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Research paper

Glow-plug-assisted combustion of nitromethane sprays in a constant volume chamber

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HIGHLIGHTS

- Glow plug assisted, constant volume, spray combustion of liquid nitromethane.
- Combustion processes observed through chamber pressure and exhaust composition.
- Emissions consistent with equilibrium calculations for low chamber pressures.
- Combustion process was a combination of three distinct phases.
- Premixed combustion, diffusion spray combustion, and diffusion film combustion.

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ABSTRACT

Experimental investigations on spray combustion of nitromethane in air within a constant volume chamber are presented. The sprays produced by a commercial gasoline injector, were ignited by using a pair of glow plugs, while the initial chamber pressure was varied from 1 bar to 7 bar. The nature of the combustion processes at various initial pressures was elucidated by measuring the pressure rise as well as using FTIR spectroscopy of the combustion products, and high speed photography. The maximum differential pressures reached during combustion were found to increase with chamber pressure up to 4 bar, and decrease thereafter while the ignition delays were found to be in the order of 10 ms for all pressures. The global equivalence ratio was found to vary from 0.43 at an initial pressure of 1 bar to 0.06 at an initial pressure of 7 bar, thus reducing the flame temperatures achieved within the chamber with increasing chamber pressures. The trends observed in the calculated heat release rates, cumulative heat released, and rate of heat loss from the chamber were found to provide key insights into the combustion process, which was concluded to be occurring through three distinct processes – turbulent premixed combustion, turbulent spray combustion, and turbulent film combustion. The effects of decreasing flame temperatures on the three processes were discussed in detail.

1. Introduction

Nitromethane was regarded as a promising monopropellant for rocket applications, prior to being replaced by the advent of hydrazine, as well as a potential fuel for piston engines [1–3]. Nitromethane has several advantages over hydrazine as a monopropellant, such as non-toxicity, non-corrosiveness, low cost, and high specific impulse. The simple molecular structure of nitromethane accompanied by its chemically bound oxygen results in lower oxygen requirement for stoichiometric combustion. Thus, using nitromethane instead of conventional hydrocarbon fuels such as petrol or diesel in an engine with a fixed displacement volume can result in more than two fold increase in the power output of the engine. This has led to nitromethane being established as a high power racing fuel [4–6] as well as nitromethane–methanol blends being used as a fuel for small model aircraft engines [7,8]. However, as the percentage of nitromethane is increased in the fuel, the compression of premixed nitromethane, alcohol, and air often leads to engine knock through early auto-ignition of nitromethane.

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Nomenclature

Latin alphabet

$B_{o.q}$	transfer number
c	speed of light (m/s)
c_{pg}	specific heat capacity at constant pressure for gaseous fuel (J/kg K)
c_{pl}	specific heat capacity at constant pressure for liquid fuel (J/kg K)
d	diameter of pool (m)
E'	energy of the lower state
f	instrument line shape (ILS)
$g(\nu - \nu_{o,i,j})$	Lorentzian line shape
h	Planck's constant (m^2 kg/s)
H	separation between the liquid surface and the flame (m)
h_{fg}	enthalpy of vaporization (J/Kg)
k	burning rate constant (mm^2/s)
k'	Boltzmann constant (m^2 kg/s^2 K)
$k_g(\nu)$	true spectral transmittance
L	path length (m)
$\dot{m}$	mass burning rate for liquid pool (gm/s)
m_{con}	percentage of droplet mass consumed during spray combustion
n	temperature exponent
N	molecular number density
N_s	number of absorbing species
N_r	number of rovibrational transitions
P	pressure (bar)
P_i	partial pressure of the i-th absorbing species
P_t	total pressure (atm)
P_r	reference pressure (1 atm)
Q	partition function
Q_r	heat released (J)
Q_i	heat input (J)
$\dot{Q}_c$	conductive heat transfer from to liquid pool (W)
S	line strength
$S_{i,j}$	line intensity for the i-th species and j-th rotational line
t	time (s)
T	temperature (K)
T_r	temperature of the reference state (298 K)
T_{ls}	liquid surface temperature (K)
T_0	initial liquid fuel temperature (K)
T_f	flame temperature (K)
V	volume of the combustion chamber (m^3)

Greek alphabet

γ	ratio of specific heats
γ_P	pressure-broadened halfwidth at half height (HWHH)
γ_{P0}	reference halfwidth
Δ_{max}	maximum retardation of the moving mirror
η_{comb}	thermal efficiency
λ_{air}	thermal conductivity of air
λ_f	thermal conductivity of fuel vapor
ν_m	wavenumber at a measured data point
$\nu_{o,i,j}$	frequency at the line center
ρ_l	liquid fuel density
$\tau(\nu_m)$	measured transmittance

Abbreviation

HRR	heat release rate
FTIR	Fourier transform infrared spectroscopy

Furthermore, the efficiency of these engines is hampered by loss of unburnt fuel through exhaust. These problems may be circumvented by utilization of nitromethane in direct-injection (DI) engines, either by itself, or blended with a suitable hydrocarbon.

Before nitromethane can be successfully utilized in reciprocating DI engines, the ignition and combustion of nitromethane sprays in an atmosphere of air needs to be investigated. Nitromethane has been the subject of various experimental [9] and theoretical [10,11] studies aimed at elucidating its fundamental combustion characteristics. However, combustion of monopropellant sprays, governed by multiphase premixed combustion, is dissimilar to diffusion-dominated hydrocarbon spray combustion due to possibility of a monopropellant flame in conjunction with the bipropellant flame, thus warranting separate in-depth investigation of the phenomena. Although several studies have been conducted in the past on spray combustion of monopropellants such as hydroxyl ammonium nitrate (HAN) [12,13], and nitromethane [14,15], the data regarding spray combustion of nitromethane in an atmosphere of air are sparse.

In order to characterize the behavior of nitromethane for the application in DI engines, direct experimentation with an engine fitted with appropriate instruments [16,17] may be conducted. However, constant volume combustion of a premixed charge or liquid spray [18–21] is known to be instrumental in elucidating fundamental combustion characteristics such as ignition delay, rate of heat release, and various spray characteristics while providing simplicity of analysis and control over the experimental conditions.

The objective of this study is to elucidate the fundamental physico-chemical phenomena governing ignition and combustion of nitromethane over a range of chamber pressures within a constant volume combustion chamber. The experiments were conducted with an atmosphere of air with the highest chamber pressure fixed at 7 bar. These conditions are similar to those found in model aircraft internal combustion engines where a typical compression ratio of six would yield a maximum pressure of approximately 12 bar. However, this value will be lower in an actual engine due to various losses. In this study, the characteristics of the spray combustion of nitromethane were inferred from the pressure traces acquired during the combustion process, the composition of the residual gases after the combustion was determined using FTIR spectroscopy, and visual observation of the spray combustion event. Various factors characterizing the combustion process, such as ignition delays, rate of pressure rise, final achieved pressure, heat release rates, combustion efficiency etc. were also determined.

2. Experimental setup and procedure

The pressure rise in the constant volume combustion chamber was considered as the primary characterizing parameter during the spray combustion of nitromethane. The experimental setup utilized for the measurement of pressure rise during the constant volume combustion of nitromethane spray consisted of a stainless steel cylindrical pressure vessel, standard automobile glow plugs, a