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Interferometric investigation of methanol droplet combustion in varying oxygen environments under normal gravity

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ABSTRACT

Non-intrusive diagnostics of droplet combustion using laser-based interferometric technique have been presented. The experiments have been conducted with methanol droplet as the model combusting material under normal gravity with oxygen-nitrogen mixtures at ambient pressure and temperature. The mixtures contained five different oxygen concentrations of 9, 13, 17, 21 and 25%. Projection data of the temperature field around the combusting droplet have been recorded using a Mach-Zehnder interferometer and the interferograms have been analyzed to retrieve the whole field flame temperature distribution around the combusting droplet. The limiting oxygen index (*LOI*) has been deduced based on real time interferometric images by varying the oxygen concentration levels. Results of the study showed an increase in the flame temperatures with increasing oxygen concentrations and an oxygen concentration level of 13% has been identified as the *LOI* for methanol droplet. The whole field temperature distribution has been used to calculate the radial temperature gradients between the flame and the droplet surface. These temperature gradients were seen to be a direct function of oxygen concentration. Based on the radial temperature gradients, instantaneous mass burning rates and burning rate constants were computed and a reasonably close agreement between the interferometric predictions and those based on the videographic method was observed. To the best of the knowledge of the authors, the present work is the first successful application of Mach Zehnder interferometry for investigating droplet combustion phenomena. In contrast to the conventional videography approach, the interferometric technique not merely acts as a visualization tool, but also provides quantitative information in the form of whole field temperature distribution, which plays an important role in the determination of mass burning rates and burning rate constants.

1. Introduction

Spray combustion process, normally observed in various liquid fuel applications, is an intricate combination of various thermo-physical phenomena. The study of spray combustion is often preceded by developing an understanding of combustion of isolated droplets as a simplified strategy aimed at elucidating the complex processes involved in actual combustion chambers. The conventional study of droplet combustion is typically concerned with understanding the details of parameters such as mass burning rate, burning rate constant and flame stand-off ratio for droplets of varying sizes. A range of such studies can be found in the published literature [1–5]. It is pertinent to note here that the parameters such as burning rate constant of a combusting droplet are intricately linked with the whole field temperature distribution around the droplet and hence it becomes imperative to develop a detailed understanding of the real time dynamics of the thermal field associated with the droplet combustion process.

The available literature shows that despite being an important factor in determining the burning rate constant of a combusting droplet, the investigations aimed at understanding the temperature field around the droplet are relatively scarce [6–8]. The previously reported studies pertaining to the measurements of the parameters have primarily focused on videography methods [1–5]. In the context of correlating temperature field distribution around the combusting droplet with its burning rate constant, the efforts have primarily been restricted to numerical simulations [6,8,9] and not much effort has been made towards determining the real time, whole field temperature distribution around the burning droplet. In this context, light based non-intrusive measurement techniques become important for reasons such as being inertia free (measurement speed is primarily limited by the image acquisition rates) so that rapid transients of the phenomenon may

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Nomenclature

A	background intensity (also surface area)
B	local intensity
Cp	specific heat
D	droplet diameter
f_0	constant vector for a given angular position of the reference mirror of interferometer
g	acceleration due to gravity (also Weight function)
h	heat transfer coefficient (also heat of vaporization of methanol)
I	intensity of laser beam
k	thermal conductivity
K	burning rate constant
l	length of the suspension rod
$\dot{m}$	mass burning rate
n	refractive index
Nu	Nusselt number
Pr	Prandtl number
$\dot{Q}$	heat transfer rate from rod to droplet
r	radial distance
Ra	Rayleigh number
t	time
T	temperature

Greek symbols

ϕ	phase
ρ	density
λ	wavelength of laser beam
ν	kinematic viscosity

Subscripts

0	reference value
avg	average
μ	microgravity
b	bulk fluid
ng	normal gravity
r	rod

be captured in real time. The probing beam scans the two-dimensional area of interest, thus providing the whole field information of the quantity being measured. In the context of combustion phenomenon, one such measurement technique, namely laser interferometry and its variants has often been employed for measuring the temperature of certain flame configurations by a range of researchers [10,11]. On the other hand, to the best of the knowledge of the authors, the interferometry-based non-intrusive diagnostics of droplet combustion for determining the whole field temperature distribution around the combusting droplet as not yet been attempted. In contrast to the conventionally employed methods such as videography etc., the technique of laser interferometry not merely acts as a visualization tool but is also capable of providing quantitative data in the form of real time whole field temperature distribution around the combusting droplet. The instantaneous temperature field can then be employed for determining the quantities of interest such as mass burning rates, burning rate constants etc. of the combusting fuel.

On the backdrop of the above-presented literature survey, the present manuscript reports the whole field investigation of the temperature distribution around a combusting droplet using a non-intrusive measurement technique. Laser-based interferometry has been employed as the diagnostic tool and the combustion characteristics of methanol droplets have been non-intrusively studied. The choice of methanol as the model fuel has been based on the fact that such alcohols (e.g. methanol, ethanol etc.) are some of the most utilized additives for conventional hydrocarbon fuels in order to reduce particulate matter emissions. Moreover, methanol has also been known for having a relatively simple molecular structure and non-sooty flame. For these attributes, the combustion phenomena of methanol droplets have also been studied in the past using conventional techniques by several researchers [12–14]. The primary focus of the present work is to quantitatively understand the combustion of methanol droplets in varying oxygen environments. The combustion experiments have been performed for 9, 13, 17, 21 and 25% oxygen concentration levels appropriately balanced by nitrogen concentration. The choice of these oxygen concentration levels has been motivated by the potential applications of the present study in areas such as; (1) semi-cryogenic engines wherein methanol is employed as a promising fuel or fuel additive for kerosene along with liquid oxygen as an oxidizer, (2) optimizing the film cooling of the engine based on the deduced flame temperatures corresponding to varying oxygen concentration levels, (3) exploring the possibility of using air as a fire extinguisher substance by increasing the nitrogen concentration or as an oxidizer for sustainable combustion by reducing the nitrogen concentration in international space station.

Results of the interferometry-based measurements have been quantified in terms of the whole field temperature distribution around the burning droplet, average flame temperatures, flame stand-off ratios and burning rate constants as determined from the retrieved two-dimensional temperature fields. The experiments have been performed under normal gravity conditions. The Mach-Zehnder interferometer has been operated in wedge fringe setting mode and the study has been carried out by coupling an environmentally-sealed combustion chamber with one of the arms of the interferometer. Based on the direct interferometric observations, parameters such as limiting oxygen index (LOI), burning rate constant etc. have also been deduced. The importance of the study lies in the fact that, to the best of the knowledge of the authors, the present work is the first successful application of the technique of Mach Zehnder interferometry for investigating droplet combustion phenomena wherein parameters such as flame stand-off ratios, mass burning rates and burning rate constants etc. have been directly determined from the whole field temperature distribution data obtained through quantitative analysis of the recorded interferometric images.

2. Apparatus and instrumentation

2.1. Combustion chamber assembly

The droplet combustion experiments have been carried out in a specially-designed aluminum chamber with dimensions of $70 \times 70 \times 100\ \text{mm}^3$. An isometric representation of the combustion chamber has been shown in Fig. 1. While designing the chamber, it has been ensured that its size is significantly large (greater than 50D where D is the maximum size of the droplet) to avoid any major depletion of the ambient oxygen environment around the droplet, which may lead to a possibility of changes in the boundary conditions during the combustion process. The combustion chamber was painted black to minimize the effects of radia-