Title

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Authors
Mikofski, Mark A
Blevins, Linda G
Davis, Ronald W
et al.

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COSMIC: CARBON MONOXIDE AND SOOT IN MICROGRAVITY INVERSE COMBUSTION

Mikofski, M.A.
University of California, Berkeley
Blevins, L.G.*
Sandia National Laboratories
Davis, R.W., Moore, E.F., Mulholland, G.W.
National Institute of Standards and Technology

INTRODUCTION

Almost seventy percent of fire related deaths are caused by the inhalation of toxins such as CO and soot that are produced when fires become underventilated.(1) Although studies have established the importance of CO formation during underventilated burning,(2) the formation processes of CO (and soot) in underventilated fires are not well understood. The goal of the COSMIC project is to study the formation processes of CO and soot in underventilated flames. A potential way to study CO and soot production in underventilated flames is the use of inverse diffusion flames (IDFs). An IDF forms between a central air jet and a surrounding fuel jet. IDFs are related to underventilated flames because they may allow CO and soot to escape unoxidized. Experiments and numerical simulations of laminar IDFs of CH_4 and C_2H_4 were conducted in 1-g and μ-g to study CO and soot formation. Laminar flames were studied because turbulent models of underventilated fires are uncertain. Microgravity was used to alter CO and soot pathways. A IDF literature survey, providing background and establishing motivation for this research, was presented at the 5th IWMC.(3) Experimental results from 1-g C_2H_4 IDFs and comparisons with simulations, demonstrating similarities between IDFs and underventilated fires, were presented at the 6th IWMC.(4) This paper will present experimental results from μ-g and 1-g IDFs of CH_4 and C_2H_4 as well as comparisons with simulations, further supporting the relation between IDFs and underventilated flames.

EXPERIMENTAL AND COMPUTATIONAL METHODS

Microgravity was attained in the 2.2 Second Drop Tower at the NASA Glenn Research Center. Normal gravity tests were conducted at UC Berkeley. Experiments were performed using the COSMIC rig, a standard NASA drop-tower rig, on which the experimental apparatus was mounted. Flames were stabilized on a burner with a 1 cm central tube surrounded by a concentric annulus with an outer diameter of 3 cm. The burner was mounted inside a standard NASA 27 liter combustion chamber. A ni-chrome wire suspended above the burner was used to ignite the IDF. Temperature measurements were made with a fine wire S-type thermocouple positioned 3.5 cm above the burner. A thin-film thermopile radiometer with a CaF_2 window was positioned adjacent to the flame with its face parallel to the axis of symmetry in order to collect radiation from flames up to 8 cm in height. A camera mounted outside the chamber window was used to record images. Fuel and air were stored in 500 cc storage bottles. Gas flow rates were measured by mass flow meters and controlled by fine metering valves. Solenoids valves were used to open and close the fuel and air lines. A NASA Droppable Data Acquisition and Control System (DDACS) was programmed to control the rig and store data. A NASA Power Distribution

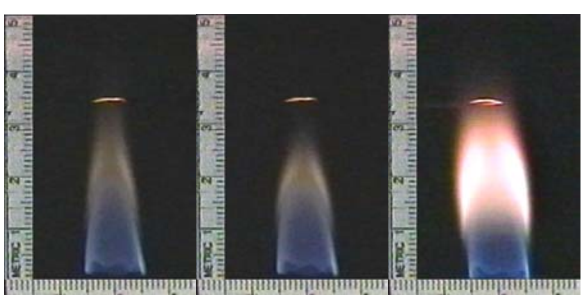
Module (PDM) distributed power to the DDACS, the camera, the igniter, pressure transducers, the mass flow meters and the solenoid valves from two 24 volt NASA batteries.

For CH_4 the mass flow rate was 41.6 mg/s (10 cm/s average velocity) with an air mass flow rate of 47.2 mg/s (50 cm/s), and for C_2H_4 the flow rate was 49.1 mg/s (7 cm/s) with an air mass flow rate of 31.9 mg/s (35 cm/s). The air to fuel velocity ratio was constant, 5:1, for both flames. The chamber was evacuated to 0.2 psia and filled with N_2 to 1 atm to prevent secondary flames from forming between the fuel and any air in the chamber. For μ-g tests, the igniter was triggered at the beginning of the drop. For 1-g tests, the igniter was triggered manually. Thermocouple and radiometer voltages were recorded during the test. After 2.1 seconds, the igniter was de-energized and the fuel and air lines closed. A post-test sampling system was then used to analyze the CO concentration of the combustion products and to collect soot samples on quartz filters. The combustion products were passed through a pump, a quartz filter, a non-dispersive IR CO analyzer, and back to the chamber in a closed loop until the CO concentration reached a steady state. The soot mass from μ-g tests was determined using a carbon burn-off technique. Filters from 1-g tests were weighed before and after sampling to deduce the soot mass.

Calculations were carried out using direct numerical simulation of the time-dependent Navier Stokes and conserved variable equations for an axisymmetric laminar flame.(5) The simulation employs assumptions of low Mach number, infinite-rate chemical kinetics, unity Lewis number, variable thermophysical properties, a semi-infinite surrounding fuel-stream, and negligible radiation heat transfer. Dilute-condition particle tracking incorporating the effects of inertial, thermophoretic, and gravitational forces is included to show basic IDF particle pathways and time-temperature histories.(6) Particles were introduced at axial positions of 0 mm, 5 mm, 10 mm, 15 mm, and 20 mm above the burner, and at radial positions corresponding to a characteristic soot formation temperature of 1250 K.(7)

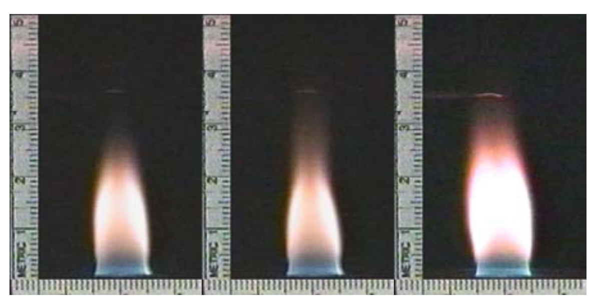
RESULTS AND CONCLUSIONS

An examination of the images shown in Figs. 1 and 2 reveals that both flames were longer, more rounded, and more luminous in μ-g, and that the CH_4 flame was longer than the C_2H_4



(a) 1-g (b) 1-g (c) μ-g

Fig. 1. CH_4 IDFs (f/#8).



(a) 1-g (b) 1-g (c) μ-g

Fig 2. C_2H_4 IDFs (f/#16)

flame for both 1-g and μ-g. The CH_4 1-g flame is mostly blue and has a faint orange cap, while the C_2H_4 1-g flame is covered by an orange annular region for most of its length. Both μ-g flames are covered by a luminous orange annular region. In addition, the 1-g flames flickered (two states of flickering are shown in the figures), but the μ-g did not. The temperature and radiometer data, shown in Fig. 3 and Table 1, indicate that both flames reached steady state faster and radiated more in μ-g. The 1-g flickering is also visible in the thermocouple signal shown in Fig. 3

Table 1. Average measured and predicted data for CH_4 and C_2H_4 1-g and μ-g IDFs

T_m = measured temperature, 3.5 cm above flame, T_p = predicted temperature, 3.5 cm above flame, H_p = predicted flame height

Fuel	Gravity	Radiometer	T_m	T_p	H_p	[CO]	[CO]/[CO_2]	m_{soot}
		V	K	K	cm	ppm		μg
CH_4	1-g	0.96 ± 0.02	1209 ± 5	1699	2.1375	167 ± 3	0.80 ± 0.02	25
CH_4	μ-g	2.2 ± 0.02	1223 ± 51	1734	2.2725	180 ± 4	0.92 ± 0.04	12
C_2H_4	1-g	0.77 ± 0.02	1072 ± 8	1592	1.4625	261 ± 1	3.31 ± 0.05	33
C_2H_4	μ-g	1.6 ± 0.04	1129 ± 24	1653	1.5075	262 ± 6	3.52 ± 0.38	43

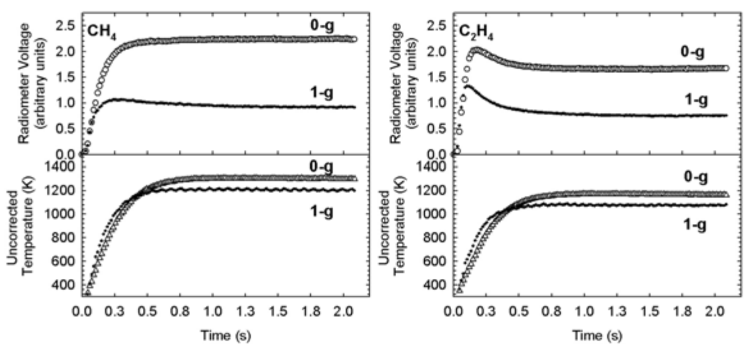


Fig. 3. Radiometer and thermocouple measurements

Post-test data are displayed in Table 1. Measured CO concentrations of the post-test gases from both flames in 1-g and μ-g were significant with [CO]/[CO_2] ratios on the order of 1 for CH_4 and 3 for C_2H_4. The CO to CO_2 concentration ratio of laminar, underventilated normal flames was measured to be 1:2 in a previous study.(8) Soot collected from both CH_4 and C_2H_4 μ-g flames displayed a spike in the low-temperature phase of the carbon burn-off analysis, qualitatively indicating that a fraction of the soot was made of volatile organics, similar to the soot of underventilated flames. The analysis of the soot from the μ-g C_2H_4 flame showed a spike in the high-temperature phase, indicating that the soot was also partially carbonized, whereas the μ-g CH_4 was flat in that region, indicating that it was mostly organic. The soot mass collected from C_2H_4 flames was greater in μ-g, but surprisingly the soot mass from CH_4 flames was less in μ-g, despite the larger CH_4 soot cap. However, different techniques were used to deduce the soot mass, and the number of data points was statistically insufficient for conclusions to be made.

The simulation results shown in Fig. 4 and Table 1 agree well with the experimental observations, predicting similar trends in flame height, shape, and temperature. The predicted particle pathways obtained from the simulations demonstrate that the particles move away from the flame for both flames in μ-g. The time-temperature histories shown in Fig. 5 demonstrate that the

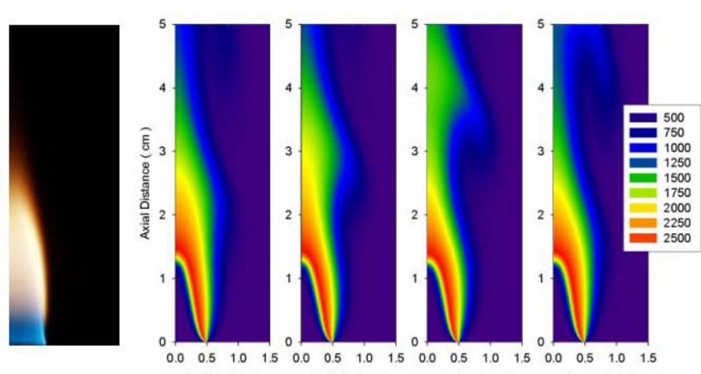


Fig. 4. Photo and calculated temperature profiles for 1-g C_2H_4 flame.

particles for both flames are accelerated by buoyancy in 1-g, that the C_2H_4 particles experience reheating due to buoyancy-induced flickering, and that the temperatures of particles in both μ-g flames decrease monotonically with time.

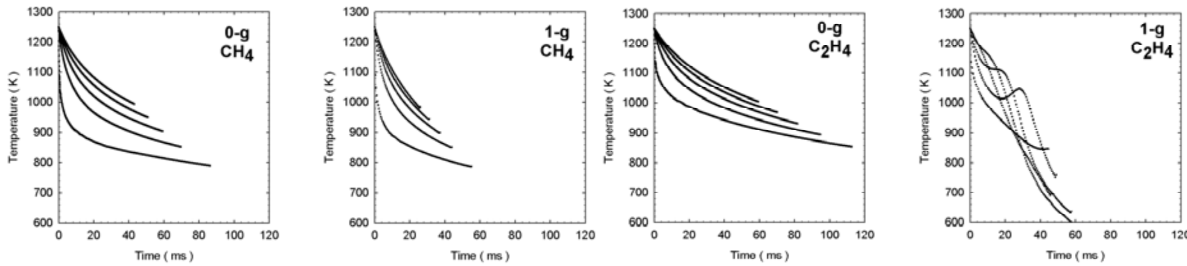


Fig. 5. Time/temperature history of particles in 0-g and 1-g CH_4 and C_2H_4 IDFs.

SUMMARY AND FUTURE PLANS

Experiments and simulations of 1-g and μ-g CH_4 and C_2H_4 IDFs have been conducted. Predicted flame heights, temperatures and shapes of IDFs correlate well with experiments. IDFs produce significant concentrations of CO, and the soot from IDFs is partially organic, which support the hypothesis that IDFs are similar to underventilated flames. Microgravity was used to alter the way IDFs behave. More drop tower experiments are planned to study soot structure and chemical composition. The results should provide insight into the formation mechanisms of undesirable CO and soot during underventilated combustion.

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