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Boron for liquid fuel Engines-A review on synthesis, dispersion stability in liquid fuel, and combustion aspects

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ABSTRACT

Energetic metal or metalloid particles are considered to be potential secondary energy source for energy generation and propulsion. This is mainly due to their higher gravimetric and volumetric heating values compared to that of hydrocarbon fuels. These energetic particles have the capacity to produce a huge amount of heat upon reaction which is very essential for any energy or thrust producing device. Many of these energetic particles may offer a beneficial role in terms of improvement in combustion efficiency and reduction in exhaust emission. Boron is considered to be one of the best suited candidates based on its heating values. However, the full potential of boron particles has not been realized yet in any practical combustion systems. Numerous studies have been carried out on ignition/combustion characteristics of boron particles considering mostly micron-size particles. Recent advancement of nanotechnology has opened up a new avenue for utilizing energetic nanoparticles as fuel additives in liquid fuel combustion systems. Few review articles highlighting mainly the ignition and combustion mechanisms of boron are available in literature; however, recent development on ignition/combustion of boron nanoparticles as well as its application in liquid fuel engines is not yet reviewed comprehensively. The present paper encompasses the present status and underlying challenges in synthesis process of boron nanoparticles, dispersion and stability of boron nanoparticles in liquid hydrocarbon fuels, effect of surfactant or surface modification on dispersion stability, ignition and combustion characteristics of boron loaded liquid fuel as well as particle combustion, understanding the positive thermal contribution from boron particles burning, and characterization of post-combustion products in terms of chemical and physical properties.

1. Introduction

Energetic particles are considered as potential additives for conventional hydrocarbon fuels to increase their energy density [1]. Recent development in the field of nanoscience and nanotechnology enables the better size control of metals and metalloids and that has created renewed interest in utilization of energetic nanoparticles. The available data of the use of nanoparticle show several promising features in terms of high combustion enthalpies, overall increment in energy density, short ignition delays, complete combustion and combustion products with low emission [1]. The nanometric size of additives facilitates a larger surface to volume ratio and hence more contact surface area for rapid oxidation. Many nanoparticles have their energy releasing capacity twice the energy release from best fuel combustion [2].

Many studies [3,4] revealed that nanoparticles laden fuel shows better ignition and combustion properties than their micron-size counterpart. In their studies [3,4], they found that the availability of high reactive surface area reduces the ignition delays substantially which favours more complete combustion of nanoparticles laden fuel. Berner et al. [5] suggested that the use of nanoparticles could effectively improve the mixing of fuel components which could enable the reactant to diffuse to the surface thereby increasing the reactivity of fuel components. Several researchers [6,7] have focused to unearth the combustion, ignition and vaporization characteristics of nano and micron particles laden liquid fuels, while others [8] have paid attention on the effect of these fuel additives on the performance and exhaust emission. Many fuel additives such as manganese (Mn), beryllium (Be), boron (B), aluminium (Al), copper (Cu), iron (Fe), platinum (Pt), cerium (Ce) etc. have been extensively investigated to know their combustion characteristics, ignition behaviour, performance of engine and emission level. Some of the energetic particles when doped in liquid fuel would be a promising choice in order to enhance the gravimetric and volumetric energy densities and ignition characteristics of liquid fuel [9–14]. The exhaust emissions associated with these types of fuel would also be low.

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Metal powders react exothermically with oxygen to produce high energy. The resulting combustion products of metal-oxidation reaction can be collected and recycled using novel technological methods [12,15–17]. Among the various additives mentioned above, boron has a very high gravimetric and volumetric energy content which makes it a prime choice as the potential fuel additive for liquid fuels [18–20]. The boron loaded liquid fuel could be a good choice for airbreathing propulsion systems [21]. Boron possesses approximately 40% higher energy density compared to hydrocarbon fuel on gravimetric basis (58 vs 44 kJ/g), and 200% higher on volumetric basis (136 vs 42 kJ/cm^3). Due to the higher volumetric energy density, it could be effectively employed in volume limited propulsion systems, such as in liquid fuel ramjet (LFRJ).

Researchers of several studies [22–24] are in harmony that the fuel additives at nanolength scale improve the catalytic role during combustion process, lead to efficient and complete combustion, which eventually results in better overall engine performance. Thus, a common consent of group of researchers [25–29] is that the nanoadditives in liquid fuel act as secondary energy carriers that are likely to enhance the ignition and combustion characteristics. Though there are several fuel additives, boron is considered as a potential contender because of its high gravimetric and volumetric energy densities. The gravimetric and volumetric heating values of all the fuel additives are presented in Fig. 1. Many researchers had performed comprehensive studies on ignition and combustion of boron nanoparticles either by injecting into different gaseous flames or by adding into conventional liquid fuels [6,30,31]. They reported an improvement in the energy content of liquid fuels by the addition of boron nanoparticles. As reported in the literature, the complete vaporization of nanoparticle laden fuel droplets involves a total of six processes 1. Liquid phase transport 2. Gas phase transport 3. Solid phase transport 4. Phase change at liquid-gas interface 5. Phase change at solid liquid interface and 6. Dynamics of nanoparticles [32,33].

Though nanoparticles have many advantages in a liquid fuel, the key issue is the stability of nanoparticles in the liquid fuel because of the inherent property of nanoparticles to aggregate and form a large agglomerate of a different structure. This poor stability of nanoparticles imposes a serious limitation on the practical use of nanofluid fuels. The rapid settlement of nanoparticles in the liquid fuel increases the probability of clogging of fuel injection systems. To counter this critical issue, many approaches could be adopted like proper selection and addition of surfactant [34–36] and surface functionalization of nanoparticles [37–39]. According to Wie et al. [34] there are several parameters that decide the better stability of nanoparticles which include temperature, concentration of reactants, and structure and shape of additives. Furthermore, the efficient utilization of any propulsion systems using nanofluid fuels can only be achieved with the ease of availability of stable nano-suspension at a reasonably low cost.

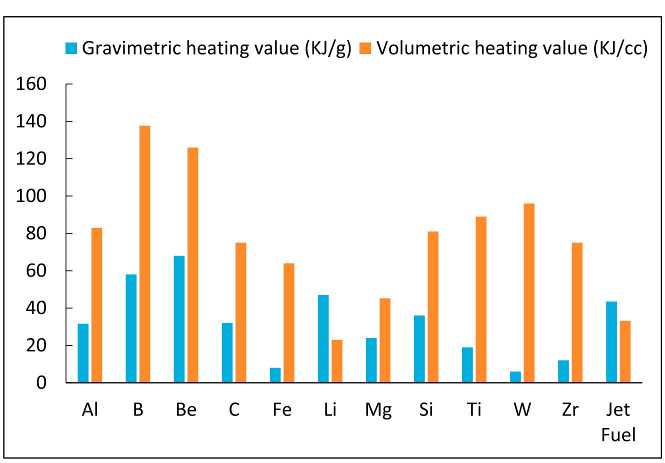

Fig. 1. Gravimetric and volumetric heating value of metal additives.

Many solid additives have been tested with different liquid fuels, but the exceptional energetic density of boron has drawn maximum attention of researchers in this domain. Few review articles [19,20,40,41] highlighting mainly the ignition and combustion mechanisms of boron are available in the literature; however, recent development on ignition/combustion of boron nanoparticles as well as its application in liquid fuel engines is not yet reviewed comprehensively. In the present work, an attempt has been made to provide a complete review on the synthesis process of boron particles and its underlying challenges, stability of boron particles in liquid fuel, and ignition and combustion behaviour of single boron particles as well as boron loaded liquid fuel. A discussion is also provided on the approaches to improve the boron ignition/combustion process. Section 2 gives an overview of different manufacturing techniques employed in the synthesis of boron particles. Details of these techniques along with their advantages and disadvantages are discussed in this section. In section 3, a general discussion on the mechanism which governs the stability of nanofluid fuels is presented. Section 4 deals with the stability aspects of boron particles in liquid fuel. The role of surfactant and surface modification of boron particles in deciding the better stability of boron laden nanofuels is discussed. Section 5 briefly discusses the ignition and combustion mechanism of boron particles. This section describes both theoretical and experimental studies conducted on boron ignition and combustion phenomena. It also reviews the reaction mechanism of boron in the hydrocarbon flame environment. This section highlights the different ways by which the ignition and combustion characteristics of boron can be enhanced. Section 6 focuses on the combustion characteristics of boron in liquid fuel droplets as well as in sprays. Combustion aspects of boron in gel fuel is also discussed briefly in this section. A discussion on the analysis of post-combustion residue is presented in section 6 as well. Section 7 briefly summarizes the effects of nanoparticles on heat transfer and exhaust emission characteristics. Several key issues are summarized in section 8 and possible approaches to overcome some of these issues are also presented in this section. Finally, section 9 presents concluding remarks by highlighting the feasibility aspects of the boron loaded liquid fuel as a next-generation high energy fuel for practical combustion systems.

2. Synthesis of boron particles

Synthesis of boron particles requires an oxidation controlled environment to produce high purity particles. The synthesised materials should have a small degree of agglomeration and also be free from impurities [42,43]. The boron powder used in most of the studies are commercially available; however, the production of boron particles requires extensive research which is getting matured with time. The preparation of boron by electrolysis of boric acid was done a century ago by Sir Humphry Davy [42]. Commonly used methods to manufacture elemental boron particles from its compounds are molten salt electrolysis, metallic reduction of boron oxide or other compounds by metals like magnesium (Mg), lithium (Li), sodium (Na), potassium (K), aluminium (Al), iron ($Fe;^3$), hydrogen reduction of boron halides such as boron tri-chloride (BCl_3) and boron tri-bromide (BBr_3), and thermal decomposition of boron compounds. The metallic reduction method generally produces amorphous boron. However, the morphology of boron powder produced by the other three methods [42,43] can have both amorphous and crystalline nature. As stated by Zhiganch and Stasinevich [43], the methods of preparation of amorphous and crystalline boron have very minimal distinction because of the large dependence of the morphology of boron on many inter-related parameters such as temperature, substrate material, impurities, supersaturation and deposition rate. Among these factors, temperature plays the most important role. Amorphous boron is generally produced at relatively low temperatures, around 873–1073 K, while crystalline boron is produced at above 1273 K [43].