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A study of the effects of diluents on near-limit H_2–air flames in microgravity at normal and reduced pressures

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Abstract

A combination of microgravity experiments and computational simulations were used to study effects of diluents on the near-limit properties of laminar, premixed hydrogen/air flames. The experiments were conducted in a short-drop free-fall laboratory facility that provided at least 450 ms of $10^{-2}g$ conditions. Outwardly propagating spherical flames were used to measure near-limit laminar burning velocities at various fuel-equivalence ratios and pressures with reactants containing varying concentrations of He, Ar, N_2, and CO_2 as fire suppressants. Burning velocities were also computed using the steady, one-dimensional laminar premixed flame code PREMIX with detailed chemical kinetics, transport properties, and radiative heat loss based on an optically thin assumption. Measured and computed results both showed the suppressant effectiveness to increase in the order He, Ar, N_2, and CO_2. This is attributed to both the increasing specific heats and the decreasing transport rates of the gases. The suppressants can also decrease the Markstein number, especially for CO_2, causing the flames to become more susceptible to preferential-diffusion instability. The resulting increase in flame surface wrinkling increases the burning velocity, thus counteracting the desired effect of the flame suppressant. The agreement between measured and computed laminar burning velocities was better than it was near the limit. Sensitivity analyses suggest that inaccuracies in three-body termination rates for $H + O_2 + M = HO_2 + M$ reactions and in mass diffusion coefficients for H_2 diffusion are the most likely explanation for the near-limit differences.

Keywords: Extinction; Diluents; Hydrogen flames; Microgravity

1. Introduction

Chemically inert diluents are an important class of fire extinguishing agents because of their relatively benign effects on people and equipment. Such diluents may be essential, for example, for extinguishing fires in confined environments such as spacecraft. Long-duration missions in particular, including proposed trips to the moon or Mars, substantially increase the risk of accidental fires, and thus development of effective fire-safety systems and procedures for their use in spacecraft environments can be critical in such applications. Chemically active agents, such as halons, have been widely used for both terrestrial and spacecraft applications, and numerous

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Nomenclature

D	mass diffusivity
K	flame stretch
K_p	Planck mean absorption coefficient
L	Markstein length
Ma	Markstein number, L/δ_D
P	pressure
r_f	flame radius
S_L	local laminar burning velocity
$S_{L\infty}$	planar unstretched laminar burning velocity
T	temperature
T_0	ambient temperature
t	time
X	mole fraction
δ_D	characteristic flame thickness, $D_u/S_{L\infty}$
ρ	density
ϕ	fuel-equivalence ratio

Subscripts

b	burned gas
i	species i
u	unburned gas
∞	unstretched flame condition

studies have been conducted to understand how they inhibit reactions. Unfortunately, halons can deplete stratospheric ozone. As a consequence their use is being increasingly restricted. Moreover, in confined environments such as spacecraft, halons generate reaction products that damage life-support systems and are difficult to remove from the interior atmosphere. As a result, chemically inert diluents are potentially more suitable for use in such applications.

In a previous study [1], we reported results on the effectiveness of various diluents at relatively low concentrations for outwardly propagating, spherical, premixed flames under normal-gravity conditions. The diluents considered were helium, argon, nitrogen, and carbon dioxide. They were chosen to allow separate identification of the relative effects of dilution, heat capacity, and transport properties. The normal-gravity conditions, however, limited that study to examining flame propagation velocities at relatively low diluent concentrations, for which the resulting flames were sufficiently fast so that buoyancy effects can be neglected. As diluent concentrations increase and the extinction limit is approached, however, the normal-gravity flames in Ref. [1] cannot be used to investigate the near-limit properties and flammability limits that are essential to characterizing flame-suppression effectiveness under microgravity conditions.

Motivated by this, we designed and built a short-drop free-fall facility in the laboratory to eliminate the intrusion of buoyancy on near-extinction flames, which was reported in Ref [2]. Flame behavior was compared in normal gravity and microgravity. The results show that near-extinction flames in normal gravity propagate upward and form a classic mushroom shape due to buoyancy. The resulting non-spherical shape limits accurate determination of the laminar burning velocity. Using a microgravity facility, however, these slow near-limit flames were shown to maintain a highly spherical shape that allowed their laminar burning velocity to be accurately inferred from measurements of the resulting flame radius versus time. The measured and computed near-limit burning velocities $S_{L\infty}$ under microgravity conditions were reported for stoichiometric H_2/air/diluent flames at normal temperature and pressure. It was found that the agreement between measured and computed laminar burning velocities was better than it was near the limit.

Here we extend these earlier studies by presenting more measurements of near-limit burning velocities under microgravity conditions for H_2/air/diluent flames at various fuel-equivalence ratios and pressures. We then compare the measured $S_{L\infty}$ values to computations with detailed chemistry and transport properties and an optically thin radiation model and show that they agree reasonably well far away from the flammability limit, but that they deviate consistently in the near-limit region. We also discuss the effects of the diluents on the preferential-diffusion instability for H_2/air flames. It is shown that the addition of the diluents (except helium) generally decreases the Markstein numbers, which makes the flames more susceptible to preferential-diffusion instability that can partially offset the effectiveness of the diluents in decreasing the flame propagation rate. Finally, we analyze possible causes for the observed discrepancies in the near-limit laminar burning velocities from the experiments and computations from the perspective of chemical kinetics and molecular diffusion, respectively.

2. Experimental methods

The low-gravity experiment duration required for the premixed flames investigated here is not long, and can be achieved in a short-drop (1-m) free-fall facility. In particular, a 1-m free-fall distance provides roughly