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FLAME EXTINCTION BY SODIUM BICARBONATE POWDER IN A CUP BURNER

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An apparatus was developed for testing the extinction efficiency of a solid powder in a coflowing non-premixed flame. Extinction measurements were performed by adding agent quasistatically to the oxidizer stream until flame extinction was observed. The concentration of powder agent was monitored by laser transmission. Extinction measurements were performed on flames burning both liquids and gases using sodium bicarbonate ($NaHCO_3$) powder as the extinguishing agent. For comparison, extinction measurements were also conducted using the gaseous agents, CF_3Br (halon 1301) and N_2. Tests were conducted using a number of fuels including heptane, two jet fuels (JP-8 and JP-5), two hydraulic fluids (83282 and 5606), as well as propane.

The agent extinction requirements for the two small particle sizes tested here were highly similar. The results showed that on average, $NaHCO_3$ was three times more effective than CF_3Br and five times more effective than N_2 on a mass basis in extinguishing flames burning the various fuels. An estimate of agent behavior based on the effectiveness of inert N_2 showed that whereas CF_3Br acted primarily through chemical kinetic effects, only half of the effectiveness of $NaHCO_3$ could be attributed to kinetics.

Introduction

The manufacture of CF_3Br (halon 1301), a commonly used fire suppressant, has been halted due to its high ozone depletion potential. The search for suitable replacement compounds has prompted examination of the effectiveness of a number of gases, liquids, and solid compounds. In a literature survey on fire-extinguishing compounds, Babushok and Tsang [1] found that alkali compounds containing Na and K are the most effective agents after the metallic compounds containing Fe, Pb, and Cr. Whereas the metallic compounds are associated with toxicity and environmental concerns, dry powders have few of these detrimental effects and may be appropriate halon replacements for a number of fire-protection applications.

The objective of the current study was to measure the suppression effectiveness of sodium bicarbonate ($NaHCO_3$) powder in extinguishing hydrocarbon diffusion flames. The cup burner, a coflowing burner configuration, was used in these studies. The cup burner, which is a standard burner used by industry for ranking the suppression effectiveness of gaseous agents, has never been used to test powder suppressants, although it has been used for many types of liquid and gaseous agents [2–6]. Most of the gaseous agents tested in the cup burner have been inert or have contained halogen atoms on a carbon backbone. In the study reported here, a cup burner apparatus was modified to test the suppression effectiveness of a solid powder.

Several studies have concluded that particle size is an important parameter in flame extinction using dry powders. Milne et al. [7] showed this for the extinction of CH_4-air counterflowing diffusion flames using $KHCO_3$. In moderate-sized heptane pan fires, Ewing et al. [8] observed enhanced extinction effectiveness with decreasing powder diameter, until a critical $NaHCO_3$ particle diameter ($\approx 16\ \mu m$) was utilized, when effectiveness (a mass fraction of 0.04) was not enhanced for smaller particles. In their experiment, the test fixture was enclosed and agent was sprayed onto a pan fire from above. Figure 2 of their paper [8], however, suggests that the powder delivery mechanism may have reduced the required agent amount through flame straining. Fischer and Leonard [9] observed enhanced effectiveness with decreasing powder size for extinction of rich premixed methane-air flames ($\phi = 1.5$). Approximately a 0.04 mass fraction of $NaHCO_3$ (4-μm particles) was required for extinction. Both Rosser et al. [10] and Mitani and Niioka [11] studied the inhibition effectiveness of $NaHCO_3$ in premixed situations and considered powder effectiveness in terms of particle size and agent residence time.

A number of experiments have also been conducted in well-controlled counterflow diffusion flames using powder agents. Measurements were reported by Dodding et al. [12] for extinction of methane-air counterflowing diffusion flames with (10–20

μm) sodium bicarbonate particles added to the oxidizer. The strain rate at extinction, however, was not reported. More recently, Seshadri and coworkers [13,14] and Reed et al. [15] have also measured the effectiveness of $NaHCO_3$ in counterflow flames. Because of the relatively short residence times of the particles in the thin counterflow flames, particle size effects must be carefully considered in interpreting experimental results [14]. Whereas a direct correspondence has been found between the concentration requirements for gaseous agents in the coflowing cup burner and the counterflow burner, such a relationship may not hold for condensed phase agents where the minimum residence time for an agent to be fully vaporized may not be available for even moderate-sized particles in the counterflow geometry.

In suppression experiments using the cup burner and counterflow flames, agent is quasistatically added to the oxidizer stream. The non-premixed reactant streams in the cup burner flow parallel to each other, and the flame is stabilized in the shear layer formed between the two coflowing streams. The resulting flame structure is two-dimensional. Studies in coflowing flames are useful because the flow-field structure has features that are similar to fires, and the agent requirements for suppression of cup burner flames scale to requirements in actual fires.

In the counterflow configuration, increasing the flow of reactants strains the flame, and less agent is required to achieve extinction. From a fire safety point of view, however, the most hazardous situation is a low-strain-rate flame such as the cup burner flame utilized here, where flames are more stable and larger agent concentrations are required to achieve extinction. Although $NaHCO_3$ is a commonly used fire suppressant, commercially known as regular dry chemical or BC powder, few experiments have investigated its effectiveness in well-controlled long-residence time bench-top experiments where its effectiveness can be compared to gaseous and liquid agents.

The work reported here is an experimental investigation of the suppression effectiveness of $NaHCO_3$ powder. Its effectiveness is measured and compared to halon 1301 and N_2. From these results, the magnitude of the chemical and physical effectiveness of the agents is calculated. Measurements were performed using two particle size distributions of the $NaHCO_3$ powder for flames burning both liquid and gaseous fuels.

Experimental Method

Gaseous Agents

The concentration of halon 1301 and N_2 in the oxidizer stream required to achieve flame extinction was measured in the cup burner, which has been described in detail previously [13]. The oxidizer, a mixture composed of dry air and agent, flowed through a 100-mm chimney around a 28-mm fuel cup. Compressed breathing air was dried by passing it through a two-stage filtering system composed of a silica-gel water-vapor trap followed by a particle trap. An air velocity of $\approx$5 cm/s was used for the gaseous agents. The volumetric flows of air and agent were controlled by rotometers that were calibrated using bubble flow and dry test meters.

A detailed experimental protocol was developed based on Ref. [13]. Measurements were performed by establishing the flame and then incrementally increasing the concentration of agent in the oxidizer stream until the flame was extinguished. Extinction tests were conducted on propane and five liquid fuels including heptane, two jet fuels (JP-5 and JP-8), and two hydraulic fluids (5606 and 83282). Fuel properties have been reported previously [13]. The jet fuels were composed primarily of kerosene. The hydraulic fluids were partially oxygenated hydrocarbons. Tests showed that the jet fuels and hydraulic fluids did not readily ignite without the use of a microtorch. Once ignition occurred, the torch was immediately removed to prevent excess preheating of the Pyrex cup. A 100-s burn period prior to agent addition minimized variation in the extinction measurements associated with apparatus heat-up. A series of preliminary measurements tested the effect of oxidizer (flow rate) on the agent extinction concentration for the gaseous agents, and it was found that once a minimum air-flow rate was achieved, increased velocity had a negligible effect [13]. The effect of the propane fuel flow was also tested and found to have minimal effect for a range of flows similar to the flow used here [13].

Powder Characterization

$NaHCO_3$ powder was milled and then sized using a centrifuge into several particle diameter fractions, nominally 2 to 6 μm, 3 to 8 μm, and 10 to 15 μm. A small amount of silica (SiO_2) ($\approx$10-nm diameter) was added to the powder to improve flow behavior and to avoid agglomeration. The (mass-based) percentage of SiO_2 in each size fraction was measured by X-ray fluorescence [16] and is shown in Table 1. The particle size distribution was measured using optical microscopy. The particles had sharp edges, implying a crystalline structure. Although the particles were asymmetric in shape, a majority could be characterized by an approximately rectangular cross section. The approximate cross-sectional area of the particles was determined, and the average equivalent diameter for a disk with the same area was calculated. The equivalent particle diameter and the standard deviation is listed in Table 1. Table 1 also lists the density of the $NaHCO_3/SiO_2$ mixtures that

TABLE 1
Particle characterization

Nominal Particle Diameter (μm)	Average Particle Diameter (μm)	SiO_2 % (kg/kg)	Measured Density (kg/m^3)
2 to 6	4.0 ± 1.6	1.34	2220
3 to 8	5.7 ± 2.5	0.67	2220
10 to 15	[a]	0.46	2220

[a]Not measured.

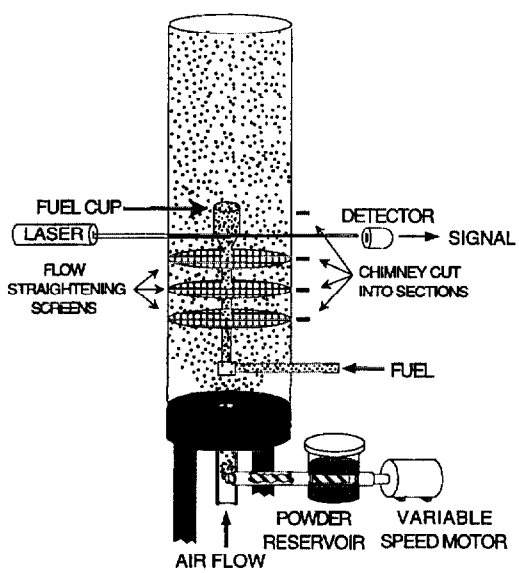

FIG. 1. Schematic diagram of the burner, powder delivery system, and optical arrangement for measuring the $NaHCO_3$ concentration.

was measured using helium pycnometry [17] and determined to be equal for all of the size fractions with a value of 2220 kg/m^3. Particle size ranges are hereafter referred to as the nominal particle diameter, as defined in Table 1.

Modified Cup Burner for Powder Agents

The cup burner was modified to foster a controlled, homogeneous flow of powder and to facilitate repeatable extinction measurements. Figure 1 is a schematic diagram of the modified cup burner, the powder delivery system, and the optical arrangement for measuring the concentration of powder. In this configuration, the oxidizer, which is a mixture of dry air and powder, flows through a glass chimney surrounding the fuel cup. To obtain a uniform flow, a series of wire mesh screens (10 mesh/cm) functioning as flow straighteners were fitted across the entire cross-sectional area of the chimney, below the fuel duct. Warping of the screens was avoided by cutting the chimney into several sections and fitting the screens between the sections. Without the screens in place, non-homogeneous powder flow and recirculation zones were observed near the fuel cup. Flow visualization under non-combusting conditions showed that the 2- to 6-μm and the 3- to 8-μm powder fractions traveled through the chimney as a homogeneous, laminar bulk flow for air velocities above 9 cm/s. The 10- to 15-μm fraction, however, did not flow in a laminar manner even for air flows as high as 20 cm/s, which was the upper range achievable for our system. Thus, experiments were not performed with the larger-diameter fraction. Experiments with the 2- to 6-μm and the 3- to 8-μm $NaHCO_3$ fractions were conducted with an air velocity equal to approximately 10 cm/s.

The powder was introduced into the air stream by turning a 9-mm drill bit through a closed container of powder. The drill bit carried the powder through a 12-mm tube. The powder was fed into the oxidizer stream via a tee located just below the base of the burner where it was swept into the oxidizer flow. The delivery rate was controlled by a variable speed motor and a voltage regulator.

Agent Quantification

The concentration of powder in the flow field was monitored by measuring the attenuation of a 10-mW helium–neon laser beam (632.8 nm) traversing an ≈7-cm chord across the Pyrex chimney (see Fig. 1). The beam was positioned ≈2 cm below the fuel duct to avoid light attenuation by soot and other combustion products. The laser signal was measured by a silicon detector with a 10-nm bandwidth line filter and connected to a data acquisition system with a 4-Hz sampling rate. Using this arrangement, the $NaHCO_3$ concentration along the line of sight was monitored as a function of time. The relationship between the intensity of the attenuated laser signal (I) and the average powder concentration [$NaHCO_3$] in the oxidizer stream was

$$I/I_0 = \exp(-K\,[NaHCO_3]\,L) \qquad (1)$$

where I_0 is the unattenuated laser signal intensity, L is the path length, and K is an absorption/scattering coefficient that is dependent on particle characteristics such as diameter and shape. K was determined for each of the powder batches.

Figure 2 shows the laser signal during a typical experiment. Increased particle loading in the flow field was indicated by increased laser attenuation, until the flame extinguished at a critical powder concentration. As the powder concentration in the oxidizer stream was increased, the flame became thinner and less luminous. Near extinction, only a small

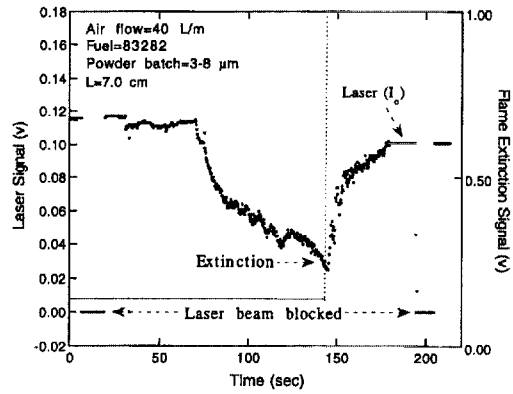

FIG. 2. The laser signal during a typical extinction experiment with $NaHCO_3$ powder.

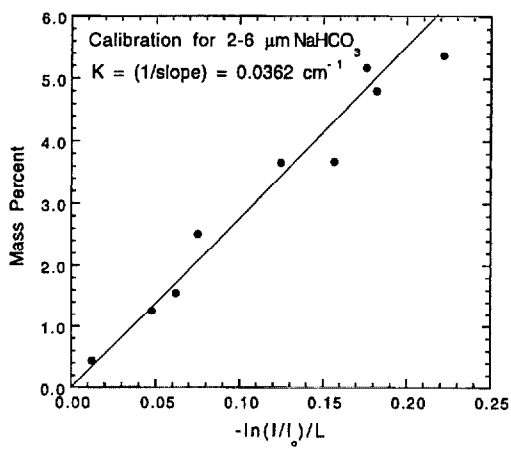

FIG. 3. Calibration results for K in equation 1 for the 2- to 6-μm-diameter $NaHCO_3$ powder.

yellowish region was apparent. At the moment of flame extinction, a signal was sent to the data acquisition system, and the laser transmission signal at extinction (I in equation 1) was determined. The oxidizer flow was immediately closed, preventing further powder adhesion on the chimney walls. After a few seconds, the powder settled and the reference laser signal (I_o in equation 1) was measured. At that time, I_o was unattenuated by flowing powder. Powder adhering to the inner wall of the chimney diminished I_o and was not cleaned until I_o was measured. The baseline signal was checked by blocking the beam. Measurements showed that flame emission did not influence the signal to the laser detector.

To determine the value of K in equation 1, calibration experiments were performed for each of the powder batches with no flame present. During the calibration, two small holes (2 mm) were drilled out of the chimney for passage of the laser beam, eliminating the possibility of laser attenuation due to powder adsorption on the chimney walls. Flow visualization showed that a negligible amount of powder escaped through the orifices. The laser signal was monitored during calibration, indicating steady powder loadings. In cold flow with no flame present, a sample of the gas–particle oxidizer mixture was extracted from the flow field using a tube with a 20-mm inner diameter, placed in the same plane as the laser beam. The powder sample was extracted isokinetically, that is, at the same velocity as that of the oxidizer to reduce sample biasing associated with particle size in the extracted sample. The sampling tube was attached by 25 cm of polyvinyl tubing to a 200-mL glass impinger filled with deionized water and to a vacuum pump. As the sample was extracted, the attenuated intensity of the laser beam was recorded. After the sampling period ($\approx$60 s), the powder accumulated in the tubing was washed out with deionized water, combined with the contents of the impinger, and further diluted to 500 mL. Typically, 0.5–2 g of powder was collected over the sampling period, which was completely soluble in the 500-mL water wash. A calibrated sodium ion-selective electrode was used to determine the concentration of the powder dissolved in the deionized water. In this manner, the value of K for each powder batch was determined from the measured values of L, I, I_o, and $[NaHCO_3]$. Calibration measurements showed that K was linear with particle loading over the range of interest. Figure 3 shows the calibration results for the 2- to 6-μm $NaHCO_3$ size fraction. In the figure, the $NaHCO_3$ mass percent in the oxidizer is shown as a function of the term $[-\ln(I/I_o)/L]$. Based on the calibrations, the values of K were determined to be 0.0362 and 0.0282 cm^{-1} for the 2- to 6-μm and the 3- to 8-μm diameter fractions, respectively, where $[NaHCO_3]$ is in units of mass percent of the oxidizer. The relative expanded uncertainty (2σ) in the K value was approximately $\pm 20\%$. The values of K differed for the two particle batches, as might be expected for particles with varying diameter distributions in the geometric scattering range.

During the extinction tests with flames burning liquid fuels, some powder was observed to accumulate inside of the fuel cup. The effect of $NaHCO_3$ powder on the extinction resistance of the fuels was tested by measuring the extinction concentration of N_2 in the oxidizer stream for flames burning fuels with and without powder sprinkled on the surface of the liquid fuels. No difference in required N_2 extinction concentration was determined for any of the liquid fuels tested. This was consistent with the observation that the powder submerged immediately upon contact with the fuel surface, suggesting that the powder did not cause extinction by interaction with the liquid-gas interface.

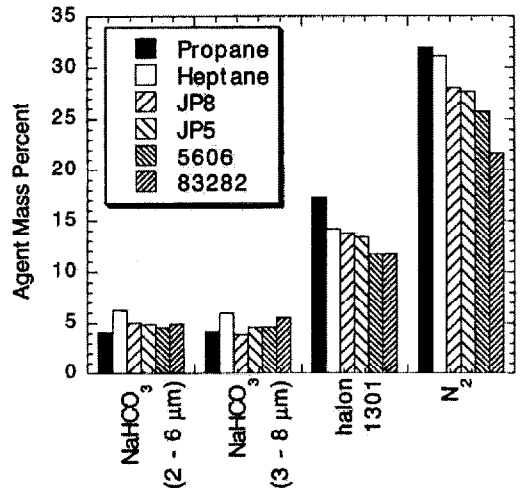

FIG. 4. The mass-based concentrations of CF_3Br, N_2, and the 2- to 6-μm and the 3- to 8-μm-diameter fractions of $NaHCO_3$ required to extinguish flames burning propane, heptane, JP-8, JP-5, and the hydraulic fluids 83282 and 5606. See text regarding the uncertainty in these measurements.

Results and Discussion

Flame Character

The color of the flame became bright yellow with the addition of even minute amounts of $NaHCO_3$ into the flame. Equilibrium calculations [18] indicate that at flame temperatures, the sodium containing species in the flame (at 2050 K) with the highest concentrations are Na and NaOH. At lower temperatures (1850 K), $Na_2CO_3(L)$ is also present. The yellow luminosity is attributed to high-temperature Na emission from the flame.

Flame Extinction

Figure 4 shows the mass-based concentrations of CF_3Br, N_2, and the 2- to 6-μm and the 3- to 8-μm-diameter fractions of $NaHCO_3$ required to extinguish flames burning propane, heptane, JP-8, JP-5, and the 83282 and 5606 hydraulic fluids. Depending on the fuel type, 12–15% by mass of halon 1301, and 22–32% of N_2 in the oxidizer stream were necessary to extinguish the cup burner flames. The results for N_2 and CF_3Br extinction of heptane cup burner flames compared favorably to results reported previously [5]. Depending on the fuel type, 4–6% by mass of the powder was required to extinguish the cup burner flames. A comparison of the agents showed that on average, $NaHCO_3$ was three times more effective than CF_3Br on a mass basis and six times more effective than N_2 in extinguishing flames burning the various fuels.

Measurement variance and a propagation of error calculation considering the air and agent flows, calibration uncertainty, and measurement variance yielded an estimate of the relative expanded uncertainty (2σ) in the gaseous agent concentration at extinction as $\pm 10\%$. The relative expanded uncertainty (2σ) for the $NaHCO_3$ concentration at extinction was an average of $\pm 30\%$ and $\pm 35\%$ for the 2- to 6-μm and the 3- to 8-μm particle diameter fractions, respectively. Measurement variance dominated the expanded uncertainty for both particle diameter fractions.

Figure 4 shows that the results for the two powder diameter fractions were highly similar. The ratio of the required powder concentration for the smaller (2 to 6 μm) particles to the larger (3 to 8 μm) particle batches for each fuel type differed by an average factor of 1.04 (± 0.12), an insignificant difference for these two powder batches. These results indicate that the difference in SiO_2 loading for the two particle batches (see Table 1) had little impact on powder effectiveness.

For the same powder batches used here, Trees and Seshadri [14] performed counterflow extinction measurements using $NaHCO_3$. They reported that the large (10 to 15 μm) particles (referred to as 20 to 30 μm in Ref. [14]) did not completely vaporize as they traversed the thin counterflow flame, whereas the 2- to 6-μm particles and the 3- to 8-μm particles did. The residence time in the cup burner flames used here is approximately an order of magnitude larger than in the low-strain-rate counterflow flames, suggesting that both particle fractions completely vaporized in the cup burner flame. The similarity in the results for the two particle diameter fractions tested here is consistent with the idea that both particle diameter fractions were below the critical diameter where vaporization is complete.

Physical Versus Nonphysical Agent Effectiveness

The dominant physical behavior of an agent is due to heat capacity and dilution, but other physical effects may also play a role. These include phase change, dissociation, degradation, preferential diffusion, and enthalpy losses associated with radiative emission. Effects other than these are denoted here as nonphysical and are interpreted as chemical kinetic in nature.

There are several metrics for quantifying the relative contributions of physical and nonphysical agent effectiveness [4,5,19]. The following procedure was used here. A critical flame temperature criterion for completely physical extinction behavior was constructed using the inert compound N_2 as a basis. The adiabatic flame temperatures for near-extinction agent concentrations in stoichiometric heptane-air mixtures were determined using the NASA CEC computer code and database [18]. The calculations

TABLE 2
Calculated flame temperatures and agent behavior of near-extinction heptane flames

Agent	Agent Volume Percent	T (K)	% Physical
None	0	2275	—
N_2	32 ± 3	1856 ± 52	100
CF_3Br	3.1 ± 0.3	2210 ± 7	12 ± 3
$NaHCO_3$ (2–6 μm)	2.3 ± 0.7	2054 ± 68	47 ± 16
$NaHCO_3$ (3–8 μm)	2.1 ± 0.7	2072 ± 72	42 ± 17

yielded equilibrium composition and temperatures, including dissociation and phase-change effects. The results are shown in Table 2. The agent concentrations used in the calculations correspond to those shown in Fig. 4. The agent concentrations are also listed in Table 2 in terms of volume percent in the oxidizer (assuming that the $NaHCO_3$ was completely vaporized). A calculated flame temperature larger than the reference temperature (based on N_2) indicates that physical effects alone do not account for the total enthalpy loss from the flame required for extinction. As expected, Table 2 shows that the flame extinguished by N_2 yielded the lowest flame temperature of all the agents.

The enthalpy abstracted by the flame mixture (the products of stoichiometric combustion and the agent) corresponding to the measured agent extinction value was calculated. For each of the agents in Table 2, the amount of supplementary agent required to lower the flame mixture temperature to the reference temperature was also calculated. The enthalpy abstracted by the flame mixture associated with the supplementary agent addition represented the contribution by *nonphysical* agent behavior. Physical agent behavior was estimated by taking the difference between the total available flame enthalpy and the enthalpy abstracted by the flame mixture associated with agent addition. The percentage physical behavior was determined by dividing the physical agent contribution by the sum of the physical and nonphysical agent contributions (where the agent concentration was normalized for one mole of fuel in the stoichiometric relation). Uncertainties in the calculated temperatures and percent physical behavior corresponded to the expanded experimental uncertainty (2σ) in agent concentration noted in Table 2.

Table 2 lists the percent physical effectiveness from these calculations. The calculated physical effectiveness for CF_3Br was 12%. The calculated physical effectiveness for the $NaHCO_3$ was nearly equal for the two particle diameter fractions and was evenly split between physical and nonphysical behavior. The combination of decomposition and phase changes play a role in $NaHCO_3$ effectiveness. Approximately 10% of the enthalpy abstracted by one mole of $NaHCO_3(s)$ is due to decomposition to 0.5 moles of $Na_2CO_3(s)$, CO_2, and H_2O.

Rosser et al. suggested the possibility of radical recombination as a mechanism by which the alkali metals could chemically destabilize a flame [10]. The results presented here are at odds with Ewing and coworkers [20], who attribute flame extinction by $NaHCO_3$ exclusively to thermal effects.

The effect of the small amount of SiO_2 (see Table 1) on the powder effectiveness was considered. Calculations like those in Table 2 showed that the SiO_2 modified the calculated flame temperatures of the powders by less than 10 K, suggesting that the small SiO_2 additions had a negligible influence on the $NaHCO_3$ powder requirements for flame extinction. Experiments showed that flame extinction using silica as an agent was not possible for achievable powder loadings in our apparatus. Rosser et al. also observed that SiO_2 is not an effective inhibitor of hydrocarbon combustion [10].

Conclusions

A modified cup burner apparatus was developed for testing the extinction efficiency of a solid powder. Measurements were performed on flames burning both liquids and gases using sodium bicarbonate ($NaHCO_3$) powder as the extinguishing agent. For comparison, extinction measurements using halon 1301 and inert N_2 are also reported. In general, $NaHCO_3$ is a highly efficient flame suppressant, an average of three and six times more effective than halon 1301 and nitrogen, respectively, on a mass basis. An estimate of the effectiveness of the agents indicated that like CF_3Br, the suppression behavior of $NaHCO_3$ was due partially to chemical effects.

The application of $NaHCO_3$, however, must be considered in terms of postfire cleanup and possible corrosion problems. When in contact with water, $NaHCO_3$ forms a highly corrosive base. In addition, storage at temperatures above 50 °C [21] leads to equilibrium formation of H_2O, which may cause powder agglomeration, undermining agent delivery.

Acknowledgments

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COMMENTS

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1. A direct correspondence between the gaseous agent extinction concentrations in the cup burner and the counterflow burner was first found by Hamins and coworkers [1,2] and later reproduced well by Saso et al. [3]. Is there any experimental evidence that implies poor correspondence for condensed-phase agents?
2. We previously suggested different measures for quantifying the chemical contribution of suppressants for counterflow diffusion flame extinction [3] and laminar flame-speed reduction [4]. Are there any advantages with the method used in the present study, compared with the previously suggested metrics? Are the results strongly affected by selection of method?
3. Saito's group in NRIFD reported [5] that there is no range of propane flow rate in which the agent extinction concentration does not change. They show that the propane flow rate in the cup burner has a significant effect on the agent extinction concentration for wide ranges measured. The present work shows a minimal effect of propane flow rate, which is contrary to Ref. [5]. Can you explain why such discrepancy exists between the two observations?

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Author's Reply.

1. There are few qualitative extinction results available for condensed-phase agents, so the correspondence between the extinction concentrations of condensed-phase agents in low strain-rate counterflowing diffusion flames and coflowing cup burner diffusion flames remains to be tested. Because particle dynamics in the two configurations can be expected to be very different, correspondence may be restricted to very small diameter

condensed-phase agents and those that rapidly decompose to gas-phase products at relatively low temperatures.

2. As mentioned in the text, there are a number of methods available to estimate agent extinction behavior. Reference [4] of this question refers to a premixed flame calculation using detailed chemistry. Such calculations are limited to the small number of agents and flame systems whose chemistry is well understood. The metric used in the present study considers the enthalpy of the flame system, which is a global characterization of agent behavior and is generally applicable. The results using the present method are similar to the results that use the method in Ref. [3] of the question.
3. As mentioned in the text, our previous results show that for gaseous agents, the propane flow in our cup burner does not significantly impact (within experimental error) the measured agent extinction concentration over a fairly wide range of fuel flows (see p. 392 in Ref. [13] in the paper). The reasons for the discrepancy that you identify are not clear. Future studies should also consider the influence of the gaseous fuel flow on the extinction requirements of a condensed-phase agent.

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Ronald S. Sheinson, Naval Research Laboratory, USA. This paper quantifies agent physical action by comparison with the physical effect of nitrogen assumed due to heat capacity. Other physical processes [1] (especially dilution for nitrogen) are significant in effecting extinguishment. Dilution is not a significant factor for halon and the sodium bicarbonate powder. Had this consideration been included in the analysis, the extent of their chemical action would have shown even greater.

REFERENCE

1. Sheinson, R. S., Penner-Hahn, J. E., and Indritz, D., *Fire Safety J.* 15:437–450 (1989).

Author's Reply. For a non-premixed flame, by definition, fuel and agent react at the location of stoichiometric combustion. For the agent and flame systems considered in this analysis, 1 mole of heptane reacts with 11 moles of air.

$$C_7H_{16} + 11\ (O_2 + 3.76\ N_2) + X \text{ agent} \rightarrow \text{products}$$

where X is the number of moles of agent at extinction. By definition, X is related to the experimentally measured concentration of agent in the oxidizer stream at extinction (A) through the relation

$$A = X/(52.36 + X)$$

where the number 52.36 represents the moles of oxygen and nitrogen in the oxidizer stream for stoichiometric combustion of heptane. The number of moles of agent in the stoichiometric relation is then given by

$$X = 52.36\ A/(1 - A)$$

In this analysis, dilution is an integral part of the calculation, which is implicitly considered through the value of X.