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# FORMATION OF SOOT IN HIGH-PRESSURE DIFFUSION FLAMES

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## SUMMARY/OVERVIEW:

Diesel engines continue to be the primary powerplant for the Army, both for propulsion and power generation. These engines operate at high pressures to maximize thermodynamic efficiency. Pressure has a direct effect on the peak temperature, the thermal and species gradients, and the species diffusion coefficients, all of which in turn affect the formation of soot in these flames. However, high-pressure flames have received very limited attention, primarily due to the experimental difficulty in operating these flames. Measurements of flame-generated species (using both sampling and non-intrusive optical diagnostics) will be made to help illuminate the chemistry-fluid mechanics interaction and the role of transport at high pressures. The overall goal is to reduce soot emission from these diesel powered vehicles in an effort to minimize their thermal signature.

## TECHNICAL DISCUSSION

### *Specific Second Year Objectives*

The objectives for the second twelve months of this effort were to (1) determine the effect of various diluents (nitrogen, argon, helium, and carbon dioxide) on smoke point in ethylene and methane flames up to 8 atm pressure, (2) to determine the reason for the discrepancy between smoke point heights measured in this flame compared with measurements by others in nominally similar flames, (3) begin to make soot surface temperature measurements using pyrometry, (4) design and build sampling system for extractive measurements of stable species.

### *Experimental Apparatus*

The apparatus used for this experiment, shown in Fig. 1, is a classic over-ventilated Burke-Schumann flame inside a water-cooled pressure vessel that is rated at pressures up to 30



Figure 1. High pressure burner.

atmospheres. Surrounding the 4.5 mm fuel tube is a 65 mm co-flow, and this is all housed in a 380 mm tall quartz chimney. A ceramic honeycomb insert straightens the air co-flow surrounding the fuel tube. The fuel tube is filled with super fine grit steel wool to make the fuel flow rate less sensitive to pressure fluctuations upstream. {The addition of this steel wool flow straightener in the fuel tube turns out to be critical in the behavior of the smoke point with dilution and pressure.} To ignite the flame within the pressure vessel, an electrode is installed and used to produce a spark against the lip of the fuel tube. The vessel has three non-intrusive glass windows to allow for optical viewing and diagnostics. Due to the high sooting tendencies of the fuels used, and the effect pressure has on these tendencies, the vessel has air ports at the windows to purge the area and prevent soot accumulation on the window surface.

To understand the effect of the flow straightener in the fuel tube, a larger burner was used at atmospheric pressure, with a fuel tube diameter of 11.9 mm and an air co-flow diameter of 101.6 mm. For all cases at velocity matched fuel and air flow rates, the flame is highly overventilated. At stoichiometric conditions for ethylene burning in air there is a 1:14.3 fuel-to-air mole ratio. For the current research, conducted at atmospheric conditions, with a fuel-to-air velocity ratio of 0.37 (which is the smallest fuel-to-air velocity ratio tested) the smoke point was reached with a volumetric fuel flow rate of 147 sccm. The air flow rate for a velocity ratio of 0.37 was 28 slpm, which is more than an order of magnitude larger than necessary to over-ventilate the flame. Thus, all flames studied here, regardless of fuel-to-air velocity ratio, were highly over-ventilated. In order to achieve a plug flow exit velocity profile, glass beads, each with a diameter of 3 mm, were placed in the fuel tube to a height of 300 mm. To achieve a parabolic exit velocity profile, the beads were removed from the fuel tube. A combination of screens and ceramic honeycomb was used to ensure a uniform air co-flow exit profile. A quartz chimney, with an inside diameter of 120 millimeters, protected each flame from the perturbations of the ambient air surrounding the burner. Images of each flame were taken at the flame's smoke point with a digital camera.

### *Results and Discussion*

Figure 2a-b shows the effect of dilution level on the smoke point by plotting the reactant (fuel and various diluents) volumetric flow rate as a function of the inverse temperature for ethylene and methane flames in air at 1 and 8 atmospheres, respectively, in log-linear space. The temperature is calculated using a standard chemical equilibrium calculator. As seen in this figure, at 8 atmospheres, the smoke point for methane is higher than that for ethylene and both increase with dilution level. From this figure, it is clear that the actual diluent is not as important as the dilution level. This is contrary to what has been reported previously by McLintock [1] and Schug et al. [2], where they observed a distinct difference between the diluents, with the soot suppression ability scaling with the heat capacity (i.e., CO<sub>2</sub> being most effective and He being least effective). It is believed that this is an effect of the velocity ratio and the shear layer. Lin and Faeth [3] have shown that the velocity ratio has a strong influence on the smoke point. At atmospheric pressure in undiluted ethylene flames, the current research measured the smoke point at various velocity ratios and observed a dramatic difference. For instance, at a velocity

ratio of unity, the fuel flow rate at the smoke point is 140 sccm, but at a fuel to air velocity ratio of 1.2 the fuel flow rate increases to 175 sccm. At a fuel to air velocity ratio of 0.5, the fuel flow rate decreases to 105 sccm. In the work of McLintock and Schug, the air flow rate was held fixed at a certain value throughout the experiments, so in addition to the velocity ratio being non-unity, but it changed for each value of dilution. The slope of the fuel flow rate to diluent flow rate relationship is shown in Table I with the initial velocity ratio listed (it is not known in the work by Schug as they only state that the flame is highly over-ventilated.) In this table, the slope for the velocity-matched case is given as a best-fit second order polynomial, while the other entries are for a fixed air flow rate. It is clear from this table that the velocity ratio plays a major role in determining the diluents ability to suppress soot formation.

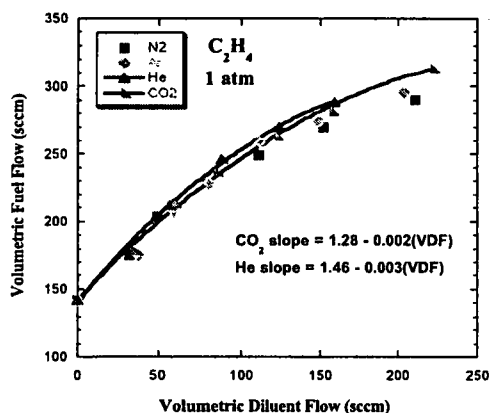


Fig 2a. Ethylene at smoke point at 1 atm vs dilution

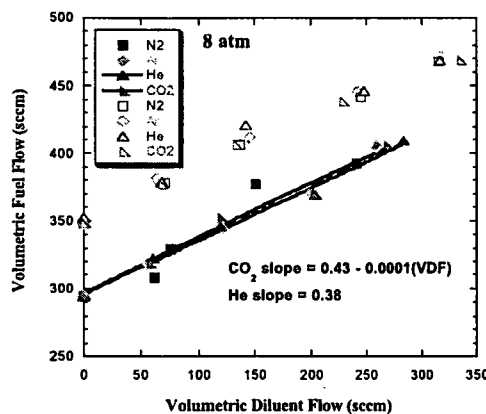


Fig 2b. Ethylene at smoke point at 8 atm vs dilution

Table I

Initial f-a velocity ratio	CO <sub>2</sub> slope	He slope	Reference
1.38	0.75	~0	McLintock
Unknown	1.10	0.2	Schug et al
1	1.28 - 0.002	1.46 - 0.003	This work
0.5	0.45	0.273	This work
1.2	0.33	0.36	This work

The visible flame height is measured from digital photographs and then normalized by the fuel tube diameter of 4.5 mm. The flame height is a strong function of the fuel to air velocity ratio, and for all of these measurements, the ratio is unity. Dilution has a much more pronounced effect on the lengthening of the flame at low pressures and virtually no effect at 8 atmospheres. It is also observed in these figures that the actual diluent is of much less importance than the dilution level, as no clear trends with heat capacity, thermal conductivity, mass diffusivity, or radiative heat loss enhancement is apparent.

Figure 3 shows smoke point volumetric fuel flow rate (non-dim. by the undiluted fuel flow rate) as a function of volumetric diluent flow rate measured in this burner with two different fuel exit velocity profiles. Data extracted from McLintock and Schug is also displayed. As observed in this figure, the effect of carbon dioxide addition on smoke point depends strongly on

whether the fuel exit velocity profile is parabolic or plug. The parabolic exit velocity measurements agree reasonably well with the measurements of McLintock and Schug. However, with a plug flow velocity profile, the effect of carbon dioxide on smoke point is markedly decreased. In contrast, the effect of helium addition on smoke point is noticeably insensitive to fuel exit velocity profile, and neither case is dramatically different from the results found by McLintock or Schug and co-workers. As seen in this figure, with a plug flow exit velocity profile, there is little difference between carbon dioxide and helium.

The volumetric fuel flow and smoke point height as a function of fuel-to-air velocity ratio is shown in Fig. 4 for undiluted ethylene. Interestingly enough, the volumetric fuel flow and smoke point height are both approximately parabolic with velocity ratio, both peaking near a velocity ratio of unity for the plug flow exit velocity profile, whereas the flow rate and flame height both decrease nearly linearly with increasing velocity ratio for the parabolic exit velocity profile.

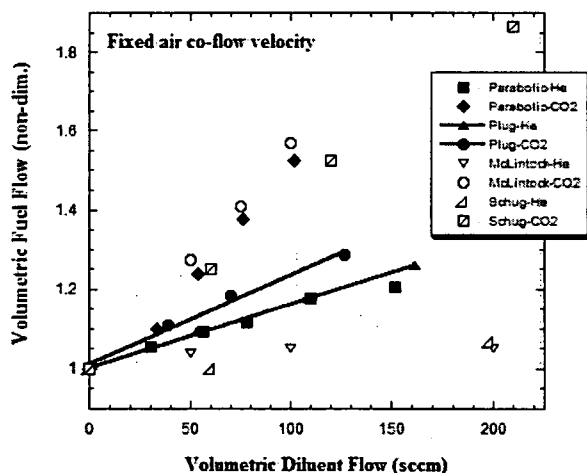


Fig. 3 Fuel flow vs diluent flow at 1 atm

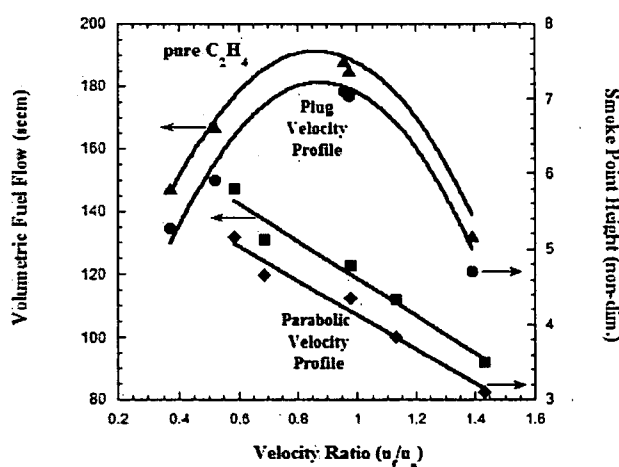


Fig. 4 Fuel flow and smoke pt vs vel. ratio

### Observations:

With a parabolic fuel exit velocity profile, carbon dioxide and helium show extremely pronounced differences in their effectiveness at increasing the smoke point with dilution. Carbon dioxide is shown to be effective while helium is very ineffective. This has been demonstrated experimentally by McLintock and Schug et al. However, when a plug exit velocity profile is used, there is little difference between the two diluents. Thus, the exit velocity profile may be as important, if not more important, than the diluent itself.

### References

1. S. McLintock, *Combust. Flame* 12 (1968) 217-225.
2. K. P. Schug, Y. Manheimer-Timnat, P. Yaccarino, I. Glassman, *Combust. Sci. Tech.* 22 (1980) 235-250.
3. K.-C. Lin, G. M Faeth, *J. Prop. Power* 12 (1) (1996) 10-17.