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Inhibition of Premixed Methane-Air Flames by Water Mist

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Introduction

The ban on production of halons has prompted renewed interest in the use of water as a fire suppression agent. Since water is ubiquitous, non-toxic, environmentally benign, and has a high heat capacity per unit mass, it is in many respects an ideal fire suppression agent. Nevertheless, water is a liquid at ambient temperature rather than a gas like Halon 1301 and current fluorocarbon alternatives. Many engineering issues thus arise concerning droplet size distribution, delivery into the space to be protected, and complexity of the generation system. As a result, most fire suppression systems based on water use far more agent than should be required based on a comparison of its sensible enthalpy with that of nitrogen or carbon dioxide. In attempting to broaden the range of fire protection applications for which water can be used, it is desirable to determine to what degree the effect predicted based on water's thermal properties can actually be achieved under favorable conditions.

Furthermore, water may be useful as a delivery method for non-volatile chemical fire suppressants. A number of elements and compounds have been demonstrated to exhibit far better chemical fire suppression than bromine [1]. Most of these contain metallic elements, and have very low volatility. Water is a good solvent for many metallic compounds; thus it may be useful as a dispersing agent for many new suppressants. Since water's effect on flames is almost entirely thermal, it is unlikely to interfere with the chemical activity of a solute.

We have determined the effect of sub-micron water droplets on the flame speed of methane-air mixtures, as a first step toward investigation of enhancement by solutes. The laminar flame speed is an indicator of the effectiveness of inhibition. Inhibition and extinction are related but distinct concepts; extinction by water mists in non-premixed flames is addressed elsewhere in these proceedings [2]. Measurements were also performed using nitrogen and tetrafluoromethane (CF_4) as benchmark agents. These measurements were in good agreement with those from a previous study [3] and the nitrogen data was in good agreement with a numerical simulation.

Experimental Procedure

A Hencken burner apparatus was used to establish a premixed methane-air flame at atmospheric pressure. The nozzle diameter was 5.4 mm. Water mist was introduced into the flame by a stream of air flowing through a constant output atomizer (TSI Model 3076). Laboratory supply air was filtered and dried (Whatman 64-01) upstream of the atomizer, producing air with relative humidity less than 5%. Gas flow rates were set in the range 550 – 1750 ml/min using mass flow control devices (Sierra Model 860C). It was determined that the uninhibited flame speed was insensitive to the total flow rate over this range. Ultra High Purity methane (99.99% - Scott Specialty Gases) was used as the fuel gas.

Flame speeds were measured using the total area method as described by Andrews and Bradley [4]. The luminous flame surface was imaged with a digital camera in a 640 x 480 pixel array using a neutral density filter. Images were captured and averaged over a period of four seconds (10 samples) using custom designed applications in LabView 4.0 (National Instruments). A sixth-order polynomial was fit to each image and integrated to give the flame surface area.

The delivery of water mist into the flame was somewhat problematic. The constant output atomizer delivered a continuous stream of sub-micron sized droplets (0.35 μm @ 30 p.s.i.), however the high delivery pressures produced flow rates that were too high to stabilize a flame on the burner. Consequently, a portion of the air flow was bled to a dump stream with a calibrated rotameter to measure the flow rate. One difficulty in controlling the water concentration is that, if metering valves are used, the water tends to collect in large droplets that do not get carried to the flame. Alternatively, controlling flow rates by varying the flow resistance introduces more surface area for droplets to collect on walls. Tube lengths between the droplet generator and the burner were minimized to eliminate droplet agglomeration on the walls. As a result, however, the range of concentrations for water was smaller than that for the gaseous agents.

Results

In order to establish the validity of the flame area measurement procedure, measurements were performed on flames inhibited by N_2 and CF_4; these results were compared with those from an earlier study [3]. Figure 1 shows these results, normalized by the uninhibited flame speed. Our measurements indicate slightly lower flame speeds for each agent than the measurements of Linteris and Truett. Modeled data are NRL calculations using PREMIX and GRI-Mech. Both sets of measurements indicate lower flame speeds for N_2 inhibited flames than are predicted by the model, however the agreement in general is fair. The precision of the measurements is high; the 95% confidence interval of the normalized N_2 inhibited flame speed is $\pm 2\%$.

The normalized flame speed is plotted in Figure 2 on a mass basis for the cases with water mist, N_2 and CF_4 as agents. The scatter in the water mist data reflects the difficulties inherent in the delivery and measurement of water mist to the flame. In spite of this, there is a clear trend towards a reduction in the flame speed with increasing agent concentration. Using least-squares fits to this data, it was determined that water mist is roughly three times more effective than both N_2 and CF_4 at reducing the flame speed on a mass basis. Table 1 (Column 3) lists the mass fraction of agent required to reduce the flame speed by 20% for each agent, based on our measurements. Previous studies [5,6] have shown that, in non-premixed flames, Halon 1301 (CF_3Br) is 2 - 2.5 times more effective at extinguishing flames than N_2 on a mass basis. If a similar relationship holds between CF_3Br and N_2 in premixed flames, the implication of this result, combined with the data in Figure 2, is that water mist can be at least as effective an inhibitor as CF_3Br on a mass basis.

Table 1 lists the calculated change in enthalpy required to raise the temperature of each agent from 300 K – 1600 K. The value for water mist includes the heat of vaporization at one atmosphere. Columns 3 and 4 list, respectively, the agent mass and mole fractions required to reduce the flame speed by 20% from the uninhibited case. Column 5 lists the product of column 2 and the ratio of agent mole fraction to oxygen mole fraction for the condition required to reduce the flame speed by 20%. Sheinson et al. [7] determined that the following quantity:

$$\Delta H = \sum_i \left(\frac{X_i}{X_{O_2}} \right) \int_{300}^{1600} c_{pi}^T \, dT \qquad (1)$$

is approximately constant for most gaseous thermal agents where the mole fractions (X) are specified as those at the condition required to extinguish a heptane pool fire. For smaller molecules such as N_2 the value is lower and the contribution of dilution and higher thermal conductivity of these molecules becomes more significant. In this expression the summation is over the agent and nitrogen present in the air. This is the expression that was used to calculate the values in column 5 of Table 1, with the exception that the calculation was performed only for the added agent. Additionally, the mole fraction used was not that for extinction but rather for the case where the uninhibited flame speed was reduced by 20%. Observation of the values in column 5 shows that the value for water is only slightly higher than those for N_2 and CF_4. This indicates that water mist can be delivered in such a way that its heat capacity is used nearly as effectively as if it were a gaseous agent.

Conclusions

Preliminary measurements performed in this study indicate that, when deployed effectively, water mist can be as effective as CF_3Br at inhibiting flames on a mass basis. This is consistent with the prediction based on Ref. [7] that water is more efficient than Halon 1301 on diffusion flames. Water mist was shown to be approximately three times more effective by mass than other inert agents at reducing the flame speed of premixed methane-air flames (Fig. 2). Additionally, the results in Table 1 show that the thermal capacity of water mist is used effectively in comparison with gaseous thermal agents. Further measurements in this study will investigate the effectiveness of metal powders in liquid solution on reducing the flame speed. It is expected that this will enhance the effectiveness of the water mist as an inhibiting agent by adding chemical inhibition pathways to complement the physical mechanisms demonstrated here.

Table 1

Agent properties. Column 2 lists the change in enthalpy of each agent for a change in temperature from 300K – 1600K. Columns 3 and 4 list the mass and mole fractions, respectively, for the conditions required to reduce the flame speed by 20% from the uninhibited case. Column 5 is the product of column 2 with the ratio of agent mole fraction (X) to O_2 mole fraction for the condition where the flame speed is reduced by 20% from the uninhibited case.

Agent	$H_f^{1600K} - H_f^{300K}$ (kJ/mol)[a]	Mass Fraction	Mole Fraction	$(H_f^{1600K} - H_f^{300K})* (X_{agent}/X_{O2})$ (kJ/mol)
N_2	42	5.4	5.4	12.6
CF_4	122	5.2	1.7	10.9
H_2O (l)	93	1.8	2.8	14.2

[a] Calculated from data in [8]

Acknowledgements

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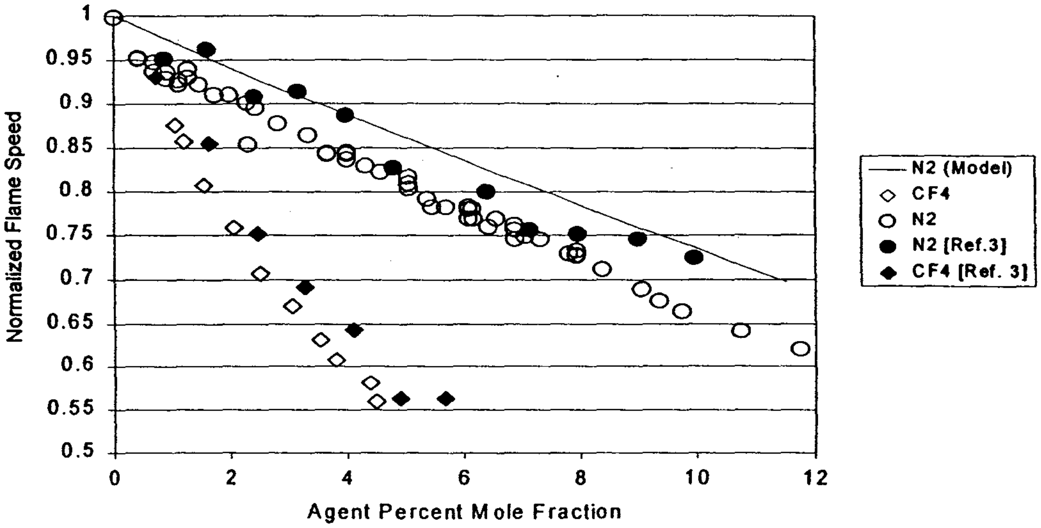

Figure 1: Premixed methane-air flame speed as a function of agent mole fraction, normalized by uninhibited flame speed. Open points are measurements from present study, filled points are from Ref. [3] and line represents model data for N_2.

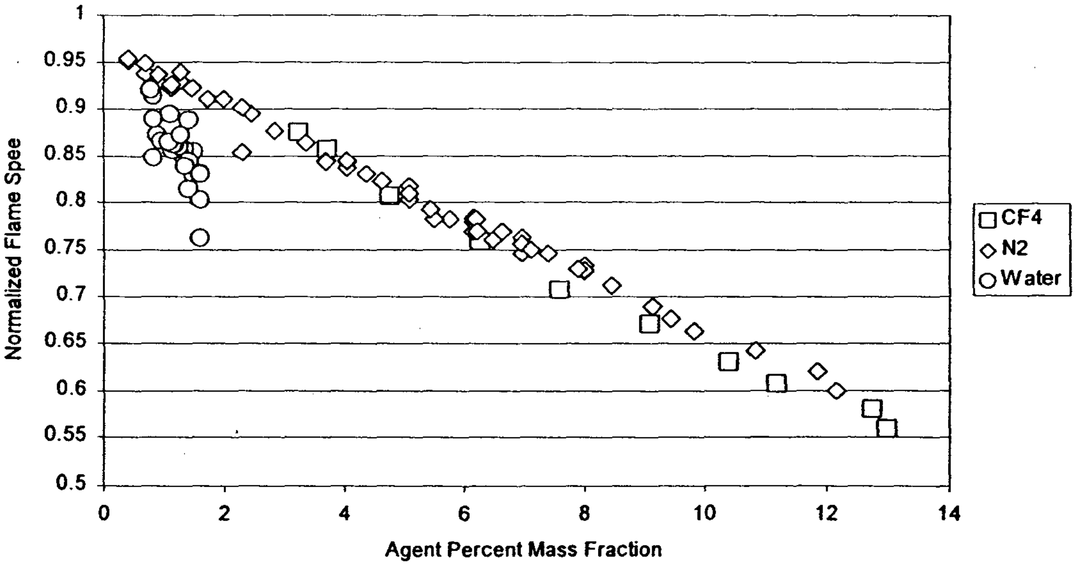

Figure 2: Premixed methane-air flame speed as a function of agent mass fraction, normalized by uninhibited flame speed. All points represent measurements from present study.