CHAPTER 1
INTRODUCTION

A rocket propulsion system is classified by the method of producing thrust and the source of energy. The source of energy could be nuclear, electrical and chemical (Sutton and Biblarz, 2001). In a nuclear propulsion system, the nuclear energy source is used for delivering the heat to a working fluid, which subsequently expands through a nozzle to provide the required propulsive thrust. In an electrical propulsion system, an electrical plasma is accelerated under a suitable electrostatic or electromagnetic field and ejected at high velocity. The specific impulse of these propulsion systems is significantly high, however, the low thrust-to-weight ratio limit their use in practical applications.

To overcome the deficiency as mentioned above, chemical propellants were identified as a suitable alternative. Chemical propellants either as a mixture or pure individual components form the driving force behind the chemical propulsion and are combusted employing an external oxidizer or an internal oxidizing agent. Chemical propellants can either be a homogeneous or heterogeneous mixture. The physical state of the propellant mixtures determines the propellant system. The well-known chemical propulsion systems are liquid propulsion system, solid propulsion system and hybrid propulsion system. The chemical propulsion system is the primary choice for rocket propulsion since the thrust–to-weight ratio is very high as compared to other propulsion systems.

In a liquid propellant rocket, the liquid fuel and liquid oxidizer are stored in separate tanks, and a feed mechanism forces these liquids into the thrust chamber. In the thrust chamber, oxidizer and fuel undergo a series of pre-
combustion events such as injection, atomization, mixing and is finally burnt to form hot combustion gases. These combustion products at high pressure and temperature are made to expand through a supersonic nozzle at high velocity and thereby producing thrust to propel the rocket vehicle (Sutton and Biblarz, 2001). Liquid propellant rockets are more flexible, have greater control over the thrust, restart capability, regenerative cooling feasibility and higher value of specific impulse. Besides these advantages, liquid rockets suffer from complexity of operation, handling of corrosive and cryogenic propellants, high structural weight penalty raised due to complex propellant feed system.

The solid propellant rockets are known as the simplest form of propulsive device (Mattingly, 2006). The fuel and oxidizer are mixed together and casted to form a solid mass called the grain. Once the grain is ignited, it burns radially outward over the exposed surface at a predetermined rate, and the hot combustion gases flow through the nozzle to impart desired thrust. Solid propellant rockets are simpler in design due to the absence of moving parts such as pumps, turbine, valves etc. However, solid rockets have lower specific impulse value compared to liquid rockets. Currently, most of space missions are propelled by using solid and liquid rocket technology since these are mature technologies used for several decades. Nevertheless, many efforts have been made to improve the solid and liquid rocket technologies for better operational safety, the problem of explosion hazard and combustion instability.

In recent years, there has been renewed interest in hybrid rocket propulsion for a potential manned space tourism exploration mission. Hybrid rocket propulsion system utilizes both solid and liquid propellants. Based on propellant physical state, hybrid rocket can be grouped into two classes. A direct hybrid system, which is a common configuration, utilizes a fuel in solid phase and oxidizer as liquid (Fig. 1.1). A reverse hybrid system has oxidizer in
solid state and fuel in liquid phase (Altman and Holzman, 2007). This concept is not as practical as classical system, because the solid oxidizer requires more critical fabrication process and has less attainable performance.

Fig. 1.1: A typical hybrid rocket system (direct configuration) (Kuo and Chiaverini, 2007)

Combustion in the hybrid rocket is diffusion-flame limited; the oxidizer is injected over the solid fuel grain where the flame zone establishes within the boundary layer. The fuel vapours enter the boundary layer as a result of ignition process at the fuel surface, while the oxidizer vapours diffuse into the boundary layer from injector end. The combustion flame occurs within boundary layer when a suitable mixture of fuel and oxidizer is achieved. Due to combustion process, a large temperature gradient and concentration gradient is established between solid fuel surface and flame zone. The heat is transferred from flame zone to solid fuel surface as a result of convection and radiation. This leads to enhanced stripping of fuel from surface and vaporize into the flame zone.

The boundary layer combustion model was first studied by the Marxman et al. (1967). The heat transfer from the flame zone to fuel surface was the controlling mechanism of diffusion combustion. The fuel regression rate depends primarily on the total mass flux, the mass flux of fuel and oxidizer, and its value decreases as the port area increased during burning (Altman and Holzman, 2007). The rate at which the solid fuel is converted to gaseous
vapour is known as regression rate (Kuo and Chiaverini, 2007). The regression rate is a key design parameter in the hybrid rocket fuel grain.

1.1. MOTIVATION FOR THE CURRENT RESEARCH

Hybrid propellant rocket take the several advantages of their liquid and solid rocket counterparts and make feasible for several space applications. Hybrid propellant rockets are able to compete in the application areas of liquid and solid propellant rockets due to following benefits:

- Physically separated propellant phases, the hybrid rockets have zero explosion hazard possibility. This enhanced safety makes solid fuels easy to transport, store and manufacture compared to conventional liquid and solid propellants.
- The hybrid-fuel grains are insensitive to cracks and imperfections in grain morphology. The heterogeneous reactions due to oxidizer injection over the fuel surface create a diffusion flame zone that shields fuel surface from oxidizer-rich flow. Therefore, the potential cracks may increase the burning surface area rather than make it chamber pressure sensitive.
- The hybrid propellant system has only the oxidizer stored in the liquid phase, it requires only one storage tank and feed system. This arrangement reduces the complexity to half as compared to its liquid counterpart and can perform all functions, including throttle to thrust control, motor shut-down, cooling and restart by adjusting only the oxidizer flow rate.
- The solid fuels are compatible with any type of oxidizer combination and it can be casted with a variety of additives for purposes such as high-energy mission and tailoring the plume signature for military applications.
The hybrid propulsion system is very economical to both manufacture and launch due to low storage cost and transportation. The added advantage is the safety due to low explosive nature. Also, the hybrid rockets have environmentally clean exhaust due to absence of hydrogen chloride or oxide with respect to solid rocket propellants.

The hybrid rockets have high performance in term of specific impulse ($I_{sp}$). Specific impulse of hybrid rocket is in the range of 247 s to 408 s while its value for solid propellant rocket is below 270 s (Karabeyoglu et al., 2001).

The hybrid rocket has fewer shortcomings despite many attractive characteristics listed above, which prevented its full development to achieve technology readiness level (TRL). The main drawbacks for hybrid rocket are the low fuel regression rates, low volumetric loading, fuel- to-oxidizer ratio shift and relatively poor combustion efficiency. The low regression rate and poor combustion efficiency are due to non-uniform diffusion into the combustion zone. This results in poor mixing of fuel and oxidizer and these characteristics are unsustainable for long duration application.

A significant amount of research (Veale et al., 2015; Kumar and Ramakrishna, 2016; Mazzetti et al., 2016; Paccagnella et al., 2017) employing paraffin as a fuel medium has been performed on paraffin-based fuels to explore their feasibility for upper stage and space mission applications. However, the paraffin wax behaves as a brittle material compared to conventional polymeric fuels. Its mechanical strength to withstand the structural deformation during grain fabrication, casting, handling and transportation is poor. In addition, the combustion efficiency of paraffin-based fuels is low leading to a blowout of unburned paraffin droplets through the exhaust nozzle during the combustion process.
The combustion and mechanical characteristics are main attributes of solid hybrid fuel, besides the ease of ignition decides the operating conditions of the fuel. The ignition temperature of solid fuel in hybrid rockets imposes several requirements on ignition system design. The physical interface, moisture free environment, safety, reliability, motor ignition time and shock output are few functional requirements of the igniter that can affect the ignition temperature of solid fuels. Therefore, the knowledge of ignition temperature in solid fuel combustion process is an important parameter for combustion stability and control.

1.2. ORGANISATION OF THE THESIS

This section briefly discusses the scheme of thesis organized in following chapters:

- **Chapter 1:** This chapter describes the introduction and motivations of current research.
- **Chapter 2:** A general overview on hybrid rocket fundamentals, literature survey and a description of various techniques adopted to overcome the slow regression rate of solid fuels.
- **Chapter 3:** The objective of the present research is presented.
- **Chapter 4:** Various methods used for characterization of paraffin-based solid fuels are discussed in this chapter. Experimental set-up used for mechanical characterization and lab scale ballistic tests are also explained. This process of data reduction measurement uncertainty is also discussed in this chapter.
- **Chapter 5:** Results of thermal, mechanical and ballistic characterization are analyzed and presented. The regression rate data and oxidizer mass flux correlation are also presented.
- **Chapter 6:** The discussion on reported results is presented in this chapter. Several results from literature are compared and discussed.
➢ **Chapter 7:** Summary of the work carried out are presented and discussed.

➢ **Chapter 8:** Possible future recommendations are summarized and discussed in this chapter.