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SUPPRESSION OF A BAFFLE-STABILIZED SPRAY FLAME BY HALOGENATED AGENTS

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A series of experiments was conducted on baffle-stabilized spray flames in an effort to provide an improved understanding of the influence of various parameters on the processes controlling flame suppression. Measurements were made of the agent mass required to suppress the spray flames as a function of the agent injection duration (which was designed to deliver a constant mass flow of agent to the burner for a controlled duration), the air velocity, the oxidizer temperature, the ambient pressure, and the fuel flow. The agent mass fraction required to extinguish the flame was estimated from the agent mass divided by the agent injection duration. Extinction measurements were performed with the gaseous agents CF_3Br, CF_3I, C_2HF_5 (HFC-125), and C_3HF_7 (HFC-227ea).

The results showed that, in general, CF_3Br was the most effective agent on a mass basis, followed by CF_3I and then C_2HF_5 and C_3HF_7, which had similar effectiveness. For elevated air temperatures ($T >$ 100°C), the three candidate replacement agents had similar effectiveness on a mass basis. As the air velocity increased, the agent mass fraction required for suppression (β) decreased. The fuel flow had little effect on β. An expression, based on treating the recirculation zone as a well-stirred reactor, was developed to describe flame suppression as the agent delivery duration varied. Two parameters were determined as crucial in that description. They were a characteristic mixing time that described the rate of agent entrainment into the recirculation zone downstream of a flame holder (or baffle) and the agent concentration at extinction for long agent injection durations. The model facilitated a comparison of the effectiveness of agents in suppressing baffle-stabilized spray and pool fires, two very different combustion configurations.

Introduction

The engine nacelle encases the jet engine compressor, combustors, and turbine. A nacelle fire is typically a turbulent flame stabilized behind an obstruction in a moderate-speed air flow. The fuel source for a fire in the nacelle can be leaking pipes carrying jet fuel or hydraulic fluid that can feed the fire either as a spray or in the form of a puddle or pool. Extinguishment occurs when a critical amount of agent is transported to the fire zone.

Because of its many positive attributes, halon 1301, or trifluorobromomethane (CF_3Br), has been used as a fire-extinguishing agent for protecting aircraft engine nacelles. Due to its high ozone depletion potential, however, halon 1301 manufacture has been halted. As halon 1301 is replaced with alternate suppressants, continued effective aircraft protection becomes a challenge.

Few studies have investigated the effectiveness of an agent in suppressing baffle-stabilized flames. Blow-off of baffle-stabilized premixed flames, on the other hand, has been well studied. Correlations have been developed that relate flame stability to the

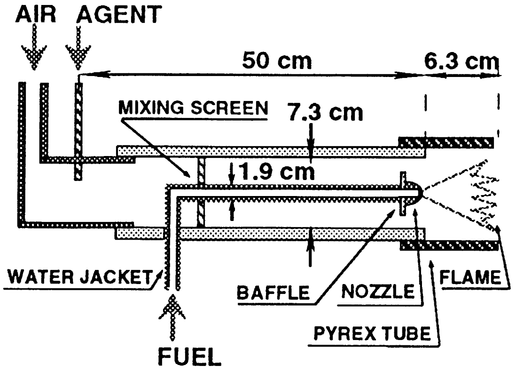

FIG. 1. A cross-sectional view of the 7.3-cm i.d. spray burner.

baffle diameter, the ambient pressure, and the laminar flame speed of the reactants [1,2]. The influence of these and other parameters on the suppression of baffle-stabilized flames by an agent remains to be tested.

In this study, a series of flame-extinction measurements was conducted on the influence of various parameters on the processes controlling flame stability in baffle-stabilized spray flames, and the relative effectiveness of key candidate replacement agents was ranked. The data were interpreted in terms of a mixing model that characterized the rate of agent entrainment into the recirculation zone in baffle-stabilized flames. The characteristic mixing time is extremely important in developing fire-protection strategies, since it influences the free stream agent concentration and duration required to obtain extinction.

Experimental Method and Apparatus

The experimental facility has been described previously in detail [3]. Figure 1 shows a cross-sectional view of the spray burner. The apparatus incorporated air, fuel, and agent delivery systems and a baffle-stabilized recirculation zone at atmospheric pressure. Air was introduced into a 7.3 cm inner-diameter (i.d.) stainless steel (ss) tube, concentrically about a 1.9-cm diameter ss tube that encased the fuel line and a water jacket. Another nearly identical 5.3-cm i.d. ss burner was used for some experiments. The air flow was controlled by varying the pressure upstream of a critical flow orifice and by measuring the upstream pressure. The temperature of water entering and exiting the fuel line water jacket was monitored by thermocouples. JP-8 jet fuel was pumped (nominally 20 ml/min) through a commercially available pressure-jet nozzle that formed a 45° solid-cone spray. Nozzles with wider spray angles were considered initially but ultimately rejected because of the high degree of fuel droplet impingement on the burner walls. The nozzle tip extended 0.2 cm beyond the burner exit. The flame was stabilized by a steel disk (nominally 3.5 cm in diameter and 0.2 cm thick) attached to the body of the nozzle. A 8.6-cm i.d. pyrex tube supported on a brass ring encased the flame 6.3 cm beyond the burner exit. The pyrex tube encased the flame recirculation zone, preventing dilution of the air/agent mixture by outside air. For experiments using heated air, the burner was insulated with a 2-cm thick thermal blanket to minimize temperature gradients within the tube. For experiments that investigated the influence of increased ambient pressure on flame stability, the spray flame was confined by replacing the pyrex tube shown in Fig. 1 with a 40-cm long brass tube fitted with a butterfly valve damper at the burner exit. This allowed control of the pressure, which was varied from ambient to 135 kPa (5 psig). A pyrex observation window facilitated observation of flame extinction. Three ports allowed access for ignition, a pressure gauge, and an automatic fuel shutoff detector triggered by flame extinction.

The agent injection system under idealized conditions was designed to deliver a constant flow of agent mass to the burner for a controlled duration. The rate and mass of injected agent were controlled by varying the initial agent reservoir pressure, the opening time of the computer-controlled solenoid valve, and the size of a flow orifice (nominally 2–6 mm). The change in the mass of agent in the reservoir was determined by measuring the initial temperature and the transient pressure, using a fast time-response pressure transducer and acquiring data at 1000 Hz. The initial and final pressures were determined by averaging the data 0.5 s before the agent release and 0.5 s after the solenoid valve closed. Assuming isentropic expansion of the gaseous agent in the reservoir, the final gas temperature was calculated. The Redlich–Kwong equation of state was used to determine the mass of agent in the reservoir as a function of time and therefore the amount delivered to the air stream [4]. Uncertainty in the agent concentration at extinction was estimated as 15% based on a propagation of error analysis and repeat measurements [3].

Because the spatial and temporal agent concentration distribution influenced the entrainment of agent into the recirculation zone and thereby flame suppression, agent concentration measurements were conducted using an aspirated hot film probe. Measurements made just upstream of the baffle under noncombusting conditions indicated that the agent was uniformly dispersed spatially across the burner and that the agent injection rate was nearly a constant over the delivery duration [3].

The independently controlled parameters were the air flow, agent delivery (or injection) duration, air temperature, ambient pressure, and fuel flow.

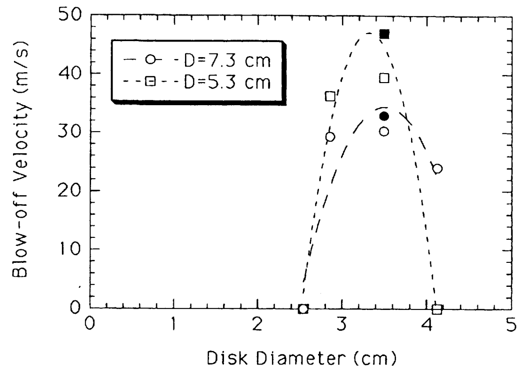

FIG. 2. The air blow-off velocity as a function of the diameter of the stabilization disk. The open and filled symbols represent disks with thicknesses of 2 and 4 mm, respectively.

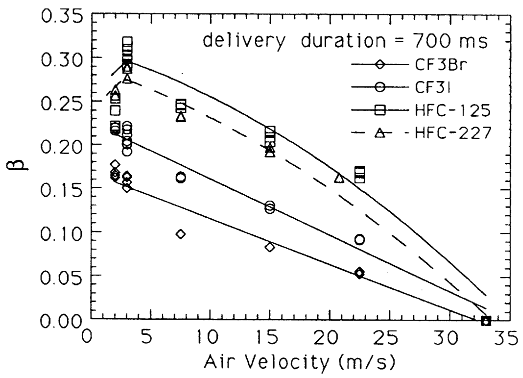

FIG. 3. The critical mass fraction (β) of CF_3Br and the three alternate agents at extinction as a function of air velocity.

The primary dependent experimental parameters were the rate and duration of agent injection required for suppression. Flame extinction measurements were performed with the gaseous agents CF_3I, C_2HF_5 (HFC-125), and C_3HF_7 (HFC-227ea). These agents were selected based on their suitability as drop-in replacements for CF_3Br in aircraft engine nacelle applications [5]. CF_3Br was also tested to establish a performance reference.

Experimental Results

Flame Character

The air and fuel flows affected flame length and appearance. For low air velocities (<2 m/s), the flame had a 3–5 cm standoff distance followed by a long luminous plume. As the air flow increased, the visible flame length decreased significantly. A rotating torroidal flame stabilized on the downstream side of the baffle, and a nonluminous zone was evident between the baffle-stabilized flame and the flame beyond the standoff distance. This dark zone disappeared for moderate air flows. As the fuel flow increased, the flame length and apparent luminosity increased.

Flame Blow-Off

The air velocity required to blow-off the JP-8 spray flame was measured in both the 5.3 and 7.3-cm diameter burners. A series of stabilization disks was tested with diameters of 2.22, 2.86, 3.49, and 4.13 cm, all 4 mm thick and made from the same steel stock. A 3.49-cm diameter (2-mm thick) disk from a different steel stock was also tested. Figure 2 shows the air velocity (just upstream of the baffle) required to blow-off the spray flame (V_{bo}) as a function of the stabilization disk diameter. Other parameters were held constant. For conditions above the data points, the flames were extinguished. The 3.5-cm diameter disks (2 and 4 mm thick) yielded the most stable flames in both burners. A stable flame was sustainable until the air velocity was approximately 33 m/s in the 7.3-cm burner. Flames could not be stabilized with the 2.2-cm disk in either burner or with the 4.1-cm disk in the 5.3-cm burner. Blow-off velocities in the 5.3-cm diameter burner were approximately 25% higher than in the 7.3-cm diameter burner for the same disk diameter. This difference is attributed to the stabilizing effect of geometric blockage that has been investigated by Winterfeld [6] and discussed by Lefebvre [7].

The results in Fig. 2 are consistent with those of Hirst and Sutton [8] who studied the blow-off of baffle-stabilized pool fires. Flame stability was measured to be a function of obstacle size. In their experiments, the blow-off velocity increased, obtained a maximum, and then decreased as the height of the obstacle above the fuel surface increased.

Effect of Air Velocity on Agent Extinction Requirements

All subsequent measurements used the 3.5-cm diameter disk (2-mm thick) and the 7.3-cm diameter burner. Figure 3 shows the critical mass fraction (β) of agent in the air stream for CF_3Br and the three alternate agents at extinction as a function of air velocity for a 700-ms agent delivery duration. This duration was sufficient for the agent concentration in the recirculation zone to obtain its free stream value. The mass fraction of agent (β) was defined as $\beta = \dot{m}_{agent}/(\dot{m}_{air} + \dot{m}_{agent})$, where $\dot{m}_{air}$ and $\dot{m}_{agent}$ are the air and agent mass flows. The agent mass flow was nearly constant over the injection period.

CF_3Br required the smallest mass fraction to

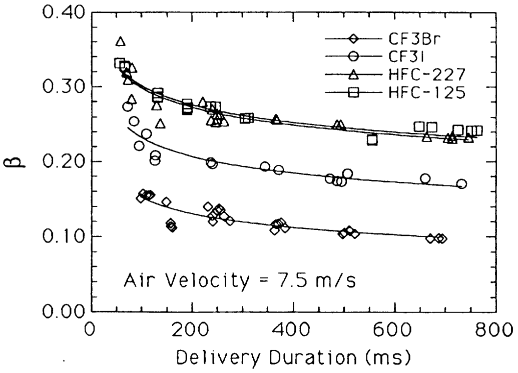

FIG. 4. The critical mass fraction (β) of CF_3Br and the three alternate agents at extinction as a function of agent delivery duration.

extinguish the flames, followed by CF_3I and the other two agents, HFC-125 and HFC-227, which were measured to have similar effectiveness. As the air velocity increased from 3 m/s, β decreased. As expected, at higher air velocities, the flames were less stable and less agent was required to extinguish them. For very low air velocities (2–3 m/s), β decreased or remained nearly the same. Experiments replacing the extinguishing agent with air demonstrated that suppression was not simply due to flame blow-off [5].

For all agents, the critical values of β for the spray flame at low air velocities (3 m/s) were very similar to agent extinction concentrations measured in simple diffusion flames burning JP-8, namely opposed flow diffusion flames (OFDF) at low global strain rates (50 s^{-1}) and co-flow cup burner flames [3,5,9]. For example, in these burner configurations and for the conditions specified earlier, β for CF_3Br was equal to 0.16, 0.13, and 0.14; β for HFC-125 was equal to 0.30, 0.28, and 0.28; and β for HFC-227 was equal to 0.28, 0.26, and 0.27, respectively. OFDF results for CF_3I are not available, but the cup burner and spray flame at low air velocities have similar agent concentration requirements, namely 0.18 and 0.21, respectively. A correspondence also exists between the critical agent mass fractions for moderate and high global strain rates (160 and 350 s^{-1}) in the OFDF burner [9] and moderate and high air velocities (15 and 22.5 m/s) in the spray burner [3]. Qualitatively, this is interpreted as caused by increased fluid mechanical strain rate in the spray burner recirculation zone as the air velocity increased. The results suggest that the testing of alternate agents in one appropriate experimental configuration may be sufficient. Quantitative understanding of the correspondence requires a detailed understanding of the transient structure of the spray flame recirculation zone.

Effect of Injection Duration on Agent Extinction Requirements

The critical agent mass fraction (β) of CF_3Br and the three alternate agents at extinction are shown in Fig. 4 as a function of agent delivery duration for an air velocity equal to 7.5 m/s. This air velocity was selected because it is representative of aircraft nacelle applications. As the delivery duration increased, the critical β decreased and approached an asymptote for long delivery durations. Again, CF_3Br was the most effective, followed by CF_3I and the other two agents, C_2HF_5 and C_3HF_7, which were measured to have similar effectiveness. The shape of the curves for each of the agents in Fig. 4 were similar but displaced along the ordinate.

These data can be explained in terms of a phenomenological model by treating the recirculation zone as a well-stirred reactor. Longwell et al. [10] used a similar model to examine blow-off of premixed flames. Here, the model is extended to treat agent entrainment into a recirculation zone and subsequent flame extinction. The characteristic mixing time of reactants to entrain from the free stream into the recirculation zone is a key parameter. The assumptions used to develop the model were as follows: The flame was stabilized in the recirculation zone downstream of the baffle. To extinguish the flame, the agent (volume-based) concentration (X) in the recirculation zone had to obtain a critical value (X_∞). Complete mixing of the agent in the recirculation zone was instantaneous. The momentum of the fuel spray and its character (e.g., droplet size, velocity distribution) were neglected.

As the agent entrained into the combustion/recirculation zone, its concentration (X) was approximated by the first-order differential equation describing mixing in a well-stirred reactor:

$$X = \tau \frac{dX}{dt} = X_f \qquad (1)$$

where X_f is the free stream agent mole fraction and τ is the characteristic mixing time for entrainment into the recirculation zone. The solution to Eq. (1) for a step function shaped transient agent concentration is given by

$$X = X_f [1 - e^{(-\Delta t/\tau)}] \qquad (2)$$

where Δt is the agent injection duration. For long agent injection durations ($\Delta t \gg \tau$), the agent concentration in the recirculation zone approached the free stream value, X_f. Experiments reported by Bovina [11] confirmed the form of Eq. (2). The model requires that at flame extinction, the agent concentration in the recirculation zone obtain the same critical value, regardless of agent injection duration. This suggests that at extinction, the critical agent concentration in the free stream, $X_c(\Delta t)$, for a finite injection duration (Δt), is related to the critical agent

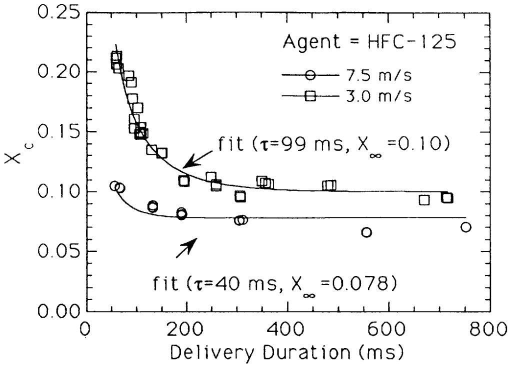

FIG. 5. The critical mole fraction (X_c) of HFC-125 at extinction as a function of agent delivery duration for air velocities equal to 3.0 and 7.5 m/s.

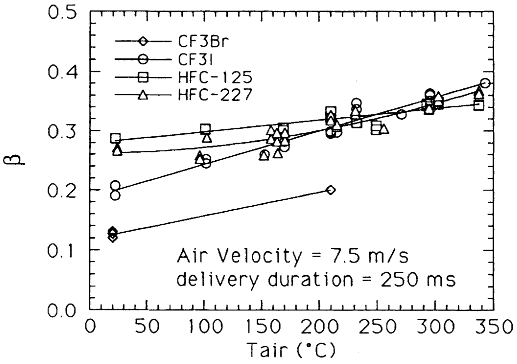

FIG. 6. The critical agent mass fraction at extinction as a function of air temperature.

concentration in the free stream for long injection durations, $X_c(\Delta t \gg \tau)$ or X_∞, and an exponential term associated with the extent of mixing,

$$X_c(\Delta t) = \frac{X_\infty(\Delta t \gg \tau)}{1 - e^{(-\Delta t/\tau)}} \tag{3}$$

For long injection durations ($\Delta t > 3\tau$), the denominator in Eq. (3) ≈ 1.0 and $X_c \approx X_\infty$. For short injection duration, large free stream agent concentrations are required to obtain extinction. Because the critical agent mole fraction X_c must be less than or equal to 1.0, Eq. (3) implies that a critical injection duration (Δt_c) exists such that a flame cannot be extinguished, regardless of agent concentration. For $X_c = 1.0$, the value of the critical injection duration is

$$\Delta t_c = -\tau \ln(1 - X_\infty) \tag{4}$$

For conditions representative of the spray burner, with the air velocity 7.5 m/s, τ equal to 40 ms, and X_∞ equal to 0.1 (characteristic of the HFC-125 data in Fig. 4), Eq. (4) yields a value of 4 ms for Δt_c, much smaller than the delivery duration possible using the current apparatus and those typical of aircraft nacelle applications, which is approximately 1 s.

For noncombusting conditions and for premixed flames, Winterfeld [6] found that the characteristic mixing time (τ) in Eq. (2) is related to the baffle diameter (d), the enclosure diameter (D), and the upstream velocity (V) of the air/agent mixture:

$$\tau = \frac{d}{V}[a + b \cdot \log(d/D)^2] \tag{5}$$

The ratio $(d/D)^2$ represents a geometric area blockage factor. Bovina [11] verified that $\tau \propto d/V$ for premixed flames.

The critical mole fraction (X_c) of HFC-125 at extinction for two air velocities is shown in Fig. 5 using a portion of the data presented in Fig. 4, where X_c is defined as

$$X_c = \frac{(\beta/M_{\text{agent}})}{(\beta/M_{\text{agent}}) + ([1 - \beta]/M_{\text{air}})} \tag{6}$$

M_{agent} and M_{air} are the molecular weights of agent and air, respectively. Interpreting the curves in terms of Eq. (3) shows that reasonable fits were obtained using τ = 99 and 40 ms, for the 3.0 and 7.5 m/s data, respectively. For simplification, τ is treated as a constant, although it varies somewhat as X_c changes (for each agent). This is because the air, and not the oxidizer velocity, was fixed. The variation in τ, however, is small, and treating τ as a constant is a reasonable approximation for moderate values of X_c. From the fits in Fig. 5, the values of X_∞ were determined to be 0.10 and 0.078, respectively. The values for τ are consistent with Eq. (5), which suggests that $\tau \propto (Yv)$ for constant values of d (= 3.5 cm) and D (= 7.3 cm). Although the value of X_∞ cannot be predicted by the well-stirred reactor model, the notion that X_∞ decreased with air velocity is consistent with Fig. 3. An analysis of the extinction data in Fig. 4 showed that agent type does not affect the characteristic agent mixing time, implying that molecular diffusion did not play a significant role in entrainment and transport in these turbulent flames.

Effect of Air Temperature

The values of β are presented in Fig. 6 as a function of the average air temperature under conditions of a constant air velocity (7.5 m/s) and agent delivery duration (250 ms). Temperatures were varied from ambient to 350°C. The air velocity just upstream of the bluff body was held fixed for these experiments, requiring a substantial reduction in the air mass flow as the temperature increased. Heating of the JP-8 fuel was minimized by use of a co-axial water jacket cooling the fuel line (see Fig. 1).

As seen in Fig. 6, the agent mass fraction (β) required to suppress the JP-8 spray flame increased as

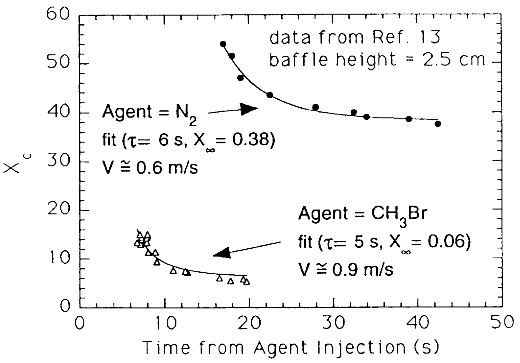

FIG. 7. The critical mole fractions (X_c) of N_2 and CH_3Br as a function of time from agent injection for suppression of a baffle-stabilized pool fire in a wind tunnel; results taken from Ref. 13.

the preheated oxidizer temperature increased. This trend was anticipated, since heating the oxidizer adds enthalpy to a flame, and a flame with higher enthalpy is more stable. However, increasing the oxidizer temperature altered the agent ranking. The relative effectiveness of CF_3I was still better than HFC-125 and HFC-227 for temperatures lower than approximately 100°C (as seen in Fig. 3) but was only as effective as those agents for temperatures greater than 100°C. CF_3Br remained the most effective agent over the temperature range studied. In relative terms, CF_3I and CF_3Br required larger changes in agent concentration to achieve extinction as the air temperature increased when compared with HFC-125 or HFC-227.

Adiabatic flame temperatures were calculated for the critical extinction conditions represented in Fig. 6, treating the agent as inert. The calculated temperatures for HFC-125, HFC-227, CF_3I, and CF_3Br were approximately 1800, 1800, 2100, and 2200 K, respectively. Under these conditions, larger chemical effects of the agents are associated with higher calculated flame temperatures, assuming similar fluid mechanical strain [12]. Thus, CF_3I and CF_3Br were seen to have the highest chemical activity, with CF_3Br found to be slightly more effective than CF_3I. As the oxidizer temperature increased, the calculated adiabatic flame temperatures showed little variation (within 40 K). Calculations showed that the overall chemical activity of these agents decreased somewhat (≈20%) as the oxidizer temperature and the required agent concentration increased.

Effect of Pressure and Fuel Flow

β was measured as a function of the ambient pressure for the three alternate agents under conditions of a constant air velocity (7.5 m/s) and agent delivery duration (250 ms). The pressure was varied from ambient to 135 kPa (5 psig). As the pressure increased, the mass flow of agent required to extinguish the spray flames increased proportionally such that β remained constant for all agents. The results imply that key chemical processes that controlled flame extinction were not sensitive over the rather narrow pressure variation studied. However, because blow-off measurements in the spray burner showed that V_{bo} decreased with pressure (consistent with results in baffle-stabilized premixed and pool fire configurations [1,7,8]), it is anticipated that β is a function of pressure for very high air velocities (most significantly, for air flows approaching the blow-off velocity). Additional measurements in the spray burner showed that the fuel flow had a negligible effect on β under conditions of constant air velocity (7.5 m/s) and agent delivery duration (250 ms).

Suppression of Baffle-Stabilized Pool Fires

In a series of papers, Hirst and co-workers and Simmons and co-workers reported experiments on the suppression of baffle-stabilized kerosene pool fires situated in a wind tunnel [8,13–16]. JP-8 jet fuel is a formulation composed almost exclusively of kerosene and shares many of its thermophysical properties. The baffle in the pool fire experiments extended 2.5 cm above the upstream edge of the burning pool. As in the spray experiments, gaseous agent (N_2 and CH_3Br) was injected into the air stream at a constant rate in a steplike fashion.

Interpretation of the pool fire suppression results in terms of Eq. (3) is shown in Fig. 7. Reasonable fits to the N_2 and CH_3Br data were obtained using τ = 6 and 5 s and yielded X_∞ = 0.38 and 0.08, respectively. These τ values were more than an order of magnitude larger than those appraised in Fig. 5 for the spray flame, for example. Also, X_∞ was significantly larger for the pool fires than for the spray flames studied here. Interestingly, X_∞ for the pool fires corresponded to the peak flammability limits of a premixed reactive system [17]. The characteristic time τ differed more than would be expected in the two configurations if only the differences in the velocities and baffles length scales were considered. Part of the explanation may be attributable to differences in the area blockage factor, which was ≈25% for the spray burner and ≈80% for the pool fire [14]. In addition to the stabilizing effect of geometric blockage, differences associated with the detailed structure of the recirculation zones are likely important. Fuel blowing effects, the baffle material, and geometric effects other than blockage may all play a role. For example, results from two-dimensional numerical isothermal flow simulations show that τ is an order of magnitude larger for entrainment into a recirculation zone with the baffle against a wall as compared to a baffle in the middle of the flow field (for small blowing rates and similar Reynolds numbers and blockage ratios) [3]. Detailed measurements of the transient structure of recirculation zones in flames near extinction would be useful for an improved understanding of flame stability.

Summary and Conclusions

On a mass basis, none of the agents performed as well as halon 1301. Of the three candidate replacement agents evaluated in the spray burner, CF_3I generally required the least amount of gaseous agent to extinguish the flames. The other two agents tested, HFC-125 and HFC-227, were measured to have similar suppression effectiveness.

A model was developed to describe suppression of baffle-stabilized flames as the agent delivery duration was varied. The well-stirred reactor model has no explicit dependence on pressure, air temperature, or fuel droplet characteristics. The model suggests the importance of two key parameters, namely, the mixing time (τ) and the minimum critical agent concentration (X_∞). The variable τ describes the rate of agent entrainment into a recirculation zone behind a flame holder or baffle. The second parameter, X_∞, is the agent concentration required to achieve extinction for long agent injection durations in baffle-stabilized flames. X_∞ is related to τ, because X_∞ requirements vary with the global strain rate that characterizes the recirculation zone and that is related to the velocity. Use of the model facilitated comparison of the effectiveness of agents in suppressing baffle-stabilized spray and pool fires, two very different configurations.

Acknowledgments

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COMMENTS

Livia Cubuzio, University of Naples, Italy. In the experiments, was soot observed on the baffle and would the presence of soot affect the measurements?

Author's Reply. Yes, soot was observed to collect on the baffle for the JP8 spray flames, with soot mass increasing as a function of burn time. A parametric study showed that agent concentrations required to achieve flame extinction increased significantly for approximately the first 30 s after flame ignition, remained constant for several minutes, and then decreased. The experimental procedure therefore called for all extinction experiments to be conducted from 30 s to 4 min after ignition. The growing layer of soot on the baffle may have acted as an insulator, influencing heat transfer to the baffle and contributing to the observed changes in flame stability.