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An experimental and computational study of soot formation in a coflow jet flame under microgravity and normal gravity

Bin Ma [a,*], Su Cao [a], Davide Giassi [a], Dennis P. Stocker [b], Fumiaki Takahashi [c], Beth Anne V. Bennett [a], Mitchell D. Smooke [a], Marshall B. Long [a]

[a] *Department of Mechanical Engineering & Materials Science, Yale University, New Haven, CT 06511, USA*
[b] *NASA Glenn Research Center, Cleveland, OH 44135, USA*
[c] *National Center for Space Exploration Research, NASA Glenn Research Center, Cleveland, OH 44135, USA*

Abstract

Upon the completion of the Structure and Liftoff in Combustion Experiment (SLICE) in March 2012, a comprehensive and unique set of microgravity coflow diffusion flame data was obtained. This data covers a range of conditions from weak flames near extinction to strong, highly sooting flames, and enabled the study of gravitational effects on phenomena such as liftoff, blowout and soot formation. The microgravity experiment was carried out in the Microgravity Science Glovebox (MSG) on board the International Space Station (ISS), while the normal gravity experiment was performed at Yale utilizing a copy of the flight hardware. Computational simulations of microgravity and normal gravity flames were also carried out to facilitate understanding of the experimental observations. This paper focuses on the different sooting behaviors of CH_4 coflow jet flames in microgravity and normal gravity. The unique set of data serves as an excellent test case for developing more accurate computational models. Experimentally, the flame shape and size, lift-off height, and soot temperature were determined from line-of-sight flame emission images taken with a color digital camera. Soot volume fraction was determined by performing an absolute light calibration using the incandescence from a flame-heated thermocouple. Computationally, the MC-Smooth vorticity–velocity formulation was employed to describe the chemically reacting flow, and the soot evolution was modeled by the sectional aerosol equations. The governing equations and boundary conditions were discretized on an axisymmetric computational domain by finite differences, and the resulting system of fully coupled, highly nonlinear equations was solved by a damped, modified Newton's method. The microgravity sooting flames were found to have lower soot temperatures and higher volume fraction than their normal gravity counterparts. The soot distribution tends to shift from the centerline of the flame to the wings from normal gravity to microgravity.

Keywords: Microgravity flame; Soot temperature; Soot volume fraction

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* Corresponding author. Fax: +1 (203) 432 6775.
E-mail address: bin.ma1@ge.com (B. Ma).

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1. Introduction

Microgravity is a unique environment in which to study combustion. The absence of buoyancy results in a simplified flow field that can serve as a "cleaner" test case to develop computational models. Highly diluted flames that extinguish in normal gravity (1 g) can be stabilized in microgravity (μ g), which enables the study of flames near extinction. Sooty flames with enhanced residence time can be also generated, which can be used to further study soot formation mechanisms. In general, the contrasting effects in normal and microgravity provide an excellent test case for developing an improved understanding of the factors that affect flame lift-off distance, extinction, and soot formation mechanisms. To better understand the factors that affect flame extinction and particulate formation, flames were investigated in the SLICE experiment on board the ISS. Although the SLICE experiment investigated flames with a wide dilution spectrum, from weak to highly sooting, the work described here emphasizes the sooting behaviors of coflow jet flames in microgravity and normal gravity.

The effect of gravity on soot formation has been studied over the past few decades. Experimentally, Greenberg and Ku [1] conducted a reduced-gravity experiment in the NASA Glenn 2.2 s drop tower, and reported the first normal gravity and microgravity comparison of soot volume fraction for laminar acetylene and nitrogen-diluted acetylene jet diffusion flames. A factor of 2–4 increase in peak soot volume fraction was reported from 1 g to μ g. Walsh et al. [2] found that the laser induced incandescence (LII) signal of a methane coflow laminar diffusion flame increased by a factor of 15 during a parabolic flight. Jeon and Choi [3] studied the buoyancy effect on soot formation in a gas-jet diffusion flame in partial gravity conditions from 0.3 g to 1 g. The soot volume fraction was measured by extinction and found to increase with reduced gravity level. Reimann et al. [4] performed LII in a drop tower, measuring both soot concentration and primary particle size. In microgravity, the maximum soot particle size is roughly double that of the 1-g case. Diez et al. [5] studied the properties of non-buoyant, laminar jet diffusion flames on board the Space Shuttle Columbia and showed the existence of a soot property-state relationship for such flames. Computationally, Kaplan et al. [6] simulated an ethylene–air diffusion flame and found that the peak soot volume fraction increased by a factor of 10 from 1 g to μ g. Their simulation did not reach steady-state conditions within ~3 s of microgravity. This result indicates that flames may not stabilize in short-duration drop tower experiments. Kong and Liu [7] recently simulated laminar coflow methane/air diffusion flames and studied the effects of the air coflow velocity. The peak soot volume fraction in microgravity was found to be about twice that in normal gravity [8]. Liu et al. [9] computed the influence of heat transfer and radiation on the structure and soot formation characteristics of a coflow laminar ethylene/air diffusion flame and showed that radiative heat loss plays a major role in the flame structure in microgravity. Charest et al. [10] recently simulated the influence of gravity on a laminar coflow methane/air diffusion flame, demonstrating that the μ-g flame has lower gas temperatures, thicker soot regions and higher soot volume fractions than the 1-g flame.

Although significant efforts have been made to experimentally study gravitational effects on soot formation processes, there are some uncertainties and complications associated with experiments. For example, flames in short-duration drop tower experiments are often not fully stabilized; on the other hand, the gravitational-jitter in parabolic flight can dramatically disturb low-momentum flames, affecting the accuracy of the measurements. Furthermore, the experimental results are quite limited due to the sheer cost of the microgravity experiments. Many computational studies have been conducted, but they were performed for conditions different from the available experimental data. Therefore, no direct comparison between experiment and computation was available for microgravity flames, making it hard to directly assess the effectiveness of the computational models. The SLICE project, on the other hand, is a joint experimental and computational study. The microgravity tests were conducted by crewmember Dr. Donald R. Pettit in 2012 in the Microgravity Science Glovebox (MSG) on board the ISS, which provides a stable microgravity environment for conducting long-duration experiments. The normal gravity SLICE experiment was performed at Yale, using a replica of the SLICE flight hardware (namely, the engineering and training hardware). Detailed near-field velocity measurements performed on the engineering unit guided the boundary conditions used in the computations. In the following sections, two-dimensional comparisons of 1-g and μ-g soot temperature and volume fraction are presented from both experiment and computation.

2. SLICE experimental setup

The basic SLICE experimental setup was originally used in the Enclosed Laminar Flames (ELF) investigation [11] to study the effect of buoyancy on the stability of coflow gas-jet diffusion flames during the STS-87 Space Shuttle mission. A schematic of the SLICE burner inside the hardware is shown in Fig. 1. The duct has a 76 mm × 76 mm square cross-section with rounded corners and is 174 mm tall. The central fuel jet tube has a

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