

EFFECTS OF FUEL PREHEAT ON SOOT FORMATION IN MICROGRAVITY LAMINAR DIFFUSION FLAMES¹

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Introduction

Nonbuoyant flames offer themselves as an attractive and promising platform to gain a better understanding of soot mechanisms [1]. The effects of buoyancy can be eliminated temporarily in drop towers which sustain brief intervals of reduced gravity—typically lower than $10^{-3}g$ —extending up to several seconds at a time. Microgravity facilities have been employed [2, 3] to show that nonbuoyant flames are longer, wider and sootier than their normal-gravity counterparts.

Sunderland et al. [4] recently verified the existence of smoke point in laminar nonbuoyant flames. As reported in [3] and [4], microgravity flames operating above their smoke point displayed a blunt tip and much broader soot-containing regimes in comparison to their buoyant counterparts. Mortazavi et al. [5] established that residence times in microgravity laminar jet diffusion flames with $Re=O(100)$ tend to be proportional to burner diameter and inversely proportional to burner exit velocity. This offers the capability to alter residence times in nonbuoyant laminar jet diffusion flames when varying the burner exit diameters and velocities [1].

Megaridis et al. [6] presented a quantitative definition of the soot-field structure within laminar microgravity jet diffusion flames which operated well above their smoke point. The experimental methodology involved a full-field laser-light extinction technique [7] and jet diffusion flames of nitrogen-diluted (50% vol.) acetylene fuel burning in quiescent air at atmospheric pressure. The work was conducted at the 2.2s drop tower of the NASA Lewis Research Center (NASA-LeRC). Parallel work on 1-g flames was also presented in [6] to facilitate comparisons on the effect of gravity on the soot fields. As reported in [6], the soot spatial distributions in 0-g flames did not change in a detectable manner after 1s within a typical 2.2s experiment. During that period, the soot field was shown to sustain a pronounced annular structure throughout the luminous nonbuoyant-flame zone. The maximum soot volume fraction measured at 0-g was nearly a factor of two higher than that at 1-g, thus confirming the enhanced sooting tendency of nonbuoyant flames [1].

Greenberg and Ku [8] presented a similar study and reported trends that matched those of [6] for the 50% (vol.) nitrogen-diluted acetylene fuel. Furthermore, they examined pure acetylene flames and reported similar trends with respect to the influence of gravity on maximum soot volume fractions and flame cross-section-averaged soot loadings. Both studies [6, 8] clearly demonstrated the improved spatial resolution of microgravity flames compared to their normal-gravity counterparts.

The current study evaluates the influence of moderate fuel preheat on soot formation within 0-g laminar gas jet diffusion flames. While fuel temperature variations have little influence on residence times in 1-g, they have a much more significant effect in 0-g [1]. The primary objective of this program is to quantify this effect and its consequences on sooting by comparing soot volume fraction distributions under preheated and unpreheated-fuel conditions. Furthermore, the current work aims at expanding the limited soot database available for nonbuoyant flames. Soot fields in such flames can be used to perform additional tests of recently developed soot sub-models which have the potential to become powerful predicting tools in combustion design.

Experimental Setup and Conditions

The laminar gas jet diffusion flames studied herein were operated at atmospheric pressure and were based on a

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1.6mm inner diameter stainless-steel burner which was positioned vertically in the experimental apparatus. The fuel mixture consisted of 50% (volume) C_2H_2 – 50% N_2 and was issued into quiescent air contained in a rectangular chamber with dimensions 30cm $\times$ 21cm $\times$ 43cm. The base fuel flow rate of 2.2 mg/s was selected because it defined flame sizes which provided adequate resolution of the soot fields both in 1-g and 0-g [6]; the flame luminosity lengths were between 25mm and 30mm. The mass flow rate of 2.2 mg/s corresponds to a volume flow rate of 2 cm³/s at room temperature. A second set of experiments was conducted at a lower fuel flow rate of 1.6 mg/s. Two fuel preheat levels were studied for the base mass flow rate of 2.2 mg/s; 120°C and 160°C. These preheat levels correspond to an increase in adiabatic flame temperature by 7K and 10K, respectively, compared to the unpreheated-fuel case. Therefore, the effect of the current fuel preheat levels on fuel pyrolysis rates – and thus on soot inception rates – should be negligible. Table I lists four burner exit conditions for the flames studied in this work. Two conditions (I and II) involved unpreheated fuel, while the other two (III and IV) featured fuel preheat temperatures of 120°C and 160°C, respectively. All burner exit flow conditions listed in Table I produced non-flickering flames in normal gravity as well as within the short time period available for measurements in the drop tower. All 1-g flames corresponding to the conditions listed in Table I emitted no soot from their closed conical tip, while their nonbuoyant counterparts released soot from their open tip. The smoke point of the diluted unpreheated acetylene fuel at 0-g was determined to be in the range from 0.77 – 1.1 mg/s (0.7 to 1 cm³/s at room temperature).

The experimental rig is the same one used in [6]. Each microgravity experiment lasts for 2.2 seconds, during which data are collected continuously. Diagnostic instrumentation includes laser-light extinction for determination of soot volume fraction distributions and direct imaging of the flame. The flame luminosity throughout each drop test is recorded and can be subsequently analyzed to determine luminous flame dimensions. Experiments are fully automated and are controlled via an onboard computer. Fuel preheat is achieved by thermocouple sensors, temperature controllers and heating tapes wrapped around the fuel feed lines. The rig design allows operation in either unpreheated or preheated mode by activating appropriate elements of the experimental setup. Soot volume fraction distributions within the flames were determined via a full-field laser-light extinction technique [7]. The instrumentation for these measurements has been described in detail in [6]. From each horizontal intensity profile (Z = constant), the radial distribution of soot volume fraction is determined using a three-point Abel deconvolution algorithm [9], and Rayleigh scattering theory with a specific value of the refractive index of soot (1.57 – 0.56i).

Results and Discussion

Detailed observations of luminous zone development after ignition in 0-g showed the initial transients to be complete before the half-way temporal point of a drop experiment ($\sim$ 1s). Figures 1a, b, c present the luminous images of Flames II, III and IV, respectively, as captured from the side after the brief initial transients in 0-g. The soot-emitting character of all 0-g flames examined in this work made the determination of a visible height impossible; notice the gradual darkening of flame tip with height in Fig. 1. The vertical scale in Fig. 1a corresponds to a length of 25mm. It is clear that fuel preheat has a visible effect on the structure of the soot field; see differences of shapes in Fig. 1. More specifically, the base and the tip of Flames III and IV (Fig. 1b, c; preheated fuel) are considerably narrower than those of Flame II (base flame seen in Fig. 1a; unpreheated fuel).

Soot fields in 0-g laminar jet diffusion flames anchored on the same burner (1.6mm diameter, Reynolds of the order of 100) were analyzed in [6] as a function of time to evaluate their transient post-ignition character. Figure 2 displays two instantaneous shadow-like images of the soot field as viewed by the CCD camera of the extinction setup during a drop experiment at 0.5s and 1.2s after the release of the package. Fuel ignition occurred 0.3s after the onset of microgravity. The flame conditions corresponding to these images are those of Case II in Table I. The burner mouth is located directly below the middle of the bottom edge of each image seen in Fig. 2. The apparent differences of the soot shadow at the upper half of the images of Fig. 2 confirm the changing character of the soot field after ignition in 0-g (0.3s). As reported in [6], the establishment of the soot field in these flames is completed within one second after the onset of microgravity. This was also verified in the current study for all flame conditions listed in Table I.

A series of images similar to those depicted in Fig. 2 were utilized to produce radial distributions of soot volume fraction (f_v) at distinct axial stations above the burner tip of each flame. The specific heights examined in this work are Z = 10mm, 15mm, 20mm and 25mm. The spatial soot distribution at each height Z was obtained by averaging the respective distributions acquired in two to three drop experiments which were conducted using identical operating conditions. Figure 3 displays the radial variations of f_v throughout the four microgravity flames (I to IV; see Table I). Each frame in this figure corresponds to a fixed height Z (10mm, 15mm, 20mm and 25mm). Figure 3 shows clearly – as also reported in [6] – that the soot distributions maintain a noticeable annular structure throughout the entire luminous flame zone. Even though the soot volume fraction is always higher on the annulus, the soot concentrations in the vicinity of the flame axis become significantly higher when the fuel is preheated (compare curves II and III or IV at Z =25mm, for example).

The radial distributions in Fig. 3 also show that the lower exit momentum of the fuel jet in Flame I causes a widening of the soot field compared to the rest of the flames. This trend is maintained at all heights and emphasizes the importance of jet momentum in flame structure in 0-g. As the fuel exit velocity increases from Flame I to IV, the soot annulus moves closer to the flame axis. It is also seen in Fig. 3 that the radial location of the soot annulus is nearly the same for the two flames with preheated fuel (III and IV).

Figure 4 compares the streamwise variation of (a) maximum and (b) on-axis soot volume fraction at each height Z for all 0-g flames. As the radial distributions in Fig. 3 indicate, the maximum values of f_v at a fixed height always correspond to the soot annulus in the 0-g flames examined in this work. Figure 4a also includes the values of f_v on the soot annulus of a flame identical to Flame II as reported in Ref. [6], and shows good repeatability of the measurements. Figure 4a shows that the overall maximum value of f_v is ~ 14 ppm and is achieved near $Z=20$ mm of Flame II (unpreheated fuel). In all preheated-fuel flames the soot volume fractions peak at $Z=15$ mm and decline thereafter. Some important conclusions can be inferred from the curves of Fig. 4 when taking into account residence time considerations. Estimates of flow residence times were produced for the base case flame (II) using the soot cloud as a flow tracer during a typical drop experiment, and taking advantage of the transient character of the extinction field after ignition in 0-g (see Fig. 2). The flow residence time through the luminous zone of Flame II was approximately 0.3s. A similar procedure for the lower flow rate (1.6mg/s) produced a residence time of about 0.4s in Flame I. These residence times scale approximately with inverse flow rate, in agreement with the analysis of Mortazavi et al. [5]. The above simplified measurements also confirm that in 0-g laminar jet diffusion flames with $Re=O(100)$ residence times are inversely proportional to burner exit velocity for a fixed burner size [5]. The fuel exit velocities listed in Table I agree with the estimate that Flame I features a residence time that is by $\sim 33\%$ longer compared to Flame II. The gradually increasing fuel exit velocities from Flame II to IV (see Table I) cause reductions in residence times by 25% and $\sim 32\%$ in Flames III and IV, with respect to Flame II. It is established that longer residence times have a soot enhancing effect, while lower fuel flow rates have a comparative soot-inhibiting influence. The values of maximum f_v shown in Fig. 4a for Flames I and III or IV are very similar near the upper end of these flames. It appears that the soot-reducing effect of the lower flow rate of Flame I is neutralized by the soot-enhancing influence of the longer residence time in this flame compared to Flames III or IV. Thus, the two competing effects result in ultimate values of $f_v|_{max}$ that are nearly identical in Flames I, III and IV. On the other hand, the combined effect of these two factors in Flame II results in soot volume fractions that are consistently higher than those in all other flames (see Fig. 4a). An exception to this trend is seen at $Z=10$ mm, where the preheated-fuel flames display slightly higher soot concentrations. Finally, the soot volume fractions along the flame axes, as plotted in Fig. 4b, clearly show that soot concentrations in the core of the flame are promoted by fuel preheat. The significant scatter of the data plotted in Fig. 4b is attributed to the increased error in the tomographic inversion procedure towards the flame centerline [9]. However, the overall trends shown in this figure are believed to be accurate. The strong soot-enhancing influence of fuel preheat on the flame centerline cannot be attributed to increased fuel pyrolysis rates, as the current fuel preheat levels correspond to an increase in adiabatic flame temperature of less than 10K. Neither this trend can be attributed to a residence time effect, because Flames III and IV feature shorter residence times compared to Flame II. Consequently, the higher soot volume fractions at the centerline of the preheated flames are probably caused by more efficient particle transport from the soot annulus to the axis of these flames. It is acknowledged that in Flames III and IV the soot particles need to traverse shorter distances to approach the centerline (Fig. 3), but they have less time available to achieve this because of the reduced residence times in these flames. The soot transport characteristics in a gaseous medium depend on local gas velocities and temperatures, temperature gradients along the cross-stream coordinate which, in turn, affect thermophoretic forces towards the cooler inner regions of the flame [10], air entrainment rates, or a combination of all or some of the above. Unfortunately, neither velocity nor temperature measurements are available in the 0-g flames examined herein, thus allowing no definitive statement regarding the origin of the higher soot concentrations on the centerline of the preheated-fuel flames.

Figure 5 depicts schematically the relative positioning of a typical soot aggregate with respect to the flame sheet and the burner centerline in 1-g and 0-g. In both cases, the thermophoretic velocity V_T carries the particles away from the high-temperature flame sheet and towards the symmetry axis. A simple estimate revealed that thermophoretic velocities in 0-g are significantly weaker than those encountered in 1-g (primarily due to lower temperature gradients present in 0-g [11]). The radial gas velocity V_r in the vicinity of the soot particles is also drawn in Fig. 5, and shows that strong air entrainment in 1-g amplifies the already strong effect of thermophoresis in pushing the soot towards the flame centerline. In 0-g, the expanding/decelerating jet flow pushes the particles away from the axis, thus opposing the weaker thermophoretic force, and, in turn, preventing the soot aggregates from reaching the centerline. It is noted that the longer residence times in 0-g would tend to facilitate transport of soot to the flame centerline. However, the soot particles on the annular region in 0-g need to traverse nearly twice as big a radial distance to reach the centerline compared to their 1-g counterparts [6]. In that respect, the larger radial extent of the 0-g flames inhibits

soot transport to the centerline.

Conclusions

An experimental investigation has been presented to quantify the influence of moderate fuel preheat (up to 160°C) on soot formation within 0-g laminar gas jet diffusion flames. The work was performed at the 2.2s drop tower of the NASA Lewis Research Center. The experimental methodology implemented jet diffusion flames of nitrogen-diluted acetylene fuel burning in quiescent air at atmospheric pressure. The study utilized a full-field laser-light extinction technique capable of determining transient soot spatial distributions in laminar axisymmetric flames. The 50% (vol.) C_2H_2/N_2 fuel mixture was injected through a 1.6mm-diameter burner with a Reynolds number $O(100)$. All 0-g flames examined released soot from their blunt tip. Moderate fuel preheat in the 0-g laminar jet diffusion flames was found to reduce soot loadings on the annular region but caused an increase in soot volume fractions on the centerline. In addition, fuel preheat reduced the spatial extent of the soot field in 0-g. Another effect of fuel preheat on soot fields was the shift of the peak soot volume fraction to lower heights (or likewise earlier residence times). This shift suggests that the soot growth stage is shortened in 0-g when elevated fuel temperatures are used in conjunction with a fixed fuel mass flow rate. Finally, a tentative explanation was sought for the sustained annular structure of the 0-g soot fields. Estimates of the soot thermophoretic velocities in the flames revealed that the component of this quantity along the radial coordinate is significantly weaker in 0-g than in 1-g. In addition, the larger radial extent of the 0-g flames delayed soot transport to the centerline. These two factors appear to dominate in shaping the pronounced annular character of the soot field in 0-g.

References

- [1] Law, C. K. and Faeth, G. M., *Prog. Energy Comb. Sci.* 20, 65 (1994).
- [2] Edelman, R. B., and Bahadori, M. Y., *Acta Astronautica* 13:681 (1986).
- [3] Bahadori, M. Y., Edelman, R. B., Stocker, D. P., and Olson, S. L., *AIAA J.* 28:236 (1990).
- [4] Sunderland, P. B., Mortazavi, S., Faeth, G. M., and Urban, D. L., *Combust. Flame* 96:97 (1994).
- [5] Mortazavi, S., Sunderland, P. B., Jurng, J., Köylü, Ü. Ö., and Faeth, G. M., *AIAA Paper* 93-0708 (1993).
- [6] Megaridis, C. M., Konsur, B., and Griffin, D. W., *Twenty-Sixth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, 1996, in press.
- [7] Greenberg, P. S., and Ku, J. C., "Soot Imaging," *Applied Optics*, accepted, (1997).
- [8] Greenberg, P. S., and Ku, J. C., *Combust. Flame* 108: 227 (1997).
- [9] Dasch, C. J., *Applied Optics* 31:1146 (1992).
- [10] Santoro, R. J., Yeh, T. T., Horvath, J. J., and Semerjian, H. G., *Combust. Sci. and Tech.* 53:89 (1987).
- [11] Bahadori, M. Y., Stocker, D. P., Vaughan, D. F., Zhou, L., and Edelman, R. B., in *Modern Developments in Energy, Combustion and Spectroscopy* (F. A. Williams, A. K. Oppenheim, D. B. Olfe, and M. Lapp, Eds.), Pergamon Press, 1993, p. 49.

Table I: Flame Conditions

Case	Fuel Exit Temp. (°C)	Fuel Flowrate (mg/s)	Fuel Flowrate (cm ³ /s)	Exit Velocity (cm/s)	Exit Reynolds
I	23	1.6	1.5	74.6	96
II*	23	2.2	2	99.5	128
III	120	2.2	2.7	132.1	105
IV	160	2.2	2.9	145.5	98

* Base case

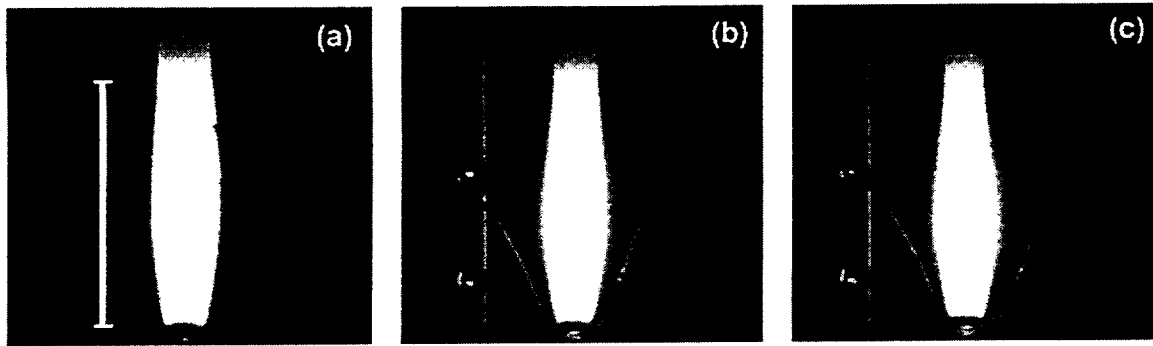


Fig. 1: Luminous flame images in 0-g: a) unpreheated fuel, b) fuel preheated to 120°C, and c) fuel preheated to 160°C. The vertical scale drawn in (a) corresponds to a length of 25mm.

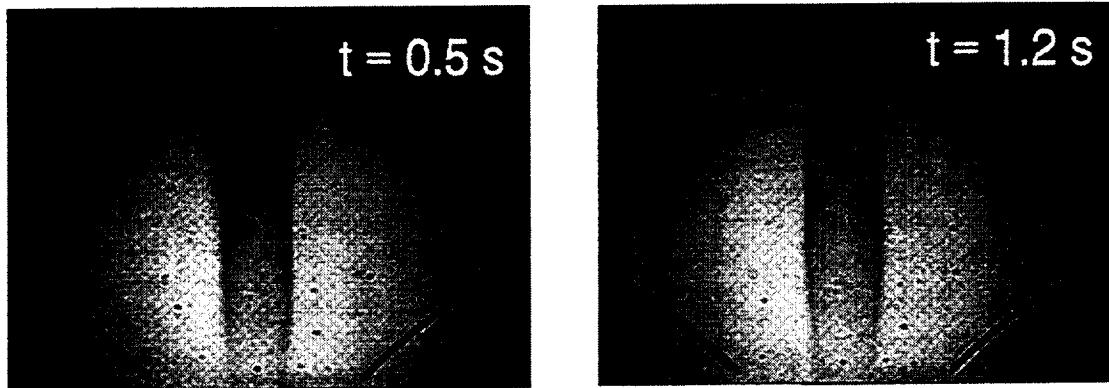


Fig. 2: Instantaneous shadow-like images of the soot field as viewed by the CCD camera of the extinction setup during a drop experiment at 0.5s and 1.2s after the onset of microgravity. Illumination is provided by the expanded laser beam. The burner mouth is located directly below the middle of the bottom edge of each image.

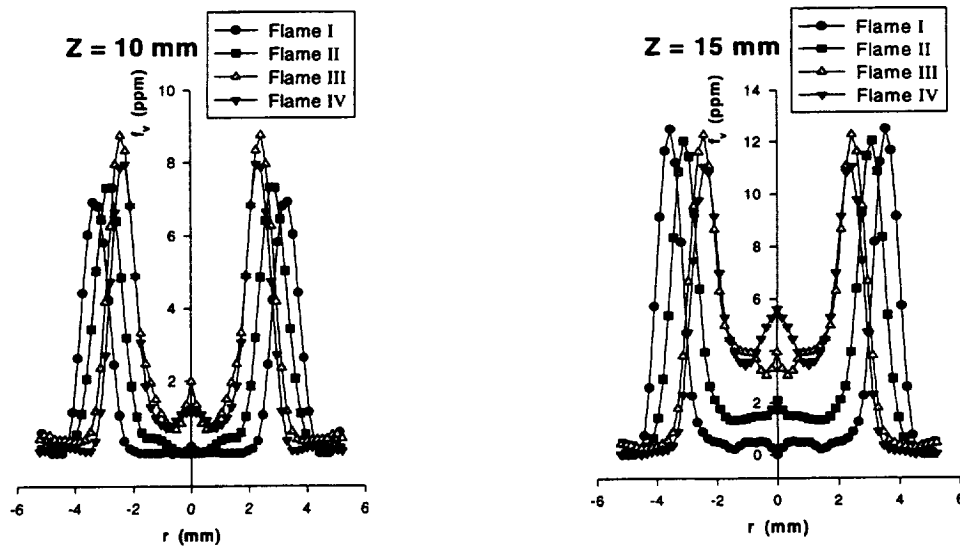


Fig. 3: Radial distributions of soot volume fraction at $Z=10\text{mm}$ and 15mm above the burner tip of the four microgravity flames examined (I to IV; see Table I).

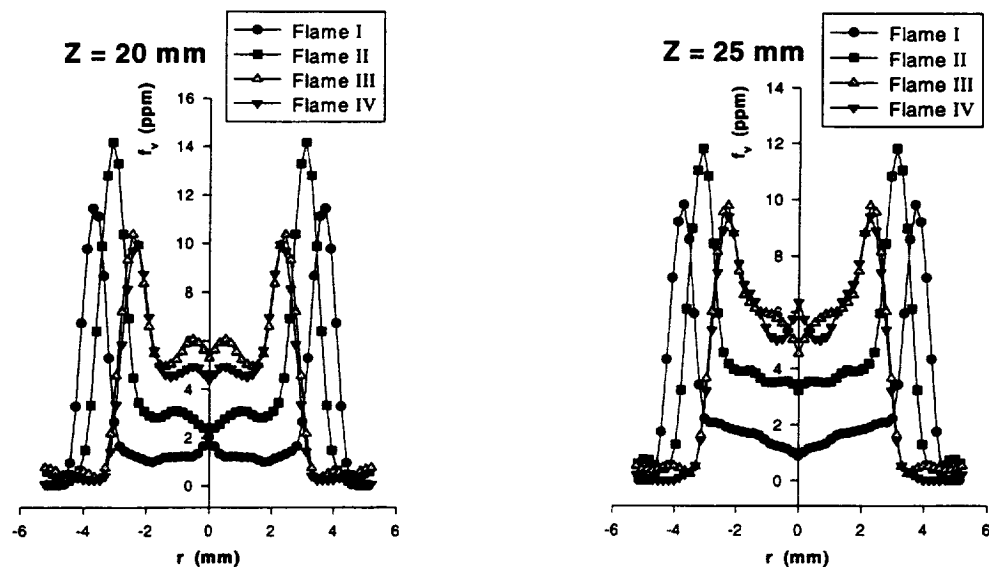


Fig. 3 (continued): Radial distributions of soot volume fraction at $Z=20$ mm and 25mm above the burner tip of the four microgravity flames examined (I to IV; see Table I).

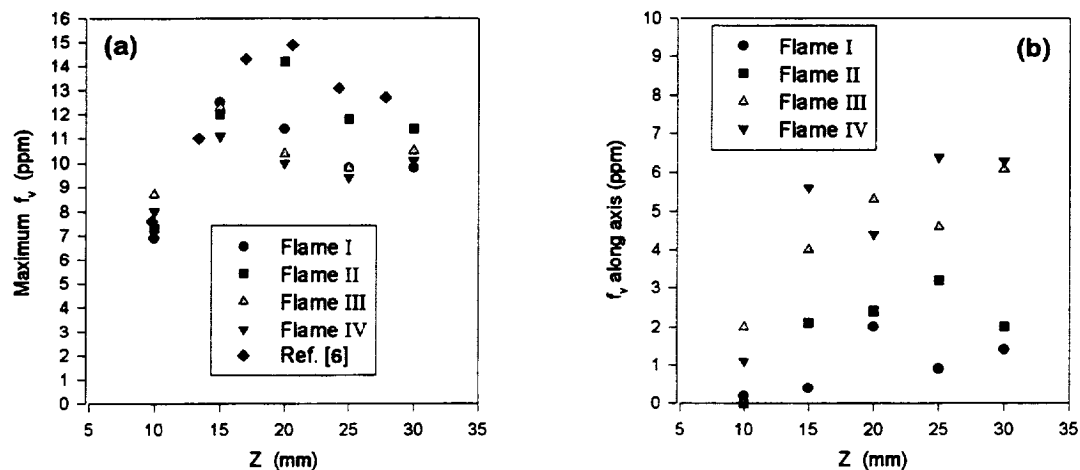


Fig. 4: Comparison of the streamwise variation of (a) maximum and (b) on-axis soot volume fraction at each height Z for all 0-g flames.

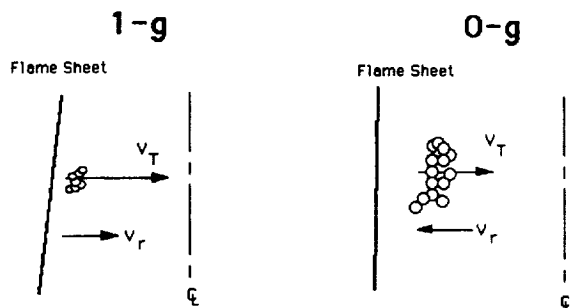


Fig. 5: Schematic illustrating the action of gas convective (v_r) and soot thermophoretic (v_T) radial velocities in typical 1-g and 0-g gas jet diffusion flames.