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Editorial

Special Issue “Hybrid Rocket (Volume II)”

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Over the past 40 years, the loss rate for commercial passenger aircrafts has decreased down to about one in ten million, whereas the loss rate for spaceflight has remained high, in the 1% range. The safety and reliability of space transportation systems have been improved by increasing system redundancy, reducing the failure rate of onboard equipment, and applying strict quality control. Statistically speaking, however, these methods have already reached their limits. Therefore, one of the biggest barriers to the future widespread use of space transportation will be the ability to achieve radical resilience to hazards in order to achieve safety and reliability comparable to those of air transportation. In this context, as discussed by Takahashi and Shimada [1], we are aiming to develop hybrid rockets, which cannot generate substantial chemical explosions unlike solid or liquid rockets, as a means of increasing the resilience of future space transportation.

In 2007, Kuo and Chiaverini gave an interesting overview of future applications of hybrid propulsion systems in a paper entitled “Challenges of Hybrid Rocket Propulsion in the 21st Century” [2]. Among them are large boosters for space launch vehicles and propulsion systems for upper stage orbit control. It also lists several considerations in designing a high performance hybrid rocket system, which can be summarized as follows: (1) reusable oxidizer supply and control system, (2) strap-on booster, (3) engine restart control function, (4) flame retention at the head end of the LOX/HTPB motor, (5) pre-combustion chamber design to promote evaporation of LOX droplets in LOX-fed motors, (6) oxidizer injector design to ensure uniform consumption of multi-port fuel grains, (7) detailed internal ballistic analysis and development of related prediction codes, (8) selection of solid fuel composition and oxidizer, as well as appropriate grain design in favor of fuel regression rate, and (9) high reliability, especially suitable for manned flight, and integrated molding of the case, throat, and nozzle for this purpose.

Now, nearly 15 years later, it is interesting to look back and see what the future trends are. While there are no examples of hybrid rockets being reused yet, the importance of reusability is evidenced by the current breakthrough of SpaceX’s Falcon 9 rocket [3]. This is a classic example of how macroeconomics can right-shift the supply curve of launch price vs. number of launches by increasing supply capacity through technological innovation. Okninski et al. [4] published a very good review of space transportation developments using hybrid rocket propulsion from 2005 to almost the present. According to them, there are not many examples of large booster flights, whereas we can see the operation of Nammo’s Nucleus rocket and Virgin Galactic’s SpaceShipTwo. In other words, at this point in time, there seems to be a shift toward the integration of small and medium-sized engines that would alleviate the scale problems of large hybrid rockets, as proposed by HyImpulse, Nammo, TISpace, and DeltaV.

In addition to reuse technology, resilience of manned space transportation and innovation in manufacturing technology must also be mentioned. Although there are still some challenges to be overcome before SpaceShipTwo is fully operational, hybrid rocket

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technology has played an important role in the technological path leading to Unity22, launched on 11 July 2021 [5], to make human space transportation more robust.

In this regard, the advantages of hybrid rockets for manned space transportation include the ability to check the engine operation with the crew on board due to zero TNT equivalency, and the ability to abort at any stage of the mission. This implies that the hybrid rocket is a propulsion system that enables robust space transportation in line with the Safety II concept [1].

As mentioned above, the hybrid propulsion system is particularly suitable for upper stage orbit control. In fact, both kick motor and de-orbit functions can be integrated into a single engine, high specific impulse can be achieved by fuel selection, propellant density is relatively high, engine restart and thrust control are guaranteed, manufacturing is safe, and cost is relatively low. Furthermore, by designing the thrust profile appropriately, the acceleration environment of the payload can be made milder, which is also desirable for practical use as an upper stage engine. In this special issue, Barato [6] has reviewed the challenges in the design of hybrid rockets for upper stage engines from a new perspective in terms of ablative cooling, packaging, and fuel regression rate; Kamps et al. [7] have studied the suitability of various oxidizers for hybrid rockets when the on-board envelope is limited to one cubic meter and showed that both hydrogen peroxide at 85% and nitorus oxide are superior to LOX.

In addition to these two application areas, the benefits of hybrid rockets for convenience in planetary exploration missions have been increasingly considered recently. In particular, the key technologies of hybrid launch vehicles are being integrated in the multi-objective optimization of both system and mission profiles. In this special issue, Casalino et al. [8] have dealt with the optimization of systems and shown the relevance of hybrid rockets as an option for Mars-ascent vehicles in sample return missions. The same authors [9] have reviewed the optimization studies on hybrid rocket engines and various systems and missions at the Politecnico di Torino.

With the need for technological research to improve the design of the propulsion system itself, including combustion instability suppression, injector performance, and propellant selection, in this special issue, Hyun et al. [10] have shown that fuel insertion and oxidizer swirl injection are effective in suppressing the occurrence of intrinsic hybrid combustion instability (LFI); Okninski et al. [11] have reviewed the technological development of hybrid rockets using 98% high concentration hydrogen peroxide as the oxidizer, mainly in the Lukasiewicz research network. Grefen et al. [12] have reported the application of 3D-printing additive manufacturing in the fabrication of fuel blocks with complex geometries.

As described by Kuo and Chiaverini [2] and as mentioned above, improved techniques for predicting the engine internal ballistic characteristics are needed to properly design missions utilizing hybrid rockets. One of the major differences between hybrid rockets and other chemical propulsion systems in terms of internal ballistic characteristics is the very large role that fluid dynamics plays in determining propellant combustion efficiency. In hybrid rockets, local and instantaneous fuel production depends on heat transfer feedback from turbulent diffusion flames in the boundary layer, which means that the fuel decomposition and evaporation processes, fuel and oxidizer mixing, and combustion are tightly coupled phenomena with a wide range of scales.

The general theoretical framework for calculating the internal ballistics of hybrid rockets was laid down half a century ago [13], and at that time it was recognized that the heating mechanism of solid fuels is essentially divided into convective and radiative heat transfer modes. Whichever heat transfer is greater, the resulting fuel regression rate will be greater, but it is not due to a simple superposition of the two heating modes; the regression rate is a nonlinear function of the ratio of the two heat fluxes to the wall.

At that time, the famous Marxman's model of convective heat transfer in the absence of radiation had already been established, based on the analysis of a turbulent boundary layer on a flat plate, taking into account the effects of combustion and blowing, with the help of Reynolds analogy [14]. Marxman's model assumed that the flame in the boundary layer does not affect the local velocity profile, but later experiments showed that the velocity profile near the flame yields a maximum exceeding the mainstream velocity, and the model itself had to be modified.

Radiative heat transfer is essentially independent of mass flux. However, as the mass flux changes, the convective heating rate changes, which in turn affects the fuel regression rate and hence the mixing ratio. As a result, the mass fractions of chemical species in the combustion gas and the density distribution of hot particles also change. It has been demonstrated that the main source of radiative heat transfer comes from hot soot particles, not only when the fuel contains metal powder, but also in the case of pure hydrocarbon fuels [15,16]. However, the mechanism of the formation of soot particles from soot precursor molecules is still unclear.

In the area of internal ballistics' simulations, Tindaro Migliorino et al. [17] have discussed in this special issue the validity of Reynolds-averaged Navier-Stokes computations considering fluid-fuel surface interaction, radiation, and gas combustion. Palacz and Cieślik [18] have studied a model to evaluate possible two-phase flow effects when supplying a self-pressurized liquid oxidizer such as N_2O. Viscor et al. [19] have proposed the concept of equivalent burning time to account for the effect of engine start-up in determining the correlation between fuel regression rate and mass flux from combustion test results and have shown its effectiveness. In addition, Viscor et al. [20] have studied the scale effect of the fuel regression model for CAMUI-type hybrid rocket.

This special issue on hybrid rockets, which follows on the heels of "Advances in Hybrid Rocket Technology and Related Analytical Methods" [21], brings together 11 papers from authors around the world. Overall, this second edition is of great value as it continues to provide the technical community with useful information on the subject and extends the current level of knowledge with new technical content, as in the previous issue. It is hoped that it will increase interest in this technology and lead to more widespread involvement by research institutions and industry.

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