Brief Communication

Effects of oxygen enhancement and gravity on normal and inverse laminar jet diffusion flames

P.B. Sunderland,[a,*] S.S. Krishnan,[b] and J.P. Gore[c]

[a] *National Center for Microgravity Research, NASA Glenn Research Center, Cleveland, OH 44135, USA*
[b] *Indiana University–Purdue University Indianapolis, Indianapolis, IN 46202, USA*
[c] *Purdue University, West Lafayette, IN 47907, USA*

1. Introduction

A fire on the Mir space station in 1997 threatened the spacecraft and its crew of six [1]. The fire involved an oxygen jet leaking from a lithium–perchlorate oxygen generator. The fire involved three factors not normally encountered in terrestrial fires: enhanced oxygen, inverse flames (in that the oxidizer is surrounded by fuel), and microgravity. The present work examines some effects of these factors on ethane laminar gas-jet diffusion flames, building on the past work of Refs. [2–6].

2. Experimental

The burner was a round 5.5-mm stainless-steel tube, which was straight and unobstructed within 25 cm of its tip. The ambient gas was quiescent at 0.98 bar and 295 K and was contained in a 27-L cylindrical pressure vessel. The microgravity tests were performed in the NASA Glenn 2.2-s drop tower with ignition in microgravity. The apparatus and methods are described in detail in Ref. [3].

The flames were imaged with a color CCD camera. Apertures and electronic shutter speeds were varied according to illumination and yielded relative exposures, in which unity corresponds to f1.6 and 33 ms. Spatial resolution was 0.1 mm. Where blue contours were identifiable, stoichiometric flame lengths were measured from the burner tip to the farthest point of blue emission. Alternatively, luminosity lengths were measured to the end of the yellow region on the flame centerline. Flame widths were found from the widest parts of the blue or yellow regions.

Table 1 summarizes the tests. For each set of conditions, flames were observed at both earth gravity and microgravity. Stoichiometric mixture fraction, Z_{st}, was defined as in Williams [7]. Adiabatic flame temperature, T_{ad}, was determined using CEA [8] assuming constant enthalpy and pressure. The burner gas velocity, u, for the inverse flames was held constant. The normal flames match the heat release rates, Q, of the corresponding inverse flames based on a lower heating value of ethane of 47,489 J/g. Reynolds numbers were determined from $Re = ud/v$, where v is the dynamic viscosity of the burner gas at 0.98 bar and 295 K and d is the burner diameter. Symbols X_{O_2} and m are, respectively, the mole fraction of oxygen in the oxidizer and the mass flow rate of the burner gas.

3. Results

Table 1 includes the lengths, L, and widths, w, of the microgravity flames (subscript μg) and the earth-gravity flames (subscript $1g$). Color images of the normal flames are shown in Fig. 1. Increasing X_{O_2} yields brighter flames. The flames are narrower in earth gravity than in microgravity owing to buoyantly induced entrainment. Stoichiometric flame length is less affected by gravity, in agreement with past observations [3] and the Roper [9] prediction that flame length is independent of gravity level for circular burners. Those microgravity flames that form soot have much larger soot regions than do their earth-gravity counterparts.

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* Corresponding author.
E-mail address: pbs@grc.nasa.gov (P.B. Sunderland).

Table 1
Summary of ethane test flames at earth gravity and microgravity

Flame	X_{O_2} [a]	Z_{st}	T_{ad} (K)	Q (W)	m (mg/s)	u [b] (mm/s)	Re [b]	L_{1g} [c] (mm)	w_{1g} [c] (mm)	$L_{\mu g}$ [c] (mm)	$w_{\mu g}$ [c] (mm)
21	0.21	0.059	2258	72	1.51	52	39	<u>25</u>	8.1	21	26
21i					24.4	866	312	14	5.9	15	6.0
30	0.3	0.081	2553	102	2.16	74	55	<u>18</u>	8.1	24	28
30i					24.5	866	310	13	6.0	14	6.4
50	0.5	0.125	2839	171	3.60	124	92	<u>16</u>	7.7	<u>32</u>	24
50i					25.2	866	310	14	6.7	15	7.4
100	1	0.211	3082	342	7.21	247	185	<u>20</u>	<u>7.0</u>	<u>39</u>	22
100i					26.9	866	311	17	9.0	19	11

[a] Balance N_2.
[b] Corresponding to plug flow at 0.98 bar and 295 K.
[c] Underlined dimensions correspond to yellow regions. All other dimensions correspond to blue regions.
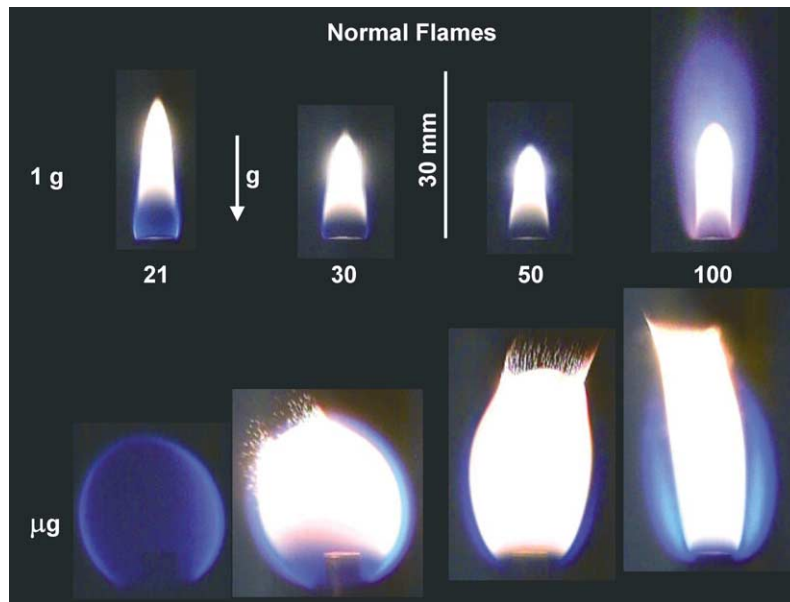

Fig. 1. Color images of the normal flames at earth gravity and after 2 s of microgravity. Relative exposures for earth-gravity flames are (left to right) 0.18, 0.04, 0.02, and 0.01. Relative exposures for microgravity flames are 1, 1, 0.18, and 0.09. The horizontal and vertical scales are the same.

Color images of the inverse flames are shown in Fig. 2. Here soot forms on the fuel side and is emitted into the ambient ethane. Increasing X_{O_2} yields brighter flames and enhanced soot production and emission. Double blue flames, also noted in Hwang and Gore [5], make it difficult to precisely identify the stoichiometric contours. Whereas gravity has little impact on the stoichiometric shapes of the inverse flames, the soot regions are larger in the microgravity flames. This is because the convective velocities are too high to be significantly modified by gravity near the flame sheets but not near the soot regions.

The earth-gravity flames were steady except for weak flickering in flames 100, 50i, and 100i. Where flickering was present, images and dimensions reported here correspond to flames of intermediate size.

Figure 3 shows the development of microgravity flame lengths with time, t. The normal flames do not reach steady lengths. (Extrapolation to infinite time following Ref. [10] has not been attempted because the slopes of the curves in Fig. 3a generally are not decreasing at drop end.) In contrast, the inverse flames reach steady lengths within 0.5 s. This behavior is related to the characteristic residence time, $L_{\mu g}/u$. This is an attractive feature of inverse gas-jet flames for ground-based microgravity tests which is similar to previous approaches involving low pressures, small burners, and burner reactant dilution.
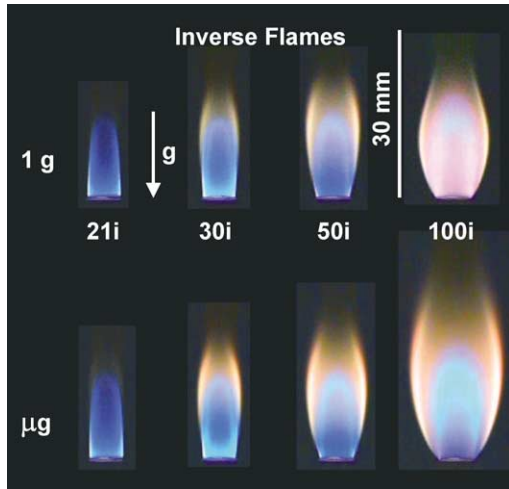
Fig. 2. Color images of the inverse flames at earth gravity and after 2 s of microgravity. Relative exposures for both earth-gravity and microgravity flames are (left to right) 0.18, 0.18, 0.09, and 0.02. The horizontal and vertical scales are the same. The burners were enhanced here.

4. Conclusions

Ethane-fueled laminar gas-jet diffusion flames were observed, emphasizing the effects of oxygen enhancement (up to 100% O_2), microgravity, and inverse burning on flame appearance and sooting behavior. The principal findings were:

(1) Oxygen-enhanced conditions led to increased luminosity, soot production, and soot emission for both normal and inverse flames. This attests to the increased fire hazards associated with oxygen-enhanced combustion.
(2) Gravity generally caused the normal flames to become shorter, narrower, and less sooty than their microgravity counterparts. Gravity had less impact on the appearance of the inverse flames owing to higher burner velocities, but did cause smaller soot regions.
(3) The inverse flames reached steady microgravity conditions within 0.5 s, whereas the normal flames were transient throughout the 2.2-s tests.
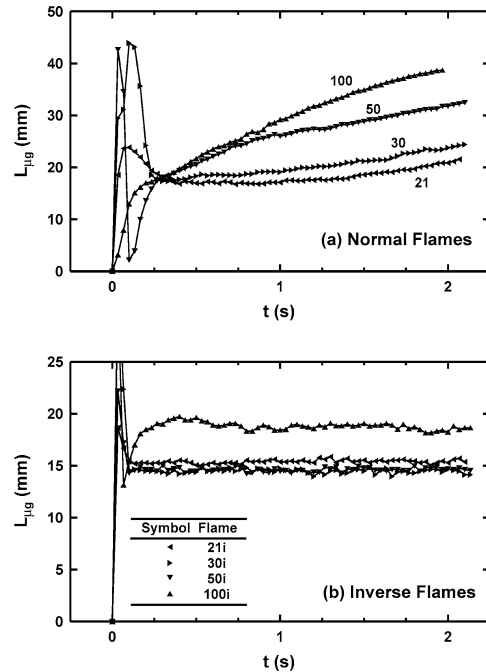
Acknowledgment

Fig. 3. Length development of microgravity (a) normal and (b) inverse flames. Luminosity lengths are shown for flames 50 and 100, whereas flame sheet lengths are shown for all others.

References

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