



Review

Combustion and heat transfer characteristics of nanofluid fuel droplets: A short review

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ABSTRACT

With the pressing need to meet an ever-increasing energy demand, the combustion systems utilizing fossil fuels have been the major contributors to carbon footprint. As the combustion of conventional energy resources continue to produce significant Green House gas (GHG) emissions, there is a strong emphasis to either upgrade or find an energy-efficient eco-friendly alternative to the traditional hydrocarbon fuels. With recent developments in nanotechnology, the ability to manufacture materials with custom tailored properties at nanoscale has led to the discovery of a new class of high energy density fuels containing reactive metallic nanoparticles (NPs). Due to the high reactive interfacial area and enhanced thermal and mass transport properties of nanomaterials, the high heat of formation of these metallic fuels can now be released rapidly, thereby saving on specific fuel consumption and hence reducing GHG emissions. In order to examine the efficacy of nanofuels in energetic formulations, it is imperative to first study their combustion characteristics at the droplet scale that form the fundamental building block for any combustion system utilizing liquid fuel spray. During combustion of such multiphase, multicomponent droplets, the phenomenon of diffusional entrapment of high volatility species leads to its explosive boiling (at the superheat limit) thereby leading to an intense internal pressure build-up. This pressure upsurge causes droplet fragmentation either in form of a microexplosion or droplet puffing followed by atomization (with formation of daughter droplets) featuring disruptive burning. Both these atomization modes represent primary mechanisms for extracting the high oxidation energies of metal NP additives by exposing them to the droplet flame (with daughter droplets acting as carriers of NPs). Atomization also serves as a natural mechanism for uniform distribution and mixing of the base fuel and enhancing burning rates (due to increase in specific surface area through formation of smaller daughter droplets). However, the efficiency of atomization depends on the thermo-physical properties of the base fuel, NP concentration and type. For instance, at dense loading NP agglomeration may lead to shell formation which would sustain the pressure upsurge and hence suppress atomization thereby reducing droplet gasification rate. Contrarily, the NPs may act as nucleation sites and aid boiling and the radiation absorption by NPs (from the flame) may lead to enhanced burning rates. Thus, nanoadditives may have opposing effects on the burning rate depending on the relative dominance of processes occurring at the droplet scale. The fundamental idea in this study is to: First, review different thermo-physical processes that occur globally at the droplet and sub-droplet scale such as surface regression, shell formation due to NP agglomeration, internal boiling, atomization/NP transport to flame zone and flame acoustic interaction that occur at the droplet scale and second, understand how their interaction changes as a function of droplet size, NP type, NP concentration and the type of base fuel. This understanding is crucial for obtaining phenomenological insights on the combustion behavior of novel nanofluid fuels that show great promise for becoming the next-generation fuels.

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Abbreviations: NP, nanoparticle; CNT, carbon nanotubes; FGS, functionalized graphene sheets; PLR, particle loading rate; Le_l , liquid phase Lewis number; R , initial droplet radius; R_f , flame stand-off distance; α , ejection impact parameter; DL-instability, Darrieus–Landau instability; SEM, scanning electron microscope; EW, ethanol–water; N , bubble population; N/V , bubble population density; A_f , projected flame area; ϕ , droplet void fraction; f_{MR} , most flame-responsive excitation mode.

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1. Introduction and motivation

Recent developments in the interdisciplinary field of nanofluid technology and the pressing need for an energy-efficient, environmental friendly alternative to conventional hydrocarbon fuels has triggered recent research in the area of novel nanofluid fuels. Nanophase fuel suspensions or popularly known as “nanofuels” are stabilized colloids containing energetic nanoscale additives (1–50 nm) typically in dilute concentrations (≤ 1 vol.%) [1–5]. The key idea is to harness the energy potential at nanoscale by adding trace amounts of energetic nanometer sized metallic particles to traditional fuels such as gasoline and diesel. In this regards, suspended NPs play role as secondary energy carriers that can be custom engineered to act as combustion enhancers. These fuels combine together the high specific surface area of NPs and the well-known high oxidation energies of metals to produce high energy density fuels that save on fuel economy and hence reduce pollutant emissions. Numerous recent investigations [6–30] have reported that conventional fuels and propellants laden with nanoparticles (NP) improve combustion performance in terms of: (1) increased volumetric energy density, (2) enhanced catalytic activity, (3) low ignition delay (4) higher ignition probability, (5) higher volumetric heat release rates, (6) faster burning rates, (7) reduction in soot and pollutant emissions, (8) greater flexibility in developing novel fuels/ propellants with custom tailored physical properties and (9) NPs can act as gelling agents to substitute the existing low-energy inert gellants. For instance, Sabourin et al. [8] reported that the addition of colloidal particles of functionalized graphene sheets (FGS₂₂) to monopropellant nitromethane enhanced its burning rates significantly (>1.75 times) while its ignition temperatures were reduced. The steady-state burning rate of nitromethane (CH₃NO₂) increased with increase in NP concentration and decreased with the rise in pressure thus indicating that burning rates of colloids are less pressure sensitive compared to pure nitromethane. Sabourin et al. [8] proposed that the observed burning rate enhancement is through two mechanisms: (a) increased heat transfer resulting from enhanced radiative heat transport properties of NPs and (b) increased thermal conductivity due to NO and FGS oxidation reactions and the catalytic effect of FGS functional groups. Jones et al. [31] reported that the volumetric heat of combustion can be increased by ~15% with the addition of 10 vol.% *n*-Al to biofuel (ethanol).

The potential advantages of nanostructured additives are attributed to their intrinsically high reaction cross sections, high specific surface area and high density of surface functionalities. At nanometer length scale a particle contains thousands of atoms and as the particle size goes below ~5–10 nm the ratio of surface to bulk atoms increases rapidly. For instance, for a spherical iron crystal the ratio is ~25% at 5 nm and increases to as high as 90% at 1 nm [32]. At such high density of surface atoms the bulk material tends to display the properties of surface atoms. As an example, NPs have lower freezing and melting point, heat of fusion [33–35] and sintering temperatures [36] compared to their micron and larger sized counterparts. A higher specific surface area at nanoscale also allows for increased reactivity [37,38] and catalytic activity [39]. However, there is a lower limit to which the NP size can be reduced since with decreasing particle size, the increasing thickness of inert oxide layer now constitutes a major mass fraction of the particle which outweighs the benefits of high energy density. Nanofluids display enhanced thermal conductivity (that increases with temperature and decreases with particle size), mass diffusivity and radiative heat transfer and aids faster ion transfer [40–45]. Optically enhanced radiative properties and high thermal conductivity accelerate the thermal exchange process between fuel droplets and the surrounding air. For instance, a 150% augmentation in the thermal conductivity of engine oil has been reported with the addition of 1 vol.% carbon nanotubes (CNTs) [46]. Since NPs are easy to disperse and added only in dilute concentrations to the host fluid their physical properties such as surface tension, viscosity and density are not altered substantially. For example, Tanvir and Qiao [47] reported that even with the addition of 3% by wt. NPs, the variation in surface tension of ethanol and *n*-decane based fuels is negligible (less than 5%; measured using the pendant drop method).

From an application viewpoint, recent studies have considered the direct usage of NPs as diesel fuel additives in compression ignition engines [48–60]. They demonstrated a reduction in CO, HC and NO_x exhaust emissions and ignition delay time with a corresponding increase in the brake thermal efficiency and decrease in break specific fuel consumption. Currently the usage of nanofluid fuels in practical combustors as combustion promoters is however quiet restricted. Limitations arise from: (1) inherent tendency of nanoparticles to aggregate (through mechanisms like differential settling, perikinetic or orthokinetic particle transport) and form

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