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Droplet combustion studies of nitromethane and its blends

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ABSTRACT

An experimental study was conducted on droplet combustion of the monopropellant pure nitromethane (NM) as well as NM blended with methanol. Pure NM droplet combustion was conducted in a quiescent atmosphere of air with the droplets supported at the tip of quartz fibers under normal gravity. Additional experiments were conducted by varying the ambient oxygen mass fractions. The dependence of burning rate constant on initial droplet diameter was determined for pure NM, pure methanol, and NM-methanol blends and explained through a correlation dependent on the classical quasi-steady burning rate constant and the Grashof number associated with the droplet allowing for prediction of the burning rate constants of smaller droplets pertinent to spray combustion. The burning rate constants for commonly available nitromethane based fuel Rapicon-16 and NM-Dibutyl sebacate (DBS) blend with 90:10 ratio were also measured. The fuels were chosen to represent a range of cases from pure nitromethane to nitromethane-methanol blends typically utilized in practical applications. The nitromethane-DBS blend was formulated as a potential alternative to the conventional nitromethane-methanol-castor oil blends. The effectiveness of DBS as a desensitizer for nitromethane was established given that the burning rate constants for NM-DBS blends were found to be comparable to those of Rapicon-16 despite the higher concentration of nitromethane.

1. Introduction

Nitromethane is capable of combusting exothermically as a bipropellant in the presence of an oxidizer or undergoing energetic thermal decomposition as a monopropellant. This dual nature of nitromethane facilitates its utilization as a monopropellant as well as a fuel in air-breathing applications. Nitromethane as a monopropellant is known to possess significant advantages such as non-toxicity, non-corrosiveness, high specific impulse, and higher thermal efficiency compared to the commonly utilized monopropellant hydrazine due to its higher adiabatic flame temperature (2400 °C). Concordantly, it has been utilized in rocket engines [1], internal combustion engines used for drag racing [2,3], amateur radio controlled airplanes [4], and unmanned aerial vehicles [5]. Such devices depend on combustion of liquid fuel sprays for energy generation, and the design of such systems entail detailed and accurate modeling of the spray combustion process. However, the complexity inherent to spray combustion such as simultaneous heat and mass transfer, turbulence, and the transient nature of the process complicates the implementation of a holistic model. A possible approach to such a problem involves separate treatment for the gas phase turbulence and the superposition of the droplet gasification and combustion via a different model. Thus, experimental and numerical study of combustion of fuel droplets is considered essential.

Furthermore, air-breathing engines utilize a ternary blend containing nitromethane, methanol, and a lubricating agent. The addition of methanol curtails the tendency of nitromethane vapor to detonate under sudden compression during operation or handling. This necessitates the study of combustion of blended nitromethane in an oxidizing atmosphere. Despite being widely utilized, fundamental studies for characterizing the droplet combustion process of nitromethane and its blends are rare. Numerous studies focusing on pure and multi-component monopropellant droplet combustion in an oxidizing atmosphere [6–10] have been reported in the literature. Additionally, studies elucidating the effect of natural convection on the combustion of monopropellant droplets [8,11] have been conducted. Since the droplets are suspended from a fiber, the studies on the effect of the supporting fiber on droplet combustion [12] can also be found in the literature.

Hence, an investigation concentrated on elucidating the combustion characteristics of single isolated droplets of pure and blended nitromethane is presented here. The primary focus of the current study was on the combustion process of droplets of pure nitromethane, pure methanol, several nitromethane-methanol blends, a nitromethane-DBS blend, and a commercially available nitromethane based fuel Rapicon-16. The fuels were chosen in order to encompass the entire range of cases from pure nitromethane to nitromethane-methanol blends

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Nomenclature

Latin alphabet

B	transfer number
c_p	specific heat capacity (J/kgK)
D	diameter (m)
g	gravitational acceleration (m/s^2)
h_{fg}	latent heat of vaporization (J/kg)
Δh_c	heat of combustion (J/kg)
k	burning rate constant (mm^2/s)
p, q	empirical constants in Eq. (9)
Q_s	quasi-steady parameter
T	temperature (K)

Greek symbols

β	thermal expansion coefficient (1/K)
ε	ratio of gas phase density to liquid phase density
$\varkappa$	flame standoff ratio
λ	thermal conductivity (W/mK)
ν	stoichiometric air-fuel ratio by mass
ν_g	gas phase kinematic viscosity (m^2/s)
ρ	density (kg/m^3)

Dimensionless numbers

Gr_D	Grashof number based on diameter
$\overline{Nu}_D$	average Nusselt number based on diameter
Pr	Prandtl number
Ra_D	Rayleigh number based on diameter

Subscripts

0	initial condition
a	air
ad	adiabatic condition
BP	boiling point
CQS	quasi-steady theory
fl	flame
F	fuel vapor
g	gas phase
Gr	natural convection effects correlated with Grashof number
l	liquid phase
Nu	natural convection effects correlated with Nusselt number
s	droplet surface
∞	free stream condition

typically utilized in practical applications. The nitromethane-DBS blend was formulated as a potential alternative to the conventional nitromethane-methanol-castor oil blends.

Quantitative measurements of burning rate constant and flame diameter were carried out along with qualitative observation of the combustion process. Additionally, pure nitromethane droplet combustion was also conducted with varying oxygen concentrations in the surrounding medium in order to simulate combustion zones within the spray with variable oxygen percentages owing to differential droplet evaporation. The variation in burning rate constant with initial droplet diameter was theoretically addressed through accounting for natural convection. The effect of composition of the nitromethane-methanol blend on the variation of the burning rate constant and the flame structure was studied to understand the effect of methanol on monopropellant combustion.

2. Experimental setup and procedure

The droplet combustion experiments were carried out with the droplets confined within an aluminum chamber as shown in Fig. 1. The internal cavity of the chamber was 70 mm in width, 90 mm in length, and 100 mm in height while the chamber walls were 10 mm thick. The chamber was equipped with three optical windows on three vertical sides while a circular port was provided on the fourth side in order to allow the deposition of the droplet. The top and bottom flanges were provided with exhaust and inlet ports for the purge gases. The flanges as well as the optical windows of the chamber were sealed using O-ring seals. The deposition port on the back side of the chamber was provided with a rubber septum to introduce a syringe loaded with fuel. The inner surfaces of the chamber were painted black in order to prevent reflected radiation from affecting the droplet combustion process as well as to improve the visibility of the flame against a dark background.

The heat absorbed by the droplet through radiation can be considered to be negligible for droplets with non-luminous flames [13,14]. Additionally, the contribution of radiation to the total heat transfer in the presence of a luminous flame and hot wall surrounding the droplet was found to be negligible [15]. However, certain cases of microgravity droplet combustion have shown the burning rate constant to decrease with increase in initial droplet diameter [16]. Recent numerical works [17,18] have established that the decreasing trend in the burning rate constants with increasing droplet diameters were introduced due to the effect of both non-luminous and luminous flame radiation that affected the flame temperatures.

The droplets were deposited at the tip of carefully cleaned quartz rods with diameters ranging from 0.15 mm to 0.87 mm using a microliter syringe. Ignition was achieved by creating an electric spark between two steel electrodes inserted in the chamber through Teflon sleeves. The gap between the tips of the two electrodes was approximately 15 mm and the spark was initiated by manually actuating a toggle switch. The duration of the spark was observed to fluctuate randomly with the average duration of 180 ± 30 ms which corresponds to a discharge of 58 mJ of energy. The trends of burning rate constant as well as flame dimensions were observed to be unaffected by the slight fluctuation of the spark energy. The entirety of spark energy was not deposited in the liquid droplet. The spark created a high temperature zone of plasma adjacent to the droplet and heat transfer from this plasma affected the evaporation and ignition of the droplet. The separation between the droplet at the tip of the fiber and the spark

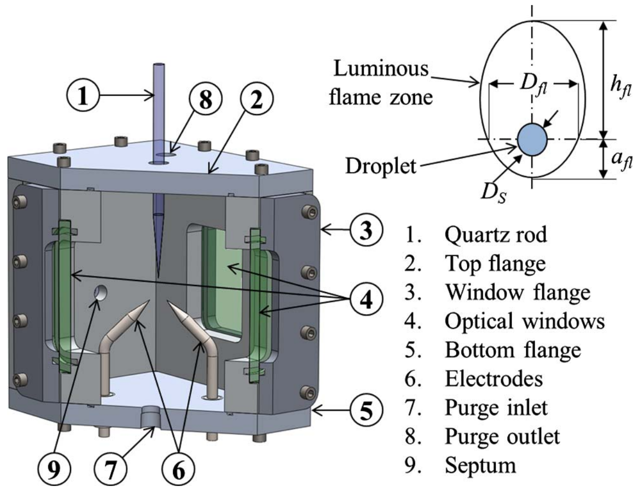

Fig. 1. Suspended droplet combustion setup.