COMPARISON OF THE FIRE SUPPRESSION EFFECTIVENESS OF SODIUM BICARBONATE PARTICLES AND FINE-WATER DROPLETS IN NON-PREMIXED AND PREMIXED FLAMES

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INTRODUCTION

Previous work by Hamins et al. [1, 2] using a cup-burner has shown that, on a mass basis, fine NaHCO, particles are more effective than the gaseous fire suppressing agents being considered as replacement for Halon 1301. Other investigations based on an alternate non-premixed counterflow flame configuration have also supported the superior effectiveness of sodium bicarbonate particles in suppressing gaseous flames [3–6]. While the cup-burner configuration includes many features of real flames, for example, the effects of flame holding, multidimensional transport, etc., detailed analyses of the cup-burner flow field to extract fundamental information on flame suppression mechanism are nearly impossible. In contrast, the counterflow field with well-established modeling approaches, can provide valuable information about the thermal and chemical mechanisms of fire suppression by these compounds. For example, the two-phase reacting flow model developed at the University of Virginia can include detailed chemistry, transport of energy and species, and particle trajectories different from the gas phase [7, 8]. The coupled solution of the gas-phase and the condensed-phase was able to predict the experimentally measured trends about mass loading of sodium bicarbonate needed for flame suppression [4].

Figures 1 and 2 show the mass loading of sodium bicarbonate particles in the air-stream as a function of the flow strain rate, with particle size as a parameter. At high flow strain rates, i.e., for low flow residence time, the mass fraction of the sodium bicarbonate needed to extinguish the flame is less compared to a flame at low strain rates. More importantly, there seems to be a critical particle size (about 20 μm) above which these particles are not as effective as the smallest particles considered. In experiments, this non-linear effectiveness of particle size is more pronounced, as seen from Figure 1.

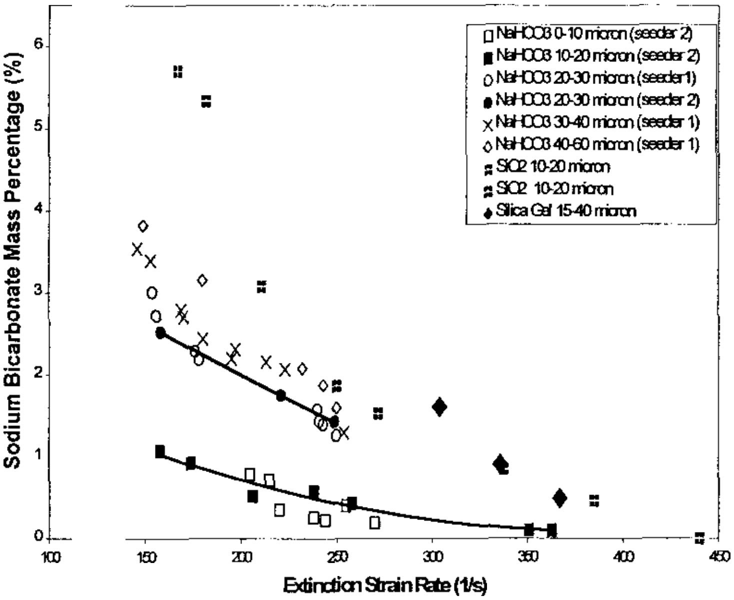

Figure 1. Experimentally measured NaHCO, and inert particle mass fraction (as a percentage) vs. flow strain, with particle size as a parameter.

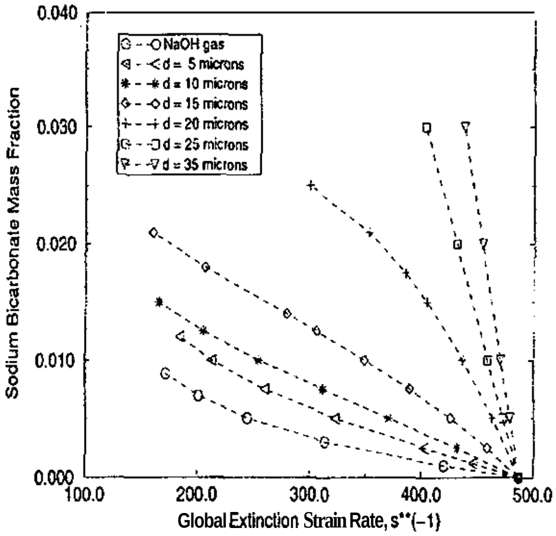

Figure 2. Plot of predicted NaHCO, particle mass fraction vs. flow strain rate, with particle size as a parameter.

In an attempt to better understand the size effects of condensed-phase fire suppressants, a premixed flame configuration was also considered. Both sodium bicarbonate and fine-water droplets were tested in this flame configuration. The experimental results on inhibition of premixed burning velocity indicate a somewhat lower effectiveness than on the counterpart non-premixed flames, and the underlying reason for this lower effectiveness is the focus of this paper.

EXPERIMENTS

The premixed burning velocity measurements are based on the cone angle of a Mache-Hebra nozzle burner [9] with an exit diameter of 15 mm and producing a near conical Bunsen-type flame. The nozzle exit flow profile was characterized by laser Doppler velocimetry, indicating a very flat flow profile at the core and somewhat narrow boundary layer (about 1 mm) on either side of the jet. Because of intense Na emission by this flame, the detection of the flame cone angle was accomplished by a Schielren imaging approach, which consisted of a collimated Ar-laser beam, focusing lens, knife-edge, and digital imaging camera. The fuel used in these experiments was methane (BOC, 99.9% pure). Digital mass flow controlers were used to control the fuel and air flow, typically held at stoichiometric mixture condition. The total flow of the premixed gases was varied to investigate the flame height effects on the measured burning velocity. The typical half-cone angle of the flame was about 20 deg.

SODIUM BICARBONATE

Sodium bicarbonate particles separated into 10 μm size ranges, i.e., 0-10, 10-20, 20-30, 30-40 μm, were used in these experiments. The particle seeding was accomplished using the same setup used previously for counterflow non-premixed flames [4]. The particle feed rate was continuously monitored with a Mie-scattering technique, which included a 670 nm diode laser, photo-diode detector, and a strip-chart recorder. After each flame experiment, the particle feed rate was calibrated using a gravimetric analysis. Typical particle feed rate was of the order of 0.1gm/min, while the fluctuation of particle scattering signal was less than +/-10%.

In addition to sodium bicarbonate particles, inert silica particles were also used for comparison. Two types of silica particles were considered: (a) crystalline silica, milled and separated into 10 μm ranges (similar to sodium bicarbonate sizing technique), and (b) porous silica particles in the range of 15-40 μm.

FINE-WATER DROPLETS

Because of the modular nature of the premixed burner designed, a droplet atomizer used previously for counterflow burner [10] was implemented here to investigate the inhibition of premixed flames with fine-water droplets. The Sono-Tek atomizer typically generates a log-normal size distribution of droplets with median droplet size of 31 μm (the median size can be varied by exchanging the atomizer horn). However, the phase-Doppler particle analyzer measurements have indicated a much narrower size distribution at the nozzle exit because of settling of the larger droplets [10]. Besides pure water experiments, inclusion of chemical agents (e.g., NaOH) in the water to enhance the thermal suppression of premixed flames was **also** investigated. Comparisons of these new premixed flame suppression results, with previously reported counterflow non-premixed flame investigations, are presented below.

RESULTS AND DISCUSSION

Figure **3** shows the variation of normalized laminar burning velocity of a stoichiometric methane-air flame (S_L / S_L^o), with superscript 'o' identifying the uninhibited case) with addition of 10-20 μm sodium bicarbonate particles. **Also** shown is the almost negligible effect of addition of inert particles to the premixture. Figure 4 shows a similar plot on variation of burning velocity with addition of fine-water (with a mean size of about 20 μm) and water-NaOH solution droplets.

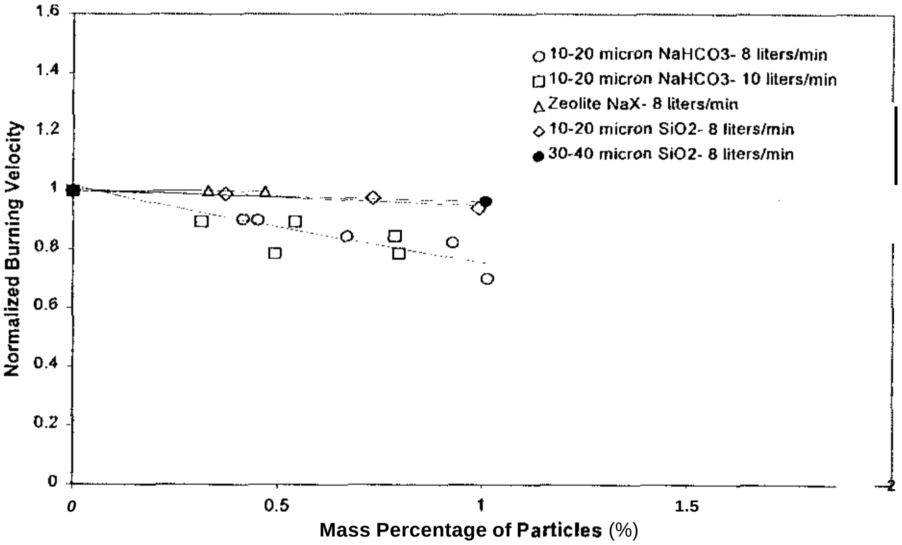

Figure **3.** Normalized burning velocity of a methane-air flame inhibited with NaHCO, and inert particles.

COMPARISONS WITH NON-PREMIXED FLAME EXTINCTION CONDITIONS

Because of the structural differences between the premixed flames and non-premixed flames, a direct comparison of the inhibition effectiveness **of** two flames requires such flame structural effects to be taken into consideration.

In non-premixed flames, stoichiometric mixture fraction, Z_{st}, determines the location of the flame within the mixing layer of fuel and air. The mixing layer can be characterized **as** a region across which the fuel and air mix, with $Z=0$ specifying the edge of this mixing layer on the oxdizer side and $Z=1$ specifying the edge of the mixing layer on the fuel side. Thus, the stoichiometric mixture fraction can be thought of **as** the location at which the fuel and air mix in stoichiometric proportions or location where the equivalence ratio, ϕ, is unity. For a pure methane and air non-premixed flame, the stoichiometric mixture fraction is

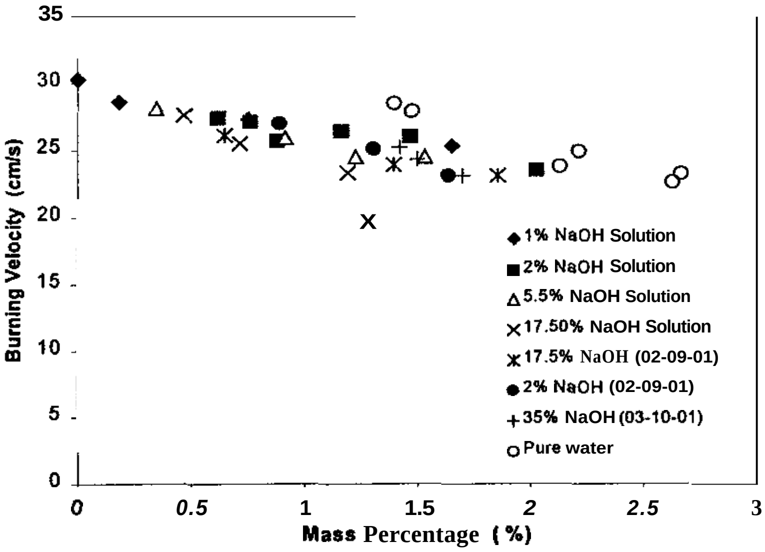

Figure 4. Burning velocity of a methane-air flame inhibited with water and water-NaOH mist.

Z_{st}=0.0554. For such small values of Zst, it can be shown [11,12] that a direct correlation exist between its laminar burning velocity, S_L^o, and the extinction strain rate of a non-premixed flame, a_{ext} given by

$$\left(\rho_o S_L^o\right)^2 \propto \left(\frac{\rho\lambda}{c_p Z^2}\right)_{st} a_{ext}$$

Assuming that the transport and thermodynamic properties are nearly constant near the flame front, the following correlation between the ratio of inhibited to uninhibited burning velocity and extinction strain rate can be obtained

$$\left(\frac{S_L}{S_L^o}\right)^2 = \left(\frac{a_{ext}}{a_{ext}^o}\right)$$

Using the above correlation for 10-20 micron sodium particles, a comparison of the flame strength defined here as the square of normalized premixed burning velocity, $(S_L/S_L^o)^2$ or the normalized extinction strain rate, a_{ext}/a_{ext}^o, is shown (Figure 5). Figure 6 presents a similar comparison between the premixed and non-premixed flame results with fine-water droplets. While the analytical correlation that includes flame structure effects shows a better agreement between the two types of flames, the absolute differences for 10-20 µm sodium bicarbonate particles and fine-water droplets with a mean diameter of about 20 microns are rather significant (Figures 5 and 6). It is interesting to note that in non-premixed flames, large sodium bicarbonate particles (e.g., 30-40 µm) and inert particles considered show a similar effectiveness (Figure 1), but they also show a significant decrease in the flame extinction strain rate with increasing particle loading. In contrast, premixed flame results (Figure 3) do not indicate a marked decrease in burning velocity for similar loading of large sodium bicarbonate or inert particles.

Early studies with various dry powders [13-15] had utilized the surface area of the particles to explain thermal vs. chemical effectiveness of finely divided particles. However, considerable uncertainties exist in such arguments because the associated flow fields were not well described, except for the work by Rosser et al. [16] where careful analysis of the flow residence time effects was carried out. We believe that with current experimental data and available modeling capabilities available, a unified model can be developed to describe the exact mechanism of fire suppression by condensed-phase agents.

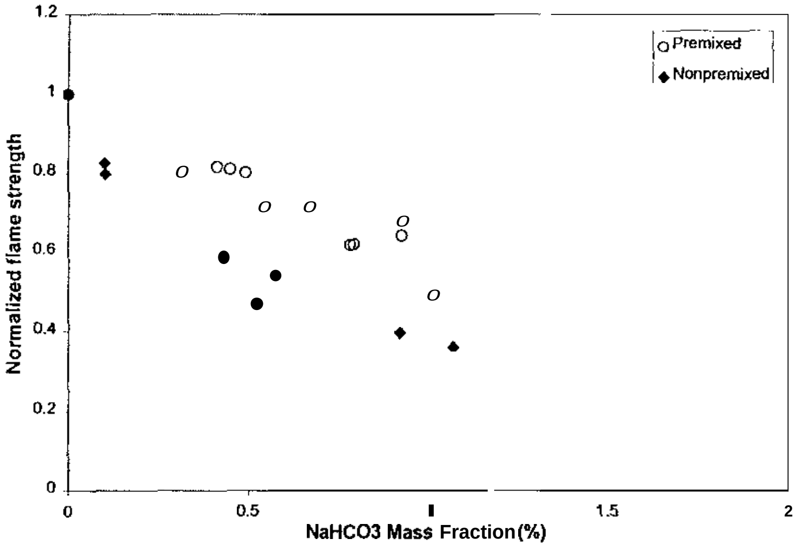

Figure 5. **A** comparison of effectiveness of NaHCO, particles on premixed and non-premixed flames, using the normalized flame strength vs. mass fraction as a %.

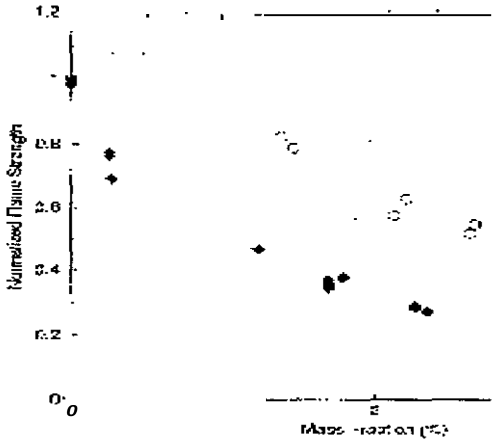

Figure comparison of effe ness of fine-water mist on premixe and non-prem e flames

CONCLUSIONS

Two laboratory-scale experimental configurations were used to investigate the fire suppression effectiveness of condensed phase agents, e.g., fine-water droplets (with and without chemical additives) and sodium bicarbonate dry powder. The two flame configurations considered were premixed and non-premixed flame, which encompass most real world fires (except for the turbulence effects). With appropriate scaling relationships that take into account the structural features of the two types of flames, the flame inhibition results with condensed-phase agents indicate a similar trend. The observed differences between the two types of flames can be attributed to flow field involved in the two flames. The major implication of these observed differences is that extension of laboratory-scale flame inhibition results with condensed-phase agents to real world applications must be pursued carefully.

ACKNOWLEDGMENTS

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REFERENCES

1 Hamins, A., Gmurczyk, G., Grosshandler, W., Presser, C., and Seshadri, K., "Flame Suppression Effectiveness," in ***Evaluation of Alternate In-Flight Fire Suppressantsfor Full-Scale Testing in Aircraft Engine Nacelles and Dry Bays,*** W.L. Grosshandler, R.G. Gann, and W.M. Pitts, eds.), NIST SP-861, 1994.

2. Hamins, A., "Flame Extinction by Sodium Bicarbonate Powder in a Cup Burner," ***Twenty-seventh Symposium (Int.)*** on ***Combustion,*** The Combustion Institute, Pittsburgh, PA, pp. 2857-2864, 1998.

3. Chelliah, H.K., Krauss, R.H., Zhou, H., and Lentati, A.M., "Characterization of Physical, Thermal, and Chemical Contributions of Sodium Bicarbonate Particles in Extinguishing Counterflow Non-Premixed Flames," ***Proceedings,*** 5th ASME/JSME Joint Thermal Engineering Conference, San Diego, CA, 1999.

4. Wanigarathne, P.C., Krauss, R.H., Chelliah, H.K., and Davis, R.J., "Fire Suppression by Particulates Containing Metallic Compounds," ***Proceedings,*** Halon Options Technical Working Conference, Albuquerque, NM, pp. 393-402,2000.

5. Fleming, J.W., Reed, E.J.P, Zegers, E.J.P, Williams, B.A., and Sheinson, R.S., "Extinction Studies of Propane/Air Counterflow Flames: The Effectiveness of Aerosols," ***Proceedings,*** Halon Options Technical Working Conference, Albuquerque, NM, pp. 333-342, 1998.

6. Williams, B.A., and Fleming, J.W., "Suppression Mechanisms of Alkali Metal Compounds," ***Proceedings,*** Halon Options Technical Working Conference, Albuquerque, NM, pp. 157-169, 1999.

7. Lentati, A.M., and Chelliah, H.K., "Dynamics of Water Droplets in a Counterflow Field and Their Effect on Flame Extinction," ***Combust. and Flame*** 115:158-179, 1998.

8. Lentati, A.M., and Chelliah, H.K., ***Twenty-Seventh (Int.) Symposium*** on ***Combustion,*** The Combustion Institute, Pittsburgh, PA, pp. 2839-2846, 1998.

9. Linteris, G.T., and Truett, L., "Inhibition of Premixed Methane-Air Flames by Fluro-Methanes," ***Combust. and Flame***, 105, p. 15, 1996.

10. Lazzarini, A.K., Krauss, R.H., Chelliah, H.K., and Linteris, G.T., "Extinction Conditions of Non-Premixed Flames with Fine Droplets **of** Water and Water-NaOH solutions," ***Proceedings of the Combustion Institute,*** The Combustion Institute, Pittsburgh, PA, Vol. 28, pp. 2939-2945,2000.

11. Seshadri, K., and Peters, N., "Asymptotic Structure and Extinction of Methane-Air Diffusion Flames," ***Combust. and Flame***, 73, pp. 23-44, 1988.

12. Chelliah, H.K., Yu, G., Hahn, T.O., and Law, C.K., "An Experimental and Numerical Study on the Global and Detailed Kinetics of Premixed and Nonpremixed Flames of Chloromethane, Methane, Oxygen, and Nitrogen," ***Twenty-Fourth Symposium (International)*** on ***Combustion,*** The Combustion Institute, p. 1083, 1992.

13. Dolan, J.E., and Dempster, P.B., "The Suppression of Methane-Air Ignition by Fine Powders," ***J. Appl. Chem.,*** 5, p. **510,** 1955.

14. DeWitte, M., Verbosch, J., and van Tiggelen, A., "Inhibition and Extinction of Premixed Flames by Dust Particles," ***Combust. and Flame,*** 8, pp. 257-266, 1964.

15. Birchall, J.D., "On the Mechanism of Flame Inhibition by Alkali Metal Salts," ***Combust. and*** Flame, **14:85,** 1970.

16. Rosser, W.A., Jr., Inami, S.H., and Wise, H., "The Effect of Metal Salts on Premixed Hydrocarbon-Air Flames," ***Combust. and Flame,*** 7(2), pp. 107-120, 1963.