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Droplet combustion studies of hydrocarbon-monopropellant blends

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HIGHLIGHTS

- Droplet combustion of IPN and its blends with *n*-heptane and DBS was studied.
- Multiple flame zones were observed for IPN droplet combustion.
- IPN burning rates and flame standoff ratios depend on initial droplet diameter.
- Burning rate constants were improved by adding IPN to *n*-heptane, and DBS.
- IPN-DBS blends were characterized by severe micro-explosions.

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ABSTRACT

An experimental investigation was conducted to characterize the monopropellant droplet combustion of pure and blended isopropyl nitrate (IPN), suspended on quartz fibers in a quiescent atmosphere. The blends were prepared by mixing varying percentages by weight of IPN with less viscous *n*-heptane, as well as highly viscous desensitizer dibutyl sebacate (DBS). Ignition was achieved by using a heated 60 μm Nichrome wire. The dependence of the burning rate constant of pure IPN on initial droplet diameter was investigated in the droplet size range of 0.79–1.97 mm. The blended IPN studies were carried out with initial droplet diameters of 2 and 1.5 mm for IPN-*n*-heptane and IPN-DBS blends respectively, to characterize the effect of gravimetric composition. The experiments revealed a strong dependence of IPN burning rate on droplet size. The IPN-DBS blends were characterized by severe micro-explosions, further atomizing the droplet, governed by the preferential evaporation of IPN over DBS. However, micro-explosions were conspicuously absent in case of IPN-*n*-heptane blends due to simultaneous gasification of both components.

1. Introduction

Liquid monopropellants undergoing an exothermic decomposition without the aid of a separate oxidizer have found alternative applications such as high altitude unmanned aerial vehicles [1], and underwater power sources [2,3]. Hydrazine and its derivatives have been consistently utilized as monopropellants owing to their relatively high specific impulse. However the volatile, toxic, and carcinogenic nature of hydrazine necessitates use of extreme caution and protective gear during handling. Among the available alternatives such as hydrogen peroxide, hydroxyl-ammonium nitrate (HAN), ammonium dinitramide (ADN), and various alkyl nitrates, IPN is known as a low sensitivity liquid propellant.

IPN has been used as a standalone propellant for gas turbine engine starting [4] and as a diesel cetane improver [5]. It has several significant advantages, namely non-toxicity, non-corrosiveness, low sensitivity to detonation, and low cost. Although adiabatic compression ignition of fuel vapor bubbles was a safety issue in handling IPN, the predicament has been found to be alleviated by de-aerating the fuel before storage, as well as blanketing it with nitrogen [6]. Additionally, blending IPN with a frequently utilized desensitizer such as DBS would further improve its safety characteristics. IPN may also be blended with other conventional hydrocarbon based fuels, such as gasoline, in order to create improved fuel blends capable of providing enhanced heat release rates and operating in oxygen deficient atmospheres.

In a liquid fueled propulsion system such as a reciprocating engine or a rocket thruster, the spray combustion process dictates engine characteristics. However, the combustion process of the droplets constituting the sprays must in turn be elucidated first to aid in the design of operational combustion chambers. Droplet combustion of propellants has been studied in the past and has been the subject of several reviews [7–9]. Combustion of single supported droplets have been numerically [10–12] and experimentally [13–17] studied, and burning rates extracted for several

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Nomenclature

D	instantaneous droplet diameter (mm)	a, b	empirical constants
D_f	flame diameter (mm)	Gr	Grashof number
D_0	initial droplet diameter (mm)	Qs	quasi-steady parameter
D_{exp}	droplet diameter at the onset of micro-explosion (mm)	ε	ratio of gas phase density to liquid phase density
g	gravitational acceleration (mm/s^2)	k_{CQS}	flame standoff ratio calculated using classical quasi-steady theory
k	burning rate constant (mm^2/s)	v	stoichiometric air–fuel ratio by mass
k_0	burning rate constant predicted by classical theory (mm^2/s)	$B_{o,q}$	transfer number
$\dot{m}$	mass burning rate (g/s)	Δh_c	heat of combustion (MJ/kg)
β	volumetric thermal expansion coefficient (1/K)	C_{pg}	gas phase specific heat (kJ/kg)
ρ	density (g/mm^3)	T_∞	ambient temperature (K)
v_g	kinematic viscosity (mm^2/s)	T_s	boiling point (K)
T_f	flame temperature (K)	h_{fg}	latent heat of vaporization (J/kg)
λ_g	gas phase thermal conductivity (W/m K)		

monopropellants such as alkyl nitrates, hydrazine and its derivatives, hydrogen peroxide, and HAN.

Allison and Faeth [12] have conducted experimental and numerical studies on the decomposition and hybrid combustion phenomenon of monopropellants such as hydrazine. While small droplets were suspended on a quartz fiber, porous alundum spheres were used to simulate larger diameters. The effect of the composition of the surrounding atmosphere was studied by varying the oxygen mass fraction from 0 to 0.42. A simplified quasi-steady theoretical model was also developed based on a previous model by Williams [8]. The theoretical results were compared with experimental results of Barrere and Moutets [13].

Unlike a diffusion flame surrounding a typical hydrocarbon fuel droplet burning in an oxidizing atmosphere, a monopropellant droplet burns as a premixed flame. The presence of an oxidizer in the vicinity of the droplet leads to the development of a diffusion flame surrounding the premixed flame, where the products from the premixed flame are oxidized. Experimental as well as numerical investigations of droplet combustion of monopropellant blends are relatively sparse [16–18], due to inherent complexities involving phase change at the droplet surface, vapor transport in the gas phase, and variation in composition due to selective evaporation of the components. Droplet combustion studies of conventional hydrocarbon fuels blended with monopropellants are also conspicuously absent in the literature. However, multi-component droplet combustion involving hydrocarbon fuels [19–21] has been studied in the past.

In the present work, an experimental study is conducted on the droplet combustion of pure and blended IPN, suspended on quartz fibers in a quiescent atmosphere. A major motivation for this work was to elucidate fundamental droplet combustion characteristics to aid in combustion chamber design of internal combustion engines, envisaged to be operated on monopropellant-hydrocarbon blends to potentially augment their maximum attainable altitudes. The blends analyzed in this study were IPN with *n*-heptane and IPN with DBS. The study investigates the dependence of burning rate constant for pure IPN on initial droplet diameter, while the effect of composition on the burning rate constant was studied in IPN-*n*-heptane and IPN-DBS blends. The flame standoff ratio is also characterized for pure IPN and IPN-*n*-heptane blends.

2. Experimental setup

The droplet combustion experiments were conducted by suspending the droplets in air under atmospheric conditions, at the tip of specially fabricated quartz rods, with support diameters ranging from 0.2 mm to 0.8 mm. The droplets were deposited at the tip of the meticulously cleaned rods by a micro-liter syringe by opening one of the access ports of a transparent acrylic chamber surrounding the experimental setup, and were ignited by a 60 μm Nichrome wire heated by a source of alternating current. The wire was stretched between two hinged arms, with a diameter of 1.5 mm, held in horizontal position by the tension in the Nichrome wire. After the droplet was ignited, the wire was broken due to intense heat produced by the flame. At this point the hinged arms swung downwards under gravity, ensuring that the broken ends of the Nichrome wire would be retracted from the vicinity of the flame zone.

The perturbation due to wire break-up and movement of the hinged arm was estimated based on the Reynolds number associated with the movement of the arm through quiescent air. The effect of Reynolds number on wake formation has been documented by Morkovin [22]. For the arms, the Reynolds number was found to be less than a critical value of 40. Therefore, the flow separates downstream and a wake zone is formed, denoted by two symmetrical standing eddies. The maximum distance affected by this disturbance in the direction transverse to the direction of travel is approximately 2.25 mm. Thus a thin sector of disturbed air will be formed along the swinging path of the hinged arm. However, the magnitude and direction of this disturbance is insignificant compared to the area of interest for the droplet combustion since no net flow is generated towards the droplet and the flame. Besides, the largest flame diameter is of the order of 10 mm. Hence, the tip of the thin sector is approximately 35 mm away from the edge of the flame zone. In case of the Nichrome wire, the Reynolds number is of the order of unity. This implies that air smoothly divides and reunites around the cylinder without the formation of any wake or disturbance.

An isolated tethered droplet undergoing combustion, receives heat from the flame by conduction through the gas phase and as well as through the tethering fiber. The contribution of heat conduction through the fiber is typically neglected, owing to the lower conductivity of the fiber material and the transient nature of the event. However, more precise estimates of the conduction through the fiber on the combustion characteristics can be examined by evaluating the ratio of the heat conducted to the droplet though the gas phase and through the fiber, as shown by Farouk and Dryer [23]. A simple model was utilized to arrive at a conservative estimate of such ratios in the current scenario.

The ignition and combustion processes were photographed by a Canon 550D digital single lens reflex (DSLR) camera fitted with a 100 mm macro-lens. Data was acquired at a rate of 60 frames per second, providing a temporal resolution of 17 ms, and at a