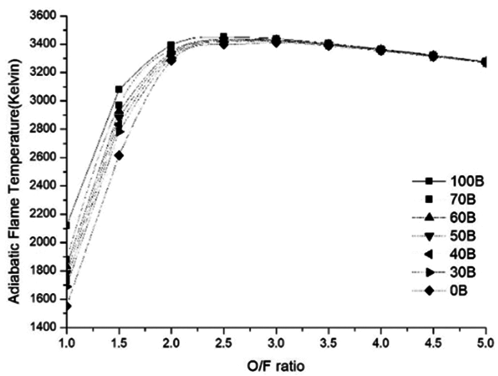

Fig. 12 — Adiabatic flame temperature variation with O/F ratio.

Adiabatic flame temperature

The maximum temperature of the products reaches a value called the adiabatic flame temperature, provided there is no loss of heat to the environment during complete combustion closer to stoichiometric air.

The adiabatic flame temperature depends on the air's mass, the degree of the reaction, and reactants. It is an essential design parameter for exhaust nozzles and combustors. There is, however, heat loss to the surrounding and the adiabatic flame temperature cannot reach theoretical values due to incomplete combustion of the reactants. Figure 12 shows the adiabatic flame temperature plot for the different propellant mixture ratios. A peak temperature of 3393 K was seen for beeswax: paraffin mixture ratio of 2.5 and a value of 1559 was seen for 100 percent Beeswax. It was seen that the adiabatic flame temperature increased with the O/F ratio up to a value of 2.5 and started decreasing for all cases. The higher the heat energy causes, the more energy is being trans-formed into kinetic energy, and it directly affects the performance.

Conclusion

The primary purpose of this research was to find out how fast non-conventional hybrid rocket fuels regressed. The paraffin wax and beeswax were been used as fuels, and five distinct compositions were considered. Over a series of static fire experiments, combustion analysis of a lab-scale hybrid rocket set up with axial and swirl injection of gaseous oxygen was been successfully carried out with solid fuel compositions of beeswax and paraffin wax using a simple cylindrical grain design. Average and Local regression rate and combustion efficiency behavior were analyzed; the local regression rate of pure paraffin was the lowest among all five formulations. Regression rates were greater in the combined fuel and pure Beeswax. The improvement in rate of regression is due to a lowering in the fuel viscosity. Swirl injectors offer a substantially higher burn area on the fuel grain surface than axial injectors, and oxidizer mass flow with swirl injectors delivers significantly higher regression rates than axial injectors. When compared to pure paraffin, pure beeswax, and 70B composition average regression rate is higher. These findings show that mixing Beeswax with paraffin can improve the performance of polymeric fuels in terms of regression rate. During the firing of the Paraffin-Beeswax blended fuel test, stable combustion was being obtained, while the pure beeswax fuel displayed very low-pressure fluctuations. The fuel grain composition with more percentage of beeswax provides the highest regression rate value of 1.649 mm/sec at 181 kg/m2s flux for 100 % Beeswax and 1.512 mm/s at an oxidizer flux 162 kg/m2s for 70 % Beeswax blended fuel. As a result of this work, all testing was carried out over an average burn time of 15 to 20 seconds; a swirl injection with the maximum beeswax content in a fuel composition provides us the best and highest possible performance. It is also being determined that combining paraffin and beeswax can influence motor performance and combustion efficiency

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