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Research Paper

An experimental technique for determination of intrinsic burning rate constants of liquid fuels

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HIGHLIGHTS

- Intrinsic burning rate constant of *n*-heptane, *n*-decane, and nitromethane evaluated.
- Supported droplet combustion studied experimentally under natural gravity in air.
- Burning rate constants were dependent on the initial droplet diameter in all cases.
- Natural convection and fiber conduction effects on burning rate constant explained.

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ABSTRACT

The burning rate constant of the droplets of a liquid fuel solely characterized by the thermo-physical properties of the fuel and the oxidizer is an intrinsic characteristic of the fuel. The classical quasi-steady approach enables estimation of such a parameter in a highly idealized scenario with a range of simplifying assumptions. Furthermore, this quasi-steady method requires the knowledge of the thermo-physical properties of the fuel along with the expected adiabatic flame temperature. The current study utilizes droplet combustion experiments in natural gravity for the estimation of the intrinsic burning rate constants of pure fuels. A semi-empirical technique has been utilized to establish a correlation between the experimental and classical quasi-steady burning rate constants. The dimensions of the droplet flame were an important aspect of the model. The experiments have been conducted in a quiescent atmosphere of ambient air with droplets of *n*-heptane, *n*-decane, and nitromethane. Quartz fibers with a range of diameters were utilized to support the droplets and obtain a variation of the initial droplet diameters. The observed variation of the burning rate constant was recognized to be the result of the augmentative effects of natural convection and the conductive heat transfer through the supporting fiber.

1. Introduction

Isolated droplet combustion has remained a classical problem for the past 65 years [1,2], involving two-phase phenomena and diffusive combustion between the fuel and the oxidizer. The process was initially idealized by a spherico-symmetric approximation of the flame surrounding the droplet [2] and a theory was proposed wherein the fuel and the oxidizer meet at a Burke-Schumann flame and generate energy to drive phase change at the droplet surface. The theory predicts that the squared droplet diameter decreases linearly with time, and its rate of change with time is termed as the burning rate constant (k). This idealized quasi-steady analytical treatment of the droplet combustion process, also termed as the D^2 law, has become a textbook method for determination of burning rate constants for various fuels [3]. After a series of early theories predicting the methodology of treatment of the properties in the gas phase surrounding the droplet, Law and Williams [4] published a seminal work that established the properties to be utilized in the formulation proposed earlier, including the effects of convection and chemical kinetics. The approximations involved were that the heat capacity in the gas phase was taken to be the same as that of the fuel vapor. The thermal conductivity was comprised of 40% of the value of the fuel vapor and 60% of the value of the oxidizer, and the properties were evaluated at the average of the boiling point of the fuel and the corresponding adiabatic flame temperature. These assumptions were determined based on another pivotal work by Kumagai et al. [5], where the burning rate constant of *n*-heptane under buoyancy-free microgravity conditions was reported as 0.78 mm^2/s. Since then, droplet combustion experiments have been predominantly conducted in

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Nomenclature

Latin alphabet

a	semi major axis (m)
a_f	stagnation distance of flame (mm)
B	transfer number
c_p	gas phase specific heat capacity (J/kg K)
D	diameter (m)
e	eccentricity
h	flame height (m)
h'	approximated flame height (m)
$\overline{h}$	convective heat transfer coefficient ($W/m^2 K$)
h_{fg}	latent heat of vaporization (J/kg)
Δh_c	heat of combustion (J/kg)
k	burning rate constant (mm^2/s)
l	length (m)
p, q	empirical constants
$\dot{Q}$	rate of heat transfer (W)
r	radial co-ordinate (m)
T	temperature (K)
t	time (s)

Greek symbols

λ	thermal conductivity (W/mK)
ρ	density (kg/m^3)
ν	air to fuel ratio by mass
θ	angular co-ordinate

Dimensionless numbers

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

Subscripts

0	initial condition
∞	free stream condition
a	air
ad	adiabatic condition
avg	average condition
burn	burning time
CQS	quasi-steady theory
con	heated contact zone
expt	experimental values
F	fuel vapor
fi	fiber
f	flame
g	gas phase
l	liquid phase
Nu	enhancement due to natural convection
s	droplet surface
total	total enhanced burning rate

microgravity conditions, achieved within a drop tower, a reduced gravity aircraft, or a space station orbiting the earth, to characterize various fuels and the associated phenomena. The spherico-symmetric flames achieved in microgravity, expected to be free of buoyancy, were expected to provide an intrinsic value of the burning rate constant for a fuel.

Subsequent studies by various groups revealed that the burning rate constant for *n*-heptane was determined to be constant or even increasing slightly with increase in droplet diameter [6], or decreasing with increase in initial droplet diameter [7]. Recent numerical works [8,9] 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 reduce the flame temperatures. However, the effect of radiation has been established [10] to be dominant only for droplets larger than approximately 2 mm diameter. Hara and Kumagai [6] revised their earlier estimate of the burning rate constant of *n*-heptane to 0.7 mm^2/s. However, in another experimental study [11] it was shown that most experiments involving a single spark ignition in microgravity inadvertently introduce a relative velocity between the droplet and the surrounding gases, which is further increased by ignition of the vapor cloud surrounding the droplet. With sufficient care to minimize these effects, the average burning rate constant of *n*-heptane was calculated to be 0.58 mm^2/s. The preceding discussion makes it clear that the droplet combustion experiments conducted in microgravity require stringent control over generation of droplets and ignition to prevent spurious factors from obscuring the determination of intrinsic burning rate constants.

Several old [12–17] and relatively recent [18–20] studies on droplet combustion process under natural gravity can be found in the literature. However, representation of the burning rate constants as intrinsic characteristic of the fuel could not be found. The intrinsic burning rate constant unaffected by buoyancy, finite reaction rates, or other spurious factors such as fiber conduction, maybe envisioned as a fundamental property of a fuel, similar to its heat of combustion. The heat of combustion of a fuel is determined in order to gauge the amount of energy released by the fuel under highly idealized conditions and is useful for comparing the fuels from a viewpoint of their available energy. In a similar manner, intrinsic burning rate constants are useful for comparison between pure fuels, blends of fuels and additives, as well as suspensions and slurries from the standpoint of their rate of combustion. However, it is of note that the classical burning rate constant cannot be calculated for various novel fuels, blends, suspensions, and slurries due to the lack of information regarding the thermo-physical properties of various species involved, such as conductivity and specific heat capacity. The quasi-steady intrinsic burning rate constant may be experimentally reproduced in strictly controlled microgravity environments. Nevertheless, such a procedure is cumbersome and prohibitively costly for characterizing new fuel compositions spanning over hundreds of compounds. On the other hand, the thermo-physical properties of pure fuels are well documented and these fuels may be utilized to establish a methodology to arrive at the intrinsic burning rate without the prior knowledge of fuel properties.

The present work focuses on combustion of droplets of pure hydrocarbons such as *n*-heptane and *n*-decane as surrogates for conventional petroleum fuels, as well as oxygenated hydrocarbons such as nitromethane for its potential as a monopropellant. The burning rate constants were measured for each fuel for a range of the initial droplet diameters, and the luminous flame dimensions such have been characterized. The burning rate constants as predicted by the established quasi-steady theory were calculated and the Nusselt number based correction for natural convection was implemented. The experimental and theoretical values were compared. The effects of natural convection as well as fiber conduction on the combustion process were determined analytically. Although these effects have been well characterized through detailed simulations [21–23], a simple semi-empirical technique was utilized to modify the established quasi-steady theory to include these effects simultaneously. The study aims to establish a methodology to arrive at an intrinsic burning rate constant as a characteristic of a fuel.