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Ignition and combustion of n-heptane droplets in carbon dioxide enriched environments ☆

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ABSTRACT

The ignition process and burning characteristics of fiber-supported n-heptane fuel droplets in carbon dioxide enriched and varying pressure environments have been studied under normal gravity. Measured values of droplet burning rates, flame dimensions, broad-band radiant emission, and ignition times were compared to droplets burning in standard air conditions. The burning rate constants increased with increasing carbon dioxide concentration or pressure. For 21% ambient oxygen concentration ignition was achieved for carbon dioxide concentrations up to 46% with the remaining being nitrogen. The experimental burning rates were compared to existing theoretical models. A flammability map for n-heptane burning under normal gravity as a function of carbon dioxide concentration and pressure was also developed using these results.

1. Introduction

Droplet combustion is one of the classical problems in diffusion flame studies. Due to its simple spherical geometry, droplet combustion experiments can be used as a prototypical model to test many combustion phenomena including the effectiveness of fire suppressants in extinguishing a fire. Currently the US module of the International Space Station employs gaseous carbon dioxide for fire suppression. Many studies have been conducted in the past to investigate the role of CO_2 in combustion processes [1–3]. Earlier, we have studied the combustion of methanol droplets in CO_2 enriched environments under microgravity [3]. The results showed that CO_2 interacts with the burning droplet largely by increasing the radiant emission of the flame. Honda and Ronney [1] studied opposed-flow flame spread rates over solid fuels for different diluents, such as carbon dioxide, helium, nitrogen, argon, and sulphur hexafluoride. They found that helium was a more effective suppressant than carbon dioxide when compared on the minimum oxygen concentration needed to support combustion. Katta et al. [2] studied how carbon dioxide suppresses fire using a numerical model and experiments in microgravity for a methane-air diffusion flame stabilized on a cup burner. They found that a carbon dioxide concentration greater than 19.4% was needed to destabilize a flame in microgravity, while only 16.4% carbon dioxide concentration was needed for normal gravity.

Though there are a number of studies that are available in the literature regarding n-heptane combustion, both in normal and microgravity conditions (see, e.g., [4] and the references cited therein), there is none where the effects of CO_2 dilution have been investigated. In this study we report on the combustion characteristics of n-heptane in CO_2 enriched environments under normal gravity conditions in atmospheric and sub-atmospheric pressures. The oxygen volume fraction is kept constant at 21% throughout the tests and the amount of carbon dioxide was varied at the expense of nitrogen. These experiments provide baseline data for the current n-heptane and methanol droplet combustion studies in CO_2 enriched environments in the International Space Station Fluids and Combustion Facility.

2. Experimental apparatus

The experiments were conducted in a translating droplet combustion apparatus employed previously [5]. In this apparatus a droplet is suspended on a quartz bead formed in the middle of a quartz fiber. The fiber diameter was 120 μm and the bead had a diameter of 200 μm. During an experiment a fuel droplet was first manually deposited on the bead by activating a stepper motor driven syringe, and subsequently an automated ignition and data acquisition sequence was initiated. During the automated sequence, the pre-positioned igniter was energized for 1.7 s with 4.3 A of DC current and then withdrawn from the field of view of the cameras. The igniter wire was made of 29 gauge Kanthal and had an electrical resistance of 0.7 Ω. The data acquisition system consisted of a droplet view camera with a backlight, a color flame view camera, and four radiometers measuring the radiant emission from the flame. Of the four radiometers three were wide-band radiometers (0.4 to 40 μm), and one was a narrow-band radiometer which measured the water-band

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Nomenclature

A_1	Empirically determined constant
B	Transfer number
$C_{p,f}$	Specific heat of fuel
d	Droplet diameter
d_0	Initial droplet diameter
Gr	Grashof number
g	Gravitational acceleration
H	Downstream flame height
i	Stoichiometric oxygen-fuel mass ratio
K	Burning rate constant
k	Average thermal conductivity in the inner region
L	Latent heat of vaporization per unit mass of fuel at its boiling point
n_1	Empirically determined constant
q	Heat of combustion per unit mass of fuel
r	Radial coordinate
S	Upstream flame standoff distance
T_f	Flame temperature
T_b	Fuel boiling point
T_∞	Ambient temperature
t	Time
W	Flame width
$Y_{o,\infty}$	Ambient oxygen concentration

Symbols

ρ_2	Average gas density
ρ_l	Liquid fuel density at its boiling point
μ_2	Average gas kinematic viscosity

emission (4.9 to 7.15 μm). Data acquisition from the cameras and the radiometers was started 0.87 s prior to powering the hot-wire igniter. The radiometer data was collected at 100 Hz while the video images were acquired at 30 frames per second. Prior to an experiment, a gaseous mixture containing desired, O_2, CO_2, and N_2 composition is injected into the combustion chamber using a premixed O_2–CO_2 (21%–79%) high pressure gas bottle and partial pressure mixing. The combustion chamber pressure was then changed to the desired value using a vacuum pump. In a fire suppression scenario CO_2 will displace air, thus causing the O_2 concentration to go down. However, in this study we fix the O_2 concentration at the nominal 21% volume fraction and replace N_2 with CO_2 so that we can exclusively examine the dilution effect of CO_2 compared to N_2.

Table 1
Experimental test matrix and measured burning rate constants.

D_0 (mm)	CO_2 %	Pressure (kPa)	K_{exp}(mm^2/s)
1.039	0.0	29	0.737
1.174	0.0	100	0.940
0.953	0.0	101	0.926
0.929	10.43	36	0.668
0.911	10.67	29	0.687
1.237	10.67	105	1.210
1.041	10.91	33	0.700
0.937	20.54	36	0.712
0.953	20.54	104	1.198
1.067	20.74	30	0.691
0.976	20.74	33	0.691
0.989	30.24	32	0.685
1.054	30.24	33	0.690
1.139	30.24	105	1.150
1.252	39.61	70	1.040
1.054	40.41	68	0.760
1.072	44.18	94	1.100
0.989	44.42	80	0.821
1.098	44.42	88	1.130
1.067	44.42	102	0.859
1.093	44.54	83	0.829
1.131	44.54	91	1.130
1.086	45.61	79	1.020
1.076	45.61	100	1.080
0.963	46.14	105	0.881
1.001	46.78	103	1.030

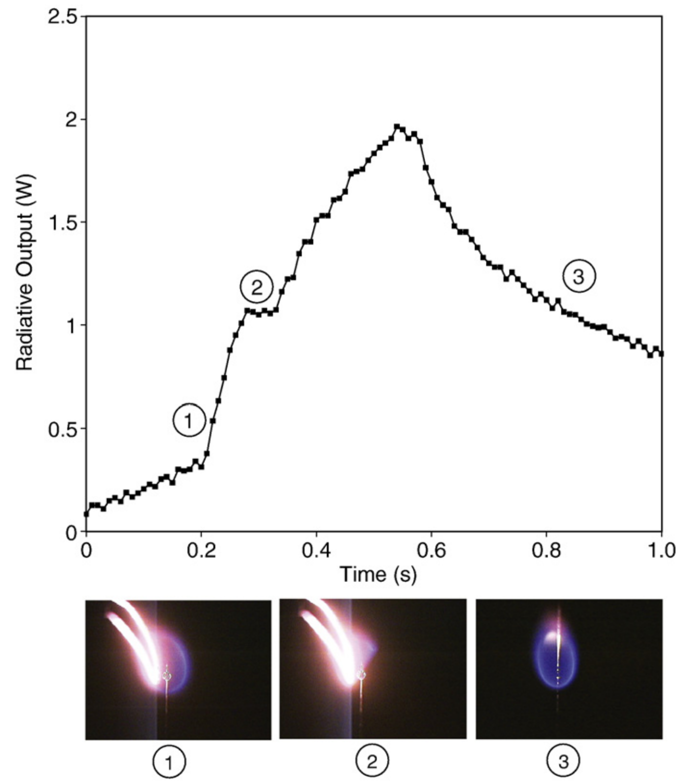

Fig. 1. Radiative output during ignition for 44.54% CO_2, 91 kPa environment.

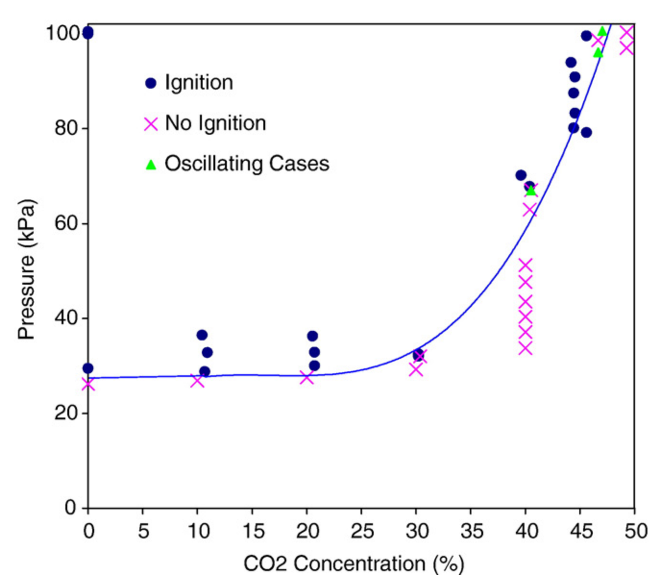

Fig. 2. Flammability map for varying carbon dioxide concentration and pressure environments.