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Review on the regression rate-improvement techniques and mechanical performance of hybrid rocket fuels

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ABSTRACT

Human spaceflight, space tourism, and the launch of microsatellites are all expected to grow in the future. In fact, with the recent increase of the satellite market, almost 1000 smallsats per year are foreseen to be launched over the next decade. Hybrid rocket propulsion has received significant attention for military and commercial applications due to its potential safety, throttleable, and restart ability when compared with solid rockets, economicity, simplicity, and compactness features when compared to liquid rockets. However, in order to make this new technology the future of the next generation of rockets, some drawbacks of the heterogeneous combustion in hybrid rockets such as low fuel regression rate and varying oxidizer-to-fuel ratio during the combustion process must be well addressed. The diffusion-limited combustion in hybrid rocket motor is responsible for the low regression and poor combustion efficiency of fuels such as Hydroxyl-terminated polybutadiene (HTPB), Poly methylmethacrylate (PMMA), and other polymeric binder-fuels. The paraffin-based solid fuel represents a potential solution to the slow regression rate of current solid polymeric fuels. However, paraffin-based fuels suffer from poor mechanical properties and rapid volatilization, preventing their full development and applications for a space mission. In this work, a review of various techniques to improve hybrid rocket fuel's ballistic and mechanical performance is presented.

Introduction

In recent years, there has been renewed interest in hybrid rocket propulsion for a potential manned space exploration mission. A hybrid propulsion system utilizes both solid and liquid fuels. Based on the propellant physical state, it can be grouped into two classes: 1. a direct hybrid system, which is the common configuration that utilizes fuel in the solid phase and oxidizer as liquid (Fig. 1); 2. a reverse hybrid system with an oxidizer in a solid-state and fuel in the liquid phase [1]. This concept is not as practical as the classical system because the solid oxidizer requires a more critical fabrication process and has less attainable performance.

Hybrid rocket takes several advantages of their liquid and solid rocket counterparts and makes feasible for many space applications. Hybrid propellant rockets are able to compete in the application areas of liquid and solid propellant rockets due to enhanced safety, insensitive to cracks and imperfections in fuel grain, reduced plumbing complexity, thrust modulation, and restart capabilities. In addition, the solid fuels are compatible with any oxidizer combination, and it can be casted with a variety of additives for purposes such as high-energy missions and tailoring the plume signature for military applications. In view of mission cost, the hybrid propulsion system is economical to manufacture and launch due to low storage cost and transportation [2]. The added advantage is the safety due to its low explosive nature. Moreover, the hybrid rockets have environmentally clean exhaust due to the absence of hydrogen chloride or oxide with respect to solid rocket propellants.

Despite many attractive characteristics listed above, the hybrid rocket has fewer shortcomings, which prevented its full development from achieving the technology readiness level (TRL). The main drawbacks for hybrid rockets are the low fuel regression rates, low volumetric loading, fuel-to-oxidizer ratio shift, and relatively poor combustion efficiency. The rate at which the solid fuel is converted to gaseous vapour is known as the regression rate [3]. The low regression rate and poor combustion efficiency are due to non-uniform diffusion into the combustion zone. This result in poor mixing of fuel and oxidizer, and these characteristics are unsustainable for long-duration application. In hybrid rockets, classical fuels such as Hydroxyl-terminated polybutadiene

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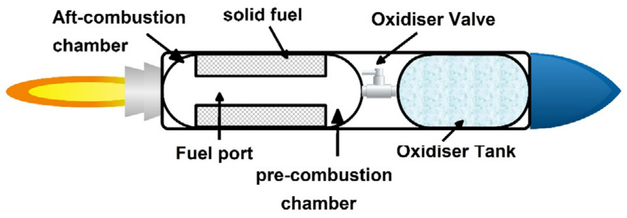

Fig. 1. A typical hybrid rocket system (direct configuration).

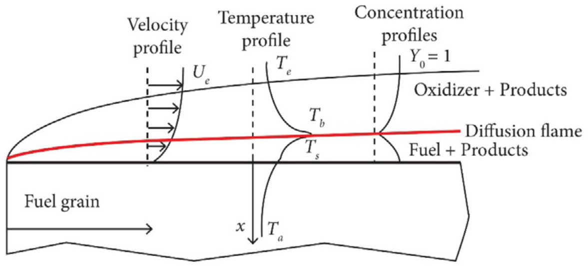

Fig. 2. Marxman's flat plate diffusion-limited combustion model [40].

(HTPB), Polymethylmethacrylate (PMMA) are characterized for low regression rates [4–9].

Several improvements have been made in recent years to address the issue of low regression rates. Physical design modifications, such as swirl oxidizer injection [10–14], multi-port fuel grain [15], metallic additives [5,16–24], and embedding mechanical devices in the fuel grain [25–29] are typical improvement approaches. The paraffin-based solid fuel stands out as a potential solution to solve the slow regression problem of traditional solid polymeric fuels [4,30–32]. Despite its poor mechanical strength to withstand the structural deformation during grain fabrication, casting, handling, and transportation it has rapid volatilization [33,32,30,31,34]. Furthermore, paraffin-based fuels have a low combustion efficiency, resulting in unburned paraffin droplets blowing out through the nozzle exhaust during combustion [35]. The mechanical performance of paraffin-based solid fuels can be improved with the addition of various additives [33].

A review of various techniques to enhance the regression rate performance of paraffin-based fuels is presented and discussed. The effect of multiple additives on the mechanical performance of paraffin-based fuels and their effect on regression rate has not been thoroughly explored and needs a concise review to balance the ballistic and mechanical performance of paraffin-based fuels.

Combustion process in hybrid rocket

In a hybrid rocket, the combustion of fuel and oxidizer vapours takes place in the boundary layer over the fuel surface. Researchers developed several combustion models to represent the combustion within the boundary layer thickness and the physical and chemical processes involved [36–39]. Marxman et al.[36] developed the first boundary layer combustion model for classic polymeric fuel (see details in section 2.1).

Diffusion-limited combustion theory

Marxman and Gilbert developed a regression rate model using a flat plate combustion approach in the turbulent boundary layer [36]. The model was developed during the 1960s and is still widely used to study the hybrid rocket combustion process (Fig. 2).

The oxidizer is injected within the combustion chamber and, after ignition, a reacting turbulent boundary layer develops over the solid fuel surface. The solid fuel pyrolyzes and vaporizes as it passes through the boundary layer. The oxidizer vapour diffuses toward the fuel vapour from the core flow region via turbulent diffusion. A diffusion flame region forms in the boundary layer where the fuel-to-oxidizer stoichiometric conditions are achieved. Marxman found that the flame resides at approximately 10–20% of boundary layer thickness above the fuel surface. The heat transfer from the flame zone to the solid fuel surface provides the pyrolysis energy for stripping the new fuel from the solid fuel surface and sustaining the process [41].

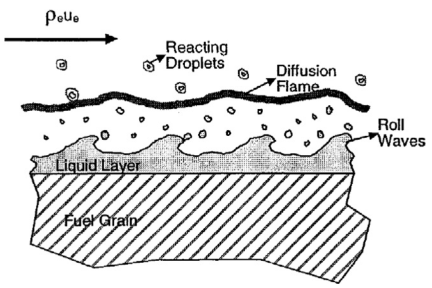

Fig. 3. Entrainment model of paraffin-based solid fuel[47].

The heat transfer to the fuel surface is mainly due to convection between the flame and solid fuel surface. If the fuel is loaded with metal additives, there is also the contribution of the radiative heat transfer. The fuel mass degrades from the solid surface in the boundary layer and diffuses toward the flame zone. Convective heat transfer from the flame zone to the fuel surface decreases, resulting in a "conductive blockage" [42]. The blockage effect lowers the rate of fuel regression. The regression rate derived for the diffusion-limited combustion model is presented in Eq. (1)

$$\dot{r} = aG_{ox}^{n} \tag{1}$$

Where $\dot{r}$ is fuel regression rate, G_{ox} is oxidizer mass flux and a and n are regression rate exponents. A research group led by Kuo and Chiaverini at Pennsylvania State University has contributed significantly to the understanding of radiative heat transfer in a hybrid rocket engine [43] and its correlation with the regression rate. They stated that the radiative heat flux from soot and gas-phase combustion products improves the regression rate along with the blocking effect, which decreases the convective heat transfer. Many researchers have attempted to improve the regression rate of classical polymeric fuels using non-conventional grain design, changing the flow pattern of oxidizer injection, generating the turbulence, or eddied in the combustion chamber (use of diaphragms), and addition of energetic additives [12,16,28,29,44,45]. However, these performance enhancement techniques improved the regression rate but ended up with complex motor design and manufacturing.

Liquefying fuels combustion theory

During the 1990s, solid cryogenic fuels were tested for high regression rates at U.S. Air Force Research Laboratory [39]. They reported high regression rates of about 3 to 10 times compared to traditional polymeric PMMA fuel. However, the authors failed to report the physical and chemical processes involved in the relatively high regression rates. The convection heat transfer from the flame zone to the solid fuel surface limits the regression rate of classical polymeric solid fuels [46]. As a result, the net regression rates of these polymeric fuels are much lower compared to solid propellant (typically burn rate of 1 cm/s). Later, Karabeyoglu developed a combustion model for liquefying solid fuels to explain the physics underlying the high regression rates of cryogenic fuels [47]. The high regression rate was due to the entrainment mass transfer mechanism [47]. The entrainment of melted paraffin droplets was due to oxidizer flow over solid fuel surface (Fig. 3).

In this combustion model, a low viscosity liquid melting layer forms on the surface of the solid fuel. The high-velocity oxidizer is injected at one end of solid fuel, which destabilizes this liquid layer. The melting layer instability generates liquid fuel droplets and rolling waves.

Compared to conventional mass transfer via gasification from the fuel surface, the additional mass transfer is generated by the entrainment of liquid droplets to the combustion zone. Therefore, the overall regression rate for the entrainment model can be written as in Eq. (2) [47]

$$\dot{r}_{tot} = \dot{r}_{gas} + \dot{r}_{ent} \tag{2}$$

Where $\dot{r}_{tot}$ denote the total regression rate, $\dot{r}_{gas}$ is vaporization regression rate component, and $\dot{r}_{ent}$ is the regression rate due to entrainment of liquid paraffin droplets to the combustion zone.

The entrainment of mass from solid fuel surface highly depends on the instability of the melting layer. Several researchers investigated the instability of the melting layer under oxidizer injection pressure [30,48–50]. Karabeyoglu et al. [47] suggested an empirical expression for calculating the mass entrainment transfer of liquefying hybrid rocket fuels.

$$\dot{m}_{ent} = \frac{p_d^{\alpha} h^{\beta}}{\mu_e^{\gamma} \sigma^{\pi}} \tag{3}$$

Where $\dot{m}_{ent}$ is entrained mass flow, p_d^{α} is the dynamic pressure h^{β} is melt layer thickness,μ_e^{γ} is surface tension, and σ^{π} is the melt layer viscosity.

Their experimental result suggested that the dynamic pressure exponent α value varies between 1 to 1.5. The values of β,γ and π were predicted as 2,1 and unity, respectively. Also, it was suggested that viscosity is a key parameter in the hybrid rocket for entrainment mass transfer rate. At Stanford University, the paraffin-based fuel tested under the gaseous oxygen as oxidizer reported a 3-4 times higher regression rate than classical polymeric fuels. The researchers also validated their predicted entrainment theory with a scale-up test conducted on the large motor. These effective methodologies to increase the regression rate can significantly increase the thrust level for the desired mission.

Regression rate enhancement techniques

The regression rate of conventional hybrid rocket fuels is low, which is undesirable for the required thrust level in space applications. Several research activities have been proposed to overcome the slow regression rate problem, and many successful techniques were implemented. The fuel regression rate is a motor design parameter and is affected by fluid dynamics in the combustion chamber, grain geometry, and chemical properties of solid fuel. The regression rate enhancement techniques can be classified into two different methods: [51] fluid dynamics and chemical methods. In the fluid dynamics method, turbulence must be boosted into the core flow to improve the oxidizer/fuel mixing and the heat transfer to the solid. The swirl or vortex oxidizer injection and mechanical device embedded in solid fuel are used to generate the turbulence in the combustion port, enhancing oxidizer and fuel mixing. The chemical method includes the doping of solid fuel with energetic metal additives or light metal hydrides to improve the kinetics of fuel/oxidizer combinations, to increase the combustion heat release and consequently the flame temperature, and lastly to increase the density of the solid fuels, which eventually can enhance the density specific impulse of the rocket motor. These regression rate enhancement techniques are discussed in detail in the following sections.

Vortex/Swirl oxidizer Injection

The vortex oxidizer injection technique was first developed by Knuth et al. [44] at Orbital Technologies in the mid-1990s to enhance the solid fuel regression rate. In the vortex hybrid approach, the swirl oxidizer flow is created in the combustion port by a pair of coaxial and bi-directional vortices. The oxidizer was injected at the nozzle end of the motor, and the vortex spiraled toward the head end of the motor, as shown in Fig. 4. This swirling motion increases the residence time, the oxidizer and fuel vapors mixing and the stripping of fuel from the surface. At the head end of the motor, the vortex turned inward, around the motor axis, traveled down the nozzle end [44].

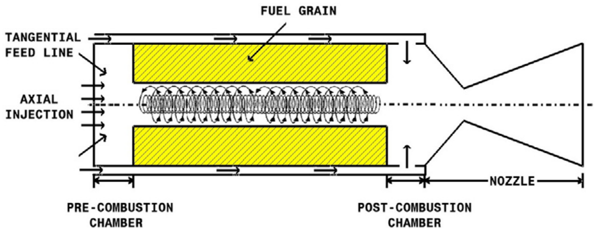

Fig. 4. Vortex-oxidizer injection system.

The HTPB/GOx propellant system (Gox = 32.63 kg/m^{2}s-100 kg/m^{2}s) was used, and the regression rate improved by 475% when compared to axial oxidizer injection. A regression correlation model was developed and validated with numerical simulation. It was concluded that the highly swirling flow near the fuel surface is responsible for high convective heat transfer from the flame zone to the solid fuel surface. Several studies have also shown that by altering the flow structures at the combustion port, such as by adopting helical grain design, the turbulence intensity and, as a result, the burning surface area can be increased [10,29,52–54]. Their approach was to enhance the regression rate of fuel using both swirl oxidizer injection and helical grain configuration. Lee *et al.* [10] performed experimental and numerical studies on PMMA and gaseous O$_2$ as an oxidizer. The helical fuel grains were produced with varying pitches (6–100). The greater regression rate was achieved with a lower pitch grain configuration when a strong oxidizer swirl was injected. Their numerical results were in good agreement with the experimental results. It was concluded that the grain with a higher pitch number provides the maximum regression rate.

Table 1 summarizes the regression rate data and results of the swirl/vortex oxidizer injection technique for different fuel and oxidizer combinations. These results show comparable regression rate trends, with swirl/vortex oxidizer injection improving the regression rate over the tested oxidiser mass flow range. In the hybrid system, the intensity of swirl oxidizer injection can significantly affect the rate performance of solid fuel.

Yuasa *et al.* [14] experimentally investigated the effect of swirl intensity on local regression rate for a PMMA/GOX hybrid motor. It was reported that the regression rates were higher at the head end of the motor and diminished along grain length. The regression rate increased about 2.7 times compared to axial oxidizer injection and reported a strong swirl strength influence on the regression rate. By varying the oxidizer swirl number and the ratio of tangential velocity component to axial velocity component, the tangential and axial momentum of the oxidizer can be altered: this can alter the oxidizer swirl strength and modify the fluid dynamics of the oxidizer in the combustion port. Lee *et al.* [10] studied the effect of oxidizer swirl strength on regression rate. The regression rates were improved up to 200% as the intensity of the swirl was varied. However, this improvement was dominated mainly at the injector-end of the motor.

Paraffin-based hybrid fuels are characterized by high regression rates. Though pure paraffin has poor combustion efficiency due to low thermal stability and blowout of unburnt paraffin from the fuel surface, the combustion efficiency of paraffin can be improved by using a small combustion chamber volume at the end of the motor, which allows the unburnt fuel to burn with an oxidizer. Saito *et al.* [13] tested paraffin-based fuel on a lab-scale motor incorporating the aft-combustion chamber. The combustion efficiency was improved up to 90% with varying the aft-combustion chamber volume.

Multi-section swirl injection is another interesting technique for changing the fluid dynamics of oxidizer flow in the combustion port (Fig. 5). In this method, an oxidizer cavity is created between the fuel grain and combustion chamber through which the oxidizer is injected at a different section of the fuel grain. The multi-section swirl injection

Table 1
Regression rate data of various fuel/oxidizer combinations for Swirl/vortex oxidizer injection technique

Fuel	Oxidizer	Oxidiser mass flux range(kg/m^2 s)	Regression rate (mm/s)	Major findings	Ref.
PVC-DBP	GOx	52–240	1.3–2.1	The multi-location swirl injection approach reported a regression rate improvement of about 72% at higher Gox, while at lower Gox, it was around 100%. The use of a swirl injector enhanced combustion efficiency from 50% to 74%.	[66]
HTPB	GOx	25.8–121.8	1.23–3.6	The vortex oxidizer injection improved the average solid-fuel regression rates up to seven times compared to the classical hybrid. A regression rate correlation was developed to describe the effect of heat transfer on the regression rate.	[44]
HTPB	N_2O	28.4–38.3	0.56–0.72	The average spatial and temporal technique was developed to predict the fuel regression rate under swirl oxidizer flow. Tangential oxidizer mass flux was attributed to regression rate enhancement. Swirling oxidizer flow in combustion port reported complete combustion.	[67]
PMMA	N_2O	32–79	0.27–0.51	Swirl oxidizer injection increased the residence time of oxidizer flow and exhibited a higher regression rate. A suitable combination of the helical grain design and the swirl injector reported the highest improvement in regression rate.	[10]
Paraffin	GOx	18.1–40.7	0.7–6.41	Swirl injection enhanced regression rates by 2.4 times compared to axial injection while delivering smoother operating conditions.	[68]
HTPB+ SUGAR	GOx	41.5–133.1	0.35–0.59	The regression rates were enhanced up to 20.23% with swirl oxidizer injection. However, it exhibited uneven fluctuations along the fuel grain length.	[69]
PE	H_2O_2	50–360	0.52-4.83	With the multi-section swirl injection method, the average fuel regression rate was increased by 8.37 times.	[45]
Paraffin	GOx	16.1–26.1	3.93–6.09	The end-burning swirling-flow hybrid rocket was tested, and the fuel regression rates were significantly dominated by the thermal boundary layer produced due to the circumferential oxidizer flow velocity.	[70]
HTPB	GOx	110–725	0.35–0.84	The swirling flow field improves the regression rate by increasing the wall heat flux and effective velocity of the oxidizer mass flowing onto the solid fuel grain.	[12]
Acrylic/ Paraffin/Al	Gox	54.9–122	1.85–4.75	The hybrid motor with a 45-degree injector head displayed a 180% increase in regression rate compared to straight-port axial injection.	[71]

PVC- Polyvinyl chloride; DBP-Dibutyl phthalate; PE- Polyethylene; H_2O_2- Hydrogen peroxide

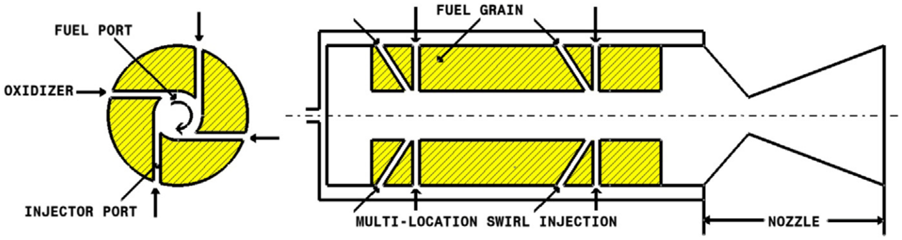

Fig. 5. Multi-section swirl oxidizer injection method.

improves the burn uniformity along the fuel grain and promotes the mixing of fuel and oxidizer. The regression rate with the multi-section swirl injection method can be enhanced up to 4 to 5 times than that of the conventional method [11]. However, this method is not applicable for paraffin-based fuels due to the poor mechanical properties of wax.

As already said before, the oxidizer-to-fuel mass ratio shift during the combustion process resulting in a loss of specific impulse performance and an increase in the propellant unburned. To overcome such issues in the hybrid rocket, several researchers proposed an innovative end-burning hybrid rocket technique [56–59]. In an end-burning hybrid rocket, the fuel grain comprises a series of small ports that run in the axial direction (Fig. 6). The oxidizer is injected through such ports at the head end of the motor, and combustion takes place at each port exit. After the ignition, the micro-diffusion flame propagates upstream,

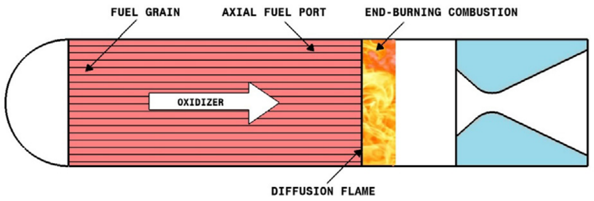

Fig. 6. Axial-injection end-burning hybrid rocket.

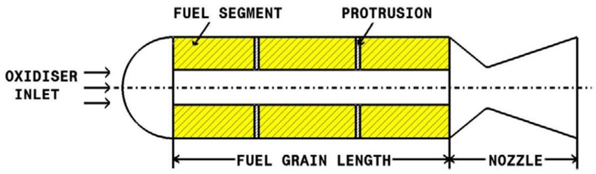

Fig. 7. Schematic of hybrid rocket motor with diaphragms embedded in the fuel port.

and the burning surface area changes with time. These neighbouring burning port exits can merge during the combustion and maintain a consistent burning surface area [59]. Hashimoto *et al.* [57] proposed an axial-injection end-burning hybrid rocket with PMMA fuel. Stabilized combustion was achieved from the end surface of the fuel grain, which propagated towards the head end of the motor. A PMMA fuel grain with an array of ports was made to merge with one neighbouring port, resulting in a constant burning surface area. The constant O/F ratio can be maintained if the fuel is injected at a constant mass flow rate.

Also, several numerical simulation studies on vortex/swirl oxidizer injection in hybrid rockets were published [12,55,56,58,59]. Bellomo *et al.* [55] studied the effect of the vortex Nitrous oxide (N_2O) injection on the regression rate of paraffin wax. Vortex injection created a more diffuse flame toward the fuel surface in the combustion chamber and enhanced reactant mixing. The regression rates of paraffin-based fuels were improved up to 50% [12].

Haag *et al.* [60] at Surrey Space Center proposed a non-conventional motor geometry so-called vortex flow pancake (VFP) hybrid rocket engine, which utilizes tangential oxidizer injectors to induce swirl flow between two fuel disks. The induced swirl flow field in the combustion chamber enhances the mixing between the fuel and oxidizer vapours leading to possible combustion enhancement. The VFP hybrid engine was developed for spacecraft orbit transfer applications due to its compact geometry, which offered low integrations cost, better design flexibility with the minimum thermal and volumetric impact of the hybrid motor on the spacecraft. Paravan et al. [61–64] designed and tested the SPLab vortex flow pancake (SVFP) hybrid motor. The SVFP internal flow field was numerically simulated to predict the oxidizer-fuel mixing under various operating conditions. The SVFP's combustion behavior was also studied in quasi-steady conditions with GOX as the oxidizer. A blend of paraffin and SEBS (polystyrene-block-poly(ethylene-ran-butylene)-block-polystyrene grafted with maleic Anhydride) formulations were investigated. The swirling fuel patterning effect was observed and it dominated as the combustion progressed. The high combustion efficiencies were reported which attributed to vortex combustion.

Ozawa et al.[65] proposed an Altering-intensity Swirling Oxidizer Flow Type (A-SOFT) method for controlling the oxidizer-fuel ratio in a hybrid rocket motor. In this method, the oxidizer feed line is subdivided into axial and tangential streams, an axial valve and swirl valve were used for controlling the strength of the oxidizer-fuel ratio. Individual control of the oxidizer mass-flow rate in each feed line is possible with this approach. The combined oxidizer injection of both feed lines generates a swirling oxidizer effect at the forward end of the motor. Because the oxidizer injection through each feed line is controllable, the throttling can be achieved by maintaining a constant mixture ratio. The swirl number required to be increased in order to improve the regression rate using an A-SOFT approach.

Mechanical device embedded in solid fuel

One of the common techniques used to improve the combustion efficiency of the hybrid rocket is to introduce a diaphragm, protrusion, or bluff-body into solid fuel (Fig. 7). The mechanical protrusion enhances the combustion efficiency and regression rate by generating a large turbulence level in the combustion port. The enhanced mixing of oxidizer and fuel vapor improves the heat transfer from the flame zone to the fuel surface. Kumar and Ramakrishna [26] studied the effect of protrusion on regression rate and combustion efficiency of paraffin-based fuel. When the protrusion was inserted in the center of the fuel grain, the regression rate and combustion efficiency of paraffin-based fuel improved. A similar study was performed by Sun *et al.* [28] to predict the effect of the diaphragm on regression rate and combustion efficiency of hybrid rocket fuel. It was shown that the fuel regression rate before the diaphragm was unchanged due to its position, whereas it slight improved after the diaphragm. The diaphragm generated the turbulence eddies, which contributed to enhancement in the regression rate and consequently in the combustion efficiency. However, the improvement in combustion efficiency was low as the location of the diaphragm moved toward the nozzle end of the motor. Table 2 summarizes the regression rates data of different liquefying and non-liquefying fuels tested under an oxidizer mass flux range for turbulence generator techniques.

The diaphragm height and location can significantly affect the fluid dynamics of the oxidizer and fuel mixture in the combustion port, altering the regression rate performance. Kumar and Kumar [72] numerically investigated the effect of the height and location of the diaphragm on combustion performance. It was reported that the regression rate, at a small L/D ratio (<10), increased significantly when a single diaphragm was used in the fuel grain. The large motor, L/D >10, required the multi-diaphragm system to improve the regression rate and combustion efficiency. Several numerical studies were also performed to investigate the flow characteristics induced by the diaphragm in solid fuel [27,55]. It was reported that the regression rate increased due to large-scale vortex-induced after the diaphragm. Another method for increasing the regression rate is to use a bluff body at the injector end of the motor. In this method, the regression rate improves by decreasing the oxidizer recirculation zone near the head end of the motor [72]. It was also reported that the bluff body produces a uniform burning along the fuel grain.

Metallic additives

The polymer-based solid fuels, such as hydroxyl-terminated polybutadiene (HTPB) and hydroxyl-terminated polyether (HTPE), exhibit a relatively low burning rate. Using additives with high energetic content, high density, and increased reactivity results in an increase of the fuel regression rate, the flame temperature and therefore the rocket specific impulse and thrust. Boron (B), Aluminum (Al), and Beryllium (Be) are high-energy additives that have the potential to be promising energetic ingredients for solid fuel. The Be exhibits the highest enthalpy of combustion; however, during combustion, it produces Beryllium oxide, which is highly toxic, thus preventing its usage in the hybrid rocket. Because of the high heat of combustion, high density, and low environmental impact of Boron and Aluminium, these are considered as potential additives for hybrid rocket applications while maintaining the safety feature of hybrid rockets. However, the addition of Boron as an additive requires a large amount of O_2 for ignition and efficient combustion [6]. During the combustion of metal-loaded fuel, the metallic additives transfer the heat through radiative heat energy and enhance the reactivity of the oxidizer with solid fuel. In addition, the metallic additives are used in the combustion process to suppress pressure oscil-

Table 2
Regression rate data over-tested oxidizer mass flux range for turbulence generator technique

Fuel	Oxidizer	Oxidiser mass flux range (kg/m^2s)	Regression rate (mm/s)	Major findings	Ref.
HTPB	Gox	132–500	0.4–1.1	The regression rate and combustion efficiency were significantly improved when diaphragms were spaced 8–10 times their height.	[72]
Paraffin	N_2O	90–310	1.6–4.3	The regression rate downstream of the diaphragm was improved by about 80% compared to grain with no diaphragm.	[73]
PE	H_2O_2	191–194	0.41–0.55	The diaphragm was used as a mixture-enhancing device. The diaphragm displayed no significant effect on regression rates before the diaphragm; however, the regression rate was tailored after the diaphragm position.	[28]
PVC/ Paraffin	Gox	35–150	2.1–4.1* 0.8 – 0.1**	The nylon protrusion used with liquefying fuels slightly improved average regression rates compared with non-liquefying fuels loaded with graphite protrusion.	[74]

* Liquefying fuels;
** Non-liquefying fuels

lations [22]. The combustion products in the condensed phase attenuate the combustion pressure oscillations along the length of the chamber. Table 3 presents the regression rate data with various additives loaded in different liquefying and non-liquefying fuels.

Boron exhibits a very high volumetric heating compared to Al, Magnesium (Mg), and other energetic fuel additives; Boron reacts with the oxygen producing mainly B_2O_3 as a combustion product. During the initial stage of heating, the liquid Boron oxide layer spreads over the core Boron particle [75]. The Boron oxide layer prevents complete oxidizer penetration into the Boron-core, inhibiting ignition and combustion at low temperatures. When the protective oxide layer breaks, facilitating the chemical reaction between core Boron and oxidant, complete combustion of B can be sustained at high temperatures [75]. Several researchers performed experiments to improve the ignition and combustion efficiency characteristics of B-based fuel. Few authors reported that the application of the coating, such as LiF, Silane, and Viton-A [76,77] over the B surfaces improves the ignition and combustion process. The addition of Magnesium and Manganese improved the burning characteristics of Boron particles and accelerated the oxidation process [76]. It was also reported that the ignition delay time decreased as Boron content increased in fuel formulation. Connell *et al.* [78] used a constant pressure strand burner to estimate the low-pressure deflagration limit and the burning behaviour of a polytetrafluoroethylene/boron (PTFE/B) propellant combination. The combustion efficiency with the addition of Boron improved from 86% to 96% on lab-scale static tests. The tests were also performed with LO_X/F_2 oxidizer combination to eliminate the problems associated with the B oxide layer. The F_2 enhanced the combustion reactivity and removed the passivating oxide layer. Young *et al.* [9] tested PTFE/B formulation with varying the B loading from 10 to 40 % under the GO_X environment. The counterflow burner tests were performed to evaluate the effect of flame strain rate. The oxidation and pyrolysis reaction was studied under the Differential Scanning Calorimeter (DSC)/ Thermogravimetry (TG) analysis at a heating rate of 10 °C/min.

Several experimental were also performed to investigate the energy performance on the axisymmetric motor of 50% of Boron carbide (B_4C) [79,80,85,86], 5% Mg, and 45% HTPB. The Boron carbide has nearly the same energy density as boron. The bypass airflow was varied to study the combustion efficiency and it was reported that the combustion efficiency was improved from 36% to 85%. Risha *et al.* [23] at PSU conducted lab-scale tests on solid fuel containing B/B_4C. The oxidation reaction was catalyzed with B_4C to HTPB, and a regression rate improvement of 108% was recorded when 13% B_4C was loaded in the fuel matrix. The low B content in the fuel formulation resulted in high combustion efficiency, revealing that Boron burns more efficiently at low concentrations.

The addition of Al particles into fuel formulation is one method for increasing the regression rate of solid fuel. Al has a high heat of combustion, high density, and melts at a lower temperature (around 650–700 °C) compared to B. In addition to its superior chemical properties, the radiation and high enthalpy release closer to the burning surface increases the regression rate. Lips [81] conducted several experiments with various polymer binders; Polyurethane (PU), carboxyl-terminated butadiene acrylonitrile (CTBN), and Polybutadiene–acrylic acid (PBAA) loaded with metallic Al. The lab-scale tests were performed with a dual FLOX (Fluorine-oxygen) oxidizer system. The propellant combination was Al (60%) loaded in binder and FLOX (40:60) as an oxidizer. The PBAA and CTBN formulation reported the highest regression rate of 0.76 mm/s and 0.85 mm/s, respectively. The regression rate studies were also performed on PU binder loaded with various metal additives such as (Al, B, Mg) and found almost similar regression rates for each set of formulations [81]. The size and shape of the Al additive have a significant effect on the solid fuel regression rate.

Many studies reported that the use of ultra-fine Al enhances solid fuel-burning rates. Since the high reactivity of ultra-fine Al tends to promote the oxidation reaction and release a large amount of heat in the combustion chamber. Strand *et al.* [8] conducted a series of ballistic tests on HTPB solid fuels loaded with Al particles. Two different sets of experiments were performed to study the effect of Al particle size and single perforated grain motor configuration on regression rate. The average particles size of 40 to 95 μm was used to quantify its effect on regression rate. Chiaverini *et al.* [51] conducted lab-scale experiments on HTPB fuel loaded with UFAl (Alex$^@$) under GOX. The 2-D slab motor was used to measure the regression rate of fuel. The average regression rate was increased up to 40% when Alex content was varied from 4 to 20%. The mass burning rate was increased up to 70% compared to that of pure HTPB formulation. It was attributed to large heat transfer from the combustion zone to solid fuel. The tests were also performed on HTPB fuel loaded with micron-size Al particles, and results indicated that the regression rate improvement was low compared to nanoparticles. Evans *et al.* [16,82] tested paraffin-based fuel loaded with Al flakes. The solid fuels were prepared by adding the 13% Al flakes. The lab-scale result was compared with formulations containing 3% carbon black (CB). The regression rate improved about 30% compared to a formulation containing 3% CB. When the regression rate data was compared to Stanford SP-1 fuel, an increment of 70% was observed. The tests were also performed

Table 3
Regression rate data over-tested oxidizer mass flux range for metal additives technique.

Fuel	Oxidizer	Adittives	Oxidiser mass flux range(kg/m^{2}s)	Regression rate (mm/s)	Key Results	Ref.
HTPB	GOx	Activated Al (0.05–0.10 μm)	120–220	0.9–1.6	The addition of activated aluminum to HTPB improved the regression rate by 40% over pure HTPB. Physical ablation of high–molecular–weight particles from the fuel surface regulated the overall regression process.	[51]
HTPB	GOx	AP (98μm)/ Al (28 μm)	40–450	0.6–2.6	The regression rates were significantly improved with the addition of AP/Al at high mass flux conditions. This was attributed to an additional heat source available near the fuel surface.	[5]
HTPB	GOx	Al (30–150nm), B (>150nm)	70–180	0.82–2.4	Viton–A coated Alex® loaded fuel formulations reported a nearly 120% increase in mass burning rate, whereas B-based additives exhibited at least 68% improvement in regression rates.	[22]
HTPB/ PARAFFIN	GOx	Tungsten/ Silberline Al flakes (10 μm)	100–150	0.9–1.5 (4–7)	An improvement of 38% in the fuel regression rate of HTPB was reported with the addition of nano-tungsten powder. Paraffin-based solid fuels loaded Silberline® aluminum flakes exhibited about 30% improvement in linear regression rates.	[16]
DCPD	H_2O_2	$LiAlH_4$	143-263	1.3-1.42 (1.64-2.37)	DCPD displayed a trivial benefit over HTPB, and the addition of $LiAlH_4$ resulted in higher regression rates.	[48]
PTFE/ HTPB	GOx	Boron (800 nm)	89–218	0.53–0.66	A burning rate correlation (rb[cm/s] = 0.042(P[MPa]))$^{0.531}$ was developed and the surface char formation over fuel prevented measurement of solid regression rates.	[78]
HTPB	GOx	nAl (50-100 nm)	244–378	0.665–1.010	The regression rate of fluorel-plus-ester-coated HTPB nAl formulations (VF-ALEX series) exhibited superior regression rates at all the oxidizer fluxes.	[7]
DCPD/ HTPB	H_2O_2	$NaBH_4$ (100–200 μm and AlH_3 (10–20 μm)	281–478	1.25–1.6 1.5–2.0	When compared to pure DCPD, the 50 wt% $NaBH_4$ fuel improved the regression rate by 47%. At high mass flux levels, AlH_3 in DCPD enhanced the regression rate of neat DCPD by 85%.	[50]
POLYURETHANE FOAM/ PARAFFIN	GOx	$LiAlH_4$ (100 µm), MgH_2 (50–150 µm) and n-Al (0.05–0.10 µm)	100–350	~0.4–2.5	The addition of $LiAH_4$ increased the regression rate up to 378% compared to pure HTPB. Wax-based fuel loaded with MgH_2 and nAl improved the regression rate approximately five times higher than HTPB.	[30]
HTPB	GOx	MgH_2 (47 μm) μAl (6.5/8 μm), Mg (10 μm) Fe, nAl (50 nm)	90–400	0.56–4.54	Fuel loaded with Mg and Fe additives displayed a 50% improvement in the regression rate. HTPB loaded with uncoated nAl showed low-frequency pressure oscillations of large amplitude, whereas fuels containing Mg and MgH_2 reported steady motor operation.	[83]
HTPB	GOx	μAl (7.5–15 µm), nAl (50 nm)	90–325	0.5–1.8	Fuel containing 10% nAl increased mass burning rate by 55% over the pristine HTPB. Mechanically activated Al in polytetrafluoroethylene enhanced the mass burning rates up to 140 %	[84]
PARAFFIN/PE	GOx	Al (10–20 µm)	42-110	0.7-2.4	The regression rate increased by 95% when al doping was increased from 5% to 25%.	[21]
HTPB/PE/ PARAFFIN	GOx	Oleamide, Polydextrose, PEG6000/Mg (1–100 µm)	75–350	0.18–0.58 (0.8–3.7)	Regression rates were increased up to 21% with the addition of PE/oleamide. Self-disintegrating fuels loaded with MgP displayed regression rates improvement of 163.2%.	[85]
HTPB/ PARAFFIN	GOx	$LiAlH_4$/MgH_2	35 to 130	0.5–3.5	The MgH_2-doped formulations demonstrated maximum improvements of up to 353% compared to base fuel and HTPB.	[86]

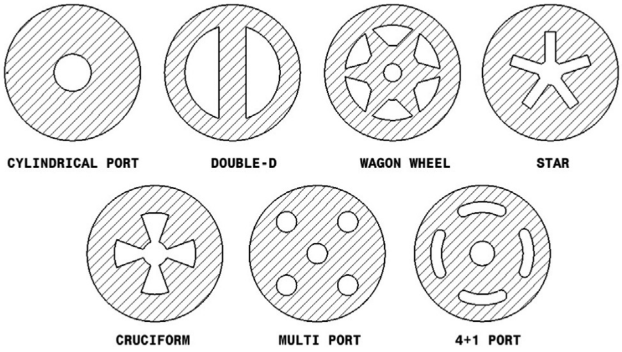

Fig. 8. Various types of multi-port fuel grain geometries

with coated Al particles, and improved combustion and specific impulse efficiencies were observed.

In hybrid rocket propulsion, the metal hydrides are also considered as a source of high energy and low molecular weight (due to hydrogen component). Most of the metal hydrides release a large amount of heat during the exothermic reaction and contribute to improvement in regression rate performance. During the thermal decomposition of metal hydrides, the release of hydrogen enhances the combustion performance, and the remaining base metal contributes to the enhancement of heat transfer to the fuel surface [50]. Aluminum hydride (AlH_3) is the most commonly studied metal hydride for hybrid rocket applications. The density of AlH_3 is higher than that of LiH, used for liquid propulsion systems [30]. Therefore, it is suitable for the upper-stage motor. The ballistic tests were conducted on HTPB fuel loaded with $AlH_{3,}$ and results showed excellent ballistic performance due to the intensive flame structure. Most of the metal hydrides are sensitive to oxidation and have low thermal stability at room temperature.

Additionally, the casting of fuel grain is difficult due to the friction sensitivity of AlH_3. Shark *et al.* [50] studied two different types of metal hydrides, AlH_3 Sodium borohydride ($NaBH_4$) added in dicyclopentadiene (DCPD) fuel binder. The lab-scale tests were performed on the DCPD fuel binder under the H_2O_2 oxidizer, and regression rates were compared with the HTPB binder. The addition of $NaBH_4$ in DCPD reduced the dehydration sensitivity and ignition delay, whereas; the addition of AlH_4 in DCPD reported the highest improvement in regression rate compared to the $NaBH_4$ formulation. It was also found that the addition of metal hydride made fuel formulation more diffusion-controlled. Corpening *et al.* [48] performed regression rate studies of DCPD polymer with 98% H_2O_2 oxidizer. The $LiAlH_4$ was used as a metal hydride to improve the regression rate performance. However, poor combustion efficiency was reported with $LiAlH_4$ additive (about 60-80%) attributed to inadequate oxidation of the Li compound. Galfetti *et al.* [30] mainly characterized the metal additives in paraffin-based fuel for mechanical and ballistic performance. The polyurethane foam (PUF) and the thermoplastic polymer were used for strengthening the paraffin wax. The nano-Al and metal hydride were used to enhance the energy density of the fuel. The addition of $LiAH_4$ increased the regression rate up to 378% compared to traditional polymeric fuels. Larson *et al.* [18] used a lab-scale hybrid motor to test a paraffin-based solid fuel loaded with LiAlH4, Multi-walled carbon nanotubes, triethyl aluminium, and diisobutylaluminum hydride. It was reported that the chamber pressure displayed a strong dependency on regression rate as $LiAlH_4$ was added to solid fuel.

Multiport fuel grain

The multi-port grain casting technique increases the burning surface area, producing a large amount of mass during the combustion. The utilization of multi-port grain geometry can solve the problem of low solid fuel regression rate (Fig. 8). Several studies were reported in the literature to augment the thrust using this technique [87], However, there are several disadvantages of the multi-port grain approach. Such design reduces solid fuel volumetric loading and increases the launch vehicle diameter to accommodate the required fuel mass for a given mission. Table 4 reports the regression rate data of various fuel-oxidizer combinations tested with different grain geometries.

Other issues include combustion instability, high sliver residues, and the non-uniform burning of each fuel grain port [29]. The uneven port burning also tends to vary the O/F from port to port which changes the flight mission profile. The cascaded multistage impinging-jet (CAMUI) method is suggested to improve the thrust of hybrid rockets using non-traditional grain geometries and injectors [88]. This approach is based on a fuel geometry that consists of multiple cylindrical fuel blocks with two axial ports on each fuel block. The oxidizer jet introduced into the combustion chamber impinges on the upstream end face of the first cylindrical fuel block and produces combustion gases. The jet of combustion gas flows through the ports of the first cylindrical fuel block and collides on the upstream end face of the second cylindrical fuel block. The CAMUI method was adopted to enhance heat transfer to the solid fuel using the impinging jet concept [89,90]. However, the cascaded multistage fuel blocks were characterized by three burning surfaces; fuel port surfaces, upstream and downstream end faces. These burning surfaces progress simultaneously and exhibits different regression rates [91,92]. The flow behaviour of the downstream end face is more intricate, with non-uniform regression rates. Therefore, predicting accurate regression rate and grain geometry evolution is a complex task with the CAMUI technique. Paraffin-based fuels, on the other hand, have a higher regression rate and so do not require such approaches to improve the fuel mass burning rate.

Mechanical performance of paraffin-based fuels

The paraffin-based fuel has poor mechanical properties, which prevented its full development and application for a space mission. It is a challenging task to cast sizable paraffin grains that can withstand inertial flight stresses, radial combustion pressure, thrust, and thermal loads. Several studies have been conducted to improve the mechanical performance of paraffin-based fuels (Table 5). Maruyama *et al.* [98] conducted tensile testing on an ethylene-vinyl acetate (EVA) polymer-based formulation. With a 20% EVA addition, the maximum strength was found to improve by approximately 1.6 times. Kumar and Ramakrishna [31] demonstrated that adding 20% EVA to paraffin wax increased tensile strength by 50%. The addition of PE to paraffin wax can improve mechanical performance, thermal stability, and combustion efficiency significantly. When 10 wt. PE is added to paraffin wax, Kim *et al.* [35] showed a 42% increase in tensile and compressive strength.

Another class of fuel, Low melting point thermoplastics (LT), exhibits excellent mechanical proprieties and the potential for a high regression rate due to its similar physical property to paraffin fuel [99]. Wada *et al.* [100] performed mechanical tests on various classes of Styrene-based LT fuels and reported maximum strain over 300% and the true stress over 1 MPa for all the test samples. The Styrene-based LT fuel displayed better mechanical performance than the conventional solid motor propellant. Bisin *et al.* [101] introduced a novel technique for improving the mechanical properties of paraffin-based fuel using a 3D printed reinforced structure embedded in the fuel matrix. The selected cellular structure was the gyroid, a triply periodic minimal surface (polymer mass fraction $\leq$ 10%) whereas, the materials used for gyroid structure were polylactic acid (PLA), acrylonitrile-butadiene-styrene (ABS), and nylon 6 (NY). It was reported that the nylon-based armored grain displayed an improvement of 35% yield stress and a 296% yield strain compared to pristine paraffin.

Furthermore, DeSain *et al.* [102] revealed that adding 4% low-density polyethylene (LDPE) to paraffin wax enhanced tensile strength and percentage elongation. For upper-stage launch vehicle applications, the fuel should have a high specific impulse and superior mechanical properties than pure paraffin. The addition of polymers such as EVA,

Table 4
Regression rate data under the tested oxidizer mass flux range for multi-port fuel technique.

Fuel	Oxidizer	Grain configurations	Oxidiser mass flux range(kg/m^{2}s)	Regression rate (mm/s)	Remarks	Ref.
HTPB	LOx+H_2O_2 (90%)	Wagon-wheel	281–562	–	Results indicated that the LOX–HTPB system was more sensitive to mixture–ratio shifts than the H_2O_2–HTPB. As the number of ports increased, the percentage variation in the port cross–sectional area increased and thus the regression rate.	[93]
PE/ PMMA	GOx	Multiport–circular (1–5 No.)	10–300	0.22–0.55	The reported regression rates of multi–port grains were high with respect to the single port. It was attributed to the increased radiative heat flux in the combustion zone.	[94]
HDPE	GOx	Double–tube	25–120	0.2–1.1	A parametric study revealed that the double–tube configuration design with swirl injection could improve the regression rate by 50% compared to a conventional axial injector.	[95]
HDPE	GOx	Double-tube	25.1–125.4	0.2–0.8	A high regression rate and stable motor operation can be achieved with a double-tube grain configuration	[96]
HDPE	H_2O_2	Multiport-circular (1–14 No.)	233.1–360.2	0.44–0.61	The cylindrical multi-port grain design can reduce the length-to-diameter ratio of the motor and enhance the ballistic performance	[97]

HDPE-High-density polyethylene; LOx- Liquid oxygen

Table 5
Mechanical Performance of paraffin-based fuels.

Fuel	**Strengthening additives**	**Strain rate (mm/min)**	**Key Results**	**Ref.**
Paraffin	LDPE (2-4%)	5.1	The maximum tensile strength and elastic modulus increased with the increasing concentration of LDPE.	[102]
Paraffin	EVA (10-20%)	1	The tensile strength was improved by 1.6 times when 20% EVA was added into pure paraffin.	[98]
Paraffin	LDPE (5-15%)	5	A 10 wt % of PE improved the tensile and compressive strength increased by 42.4 and 42.2%, respectively.	[35]
Paraffin	nAl/μAl	5	The nAl improved both the tensile and compressive strength of paraffin wax, whereas the μAl based fuel was displayed a less significant effect.	[34]
Paraffin	EVA (10-20%)	5	The fuel curing technique influenced the mechanical properties, and the addition of EVA (20%) improved the tensile strength by three times.	[31]
Paraffin	Al (40%)	100	The Al-doped fuel samples increased the ultimate tensile strength by 60–70% at room temperature.	[103]
Paraffin	μAl/PE/μCB/μB	50	The addition of B and Al additives in the P/PE formulation significantly improved the compressive strength.	[104]
Paraffin	HTPB (10-90%)	5	Blending the paraffin with HTPB increased the maximum tensile strength and Young's modulus by 74% and 97%, respectively. However, at low HTPB concentration, the elongation % is decreased by 98%.	[105,106]
Styrene series	-	500	The maximum strain reported over 300% and the true stress of 1 MPa at all the test LT fuel samples.	[100]

PE, and HTPB in paraffin wax improves mechanical properties and combustion efficiency, whereas metal additives enhance the regression rate [31,104]. Therefore, serious attention is required to understand the couple binder-additive effect of polymer-metal additives; the scale-up tests of lab-scale motor, mechanical properties, and ballistics performance should be dedicated to upgrading the performance of paraffin-based fuel for hybrid propulsion.

Conclusions

Since the last two decades, several research and developments activities have shown hybrid rocket propulsion as a potential solution for many space applications. The enhanced safety feature, thrust termination, re-ignition capability, and less sensitivity to solid fuel imperfections are a few advantages of hybrid propulsion, making it unique among other chemical propulsion systems. However, the hybrid propulsion maturity level was limited by the low regression rate and poor mechanical properties of the solid fuel. This paper discusses various techniques to improve solid fuel regression rates and mechanical performance. Many of these techniques seemed adequate to achieve the desired ballistic and mechanical performance level and permit the hybrid technology to replace the solid rocket boosters and liquid bipropellant stages. The paraffin-based solid fuels were identified as a viable alternative further to improve the performance of the hybrid rocket system. Based on the results discussed in this paper, the scale-up tests are recommended to translate the lab-scale hybrid motor results into the flight-sized motor.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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