EFFECTS OF OBSTRUCTION ON FLAME SUPPRESSION EFFICIENCY

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ABSTRACT

The suppression phenomena of a pool flame of JP-8 fuel formed behind an obstacle (backward-facing step or J-shape flange) in a combustion tunnel have been studied by impulsively injecting **a** gaseous fire extinguishing agent (CF_3Br or C_2HF_5) into the airflow. The extinction-limit behavior was similar to that of methane flames studied previously. The critical agent mole fraction at extinction for long agent injection periods approached minimum values of ~0.04 and ~0.09-0.11 for CF_3Br and C_2HF_5, respectively, which were comparable to the values obtained by the conventional cup-burner method. On the other hand, the critical agent mole fraction at extinction increased dramatically as the agent injection period decreased below the characteristic mixing (residence) time in the recirculation zone behind the obstacle. measured previously by the sodium D-line emission method. Under relatively high air velocities, the critical agent mole fraction at extinction, normalized by the minimum value, was **a** unique function of the agent injection period normalized by the characteristic mixing time, independent of types **of** fuels, agents, and obstacles. **A** theoretical expression, including the minimum agent mole fraction and the characteristic mixing time, closely followed the universal data trend.

INTRODUCTION

As Halon 1301 (bromotrifluoromethane, CF_3Br) is replaced with a possibly less effective agent, the amount of replacement agent required for fire suppression over a range of operating conditions must be determined. In the complex geometries found in aircraft engine nacelles, dry bays, shipboard compartments. ground armored vehicles, and facilities. flame stability may be a dominant factor affecting fire suppression. It has long been known that an obstruction such as a baffle plate, bluff body, or backward-facing step in a flow can enhance the stability of both premixed [1] and diffusion flames [2,3]. **A** recirculation zone behind the obstruction provides conditions favorable for flame holding, e.g., lower velocities, heat recycling to the flame stabilizing region, augmented heat transfer to condensed fuel surfaces, and enhanced mixing of fuel, air, and hot combustion products. Thus, clutter in the aircraft engine nacelle, which is ventilated to prevent the build-up of combustible vapors, can affect the behavior of fires and the performance of fire suppression agents [4-7]. The fuel sources are leaking jet-fuel and hydraulic-fluid lines that can feed the fire in the form of a spray or pool. Similar conditions may exist in **fires** in aircraft dry bays, ships. or ground vehicle engine compartments. Suppression occurs when the concentration of fire-extinguishing agent reaches a critical value in the fire zone. After the fire is extinguished, reignition may occur as the fuel-air mixture makes contact with hot metal surfaces or sparks from damaged electrical circuits.

It is not known whether conventional cup-burner or counterflow-diffusion-flame methods [8-13] can characterize the flames stabilized by an obstruction. An early study [5] concluded that the most stable type of flame to be encountered in an aircraft engine fire is a liquid surface diffusion flame from a pool of fuel burning behind an obstruction in an airflow. By using an axisymmetric baffle-stabilized spray flame and various halogenated agents, Hamins et al. [14] identified two crucial parameters: (1) a characteristic mixing time that describes the rate of agent entrainment into the recirculation zone and (2) the agent concentration at extinction for long agent injection durations.

The objective of this study is to gain a better understanding of the flame stabilization and suppression behavior of obstacle-stabilized, nonpremixed flames. In addition to the baseline extinction-limit data previously obtained for step-stabilized methane and JP-8 flames using Halon 1301 [15-18], new results including additional parameters, e.g., HFC-125 (C_2HF_5) fire-extinguishing agent and J-flange obstruction, are reported in this paper. An attempt is made to obtain a universal extinction-limit curve valid for various parameters and to extract a physical insight into underlying mechanisms common in obstacle-stabilized flames.

EXPERIMENTAL TECHNIQUES

The experimental apparatus (Figure 1) consists of the fuel, air, and agent supply systems, a horizontal small-scale combustion tunnel (154 mm square cross section, 77 cm length), and a scrubber. A liquid fuel (JP-8) pool is formed over a porous plate (150 mm square by 12.7 mm thick, stainless steel) lowered about 6.4 mm from the bottom surface of the test section downstream of an obstruction, i.e., backward-facing step (height [h_s]: 32 mm or 64 mm) or J-flange (h_s: 64 mm; downstream overhang: 38 mm length by 13 mm height with 6 mm radius corners). A liquid fuel supply and leveling system consists of a fuel tank (volume: 7.6 l), liquid fuel tubing connecting the fuel tank and the porous plate housing, and pressure tap tubing from the top of the test section to the other end emerging into the fuel tank sight glass. By adjusting the height of the tip of the pressure tap tubing in the fuel tank sight glass, the liquid level in the test section can be controlled automatically.

The airflow is regulated as it passes through honeycombs, a diffuser, mesh screens (#100), a contraction nozzle, and a turbulence generating perforated plate (33% opening, 2.4 mm diameter holes). The turbulence level in the wind tunnel is typically ~6%. The mean air velocities at the test section inlet (U_{a0}) and the step (U_{as}) are calculated by dividing the volumetric flow rate by the cross-sectional areas of the full test section and the air passage above the step, respectively. Hence, $U_{as} = [1/(1-h_s/h_T)]U_{a0}$, where h_T (0.154 m) is the total height of the test section.

The agent supply system, which is similar to that of Hamins et al. [7,9,14], consists of a (liquid) agent reservoir (3.8 liters), two connected gaseous agent storage vessels (38 liters each), and up to eight computer-controlled solenoid valves (Peter Paul Valves, Inc., 9.5 mm orifice, ~12 msec response time) that are connected in parallel. The gaseous agent was injected impulsively perpendicular to the airflow in a reduced diameter (108 mm) section through 16 by 6.4 mm diameter holes in a 25.4 mm o.d. closed-end tube ~1 m upstream of the flame. The agent storage volume, including two pressure vessels and associated plumbing, is 80.4 l. The amount of injected agent is controlled by varying the initial vessel pressure and the time period that the valve is open and is determined from the difference between the initial and final pressures in the storage vessel using the ideal-gas equation of state. The mean volumetric agent concentration is determined by

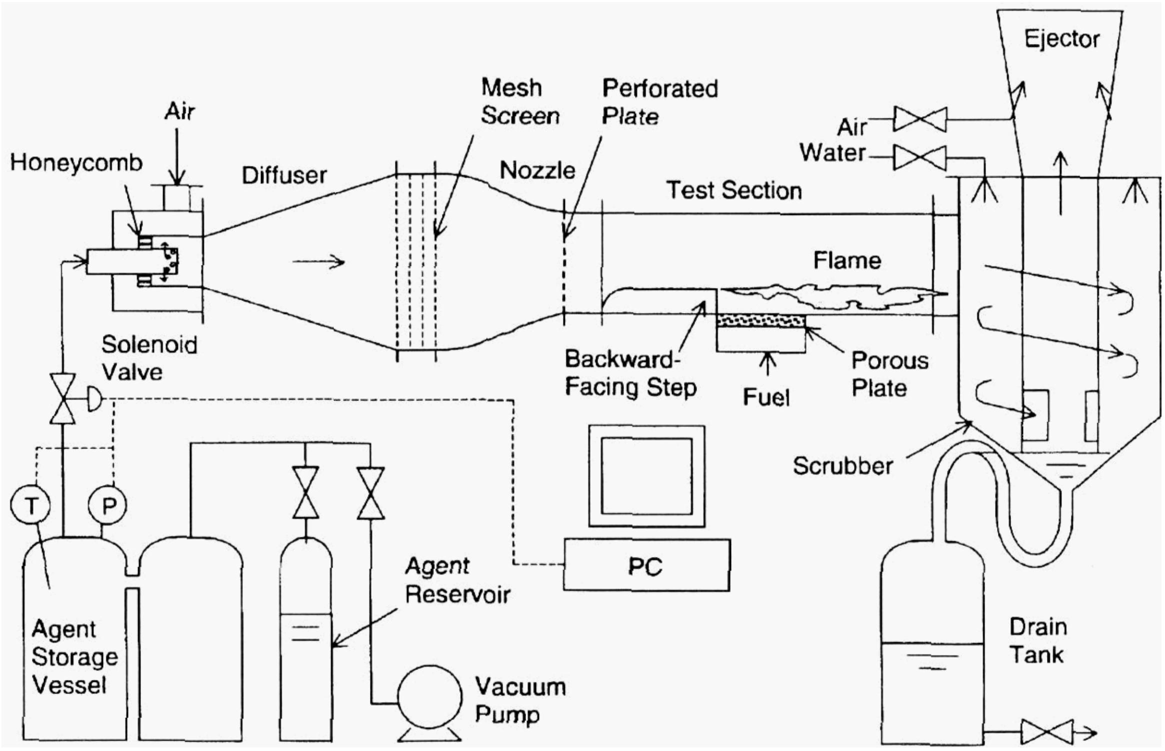


Figure 1. Experimental apparatus.

dividing the mean agent flow rate ([volume]/[injection period]) by the total flow rate. **A** unique scrubber is used to remove acidic gases (HF) by water sprays, and an air-driven ejector is used to reduce the backpressure and adjust the pressure of the test section equal to atmospheric.

To measure the extinction limit, a stable flame is established for **a** fixed air velocity; the agent is then injected for **a** particular storage vessel pressure and an injection period. The agent injection test is repeated 20 times to determine the probability of extinction. Then either the storage vessel pressure or injection period is varied step-wise and the experiment is repeated. The extinction condition is confirmed at a probability of 90% chosen arbitrarily.

The characteristic mixing time in the recirculation zone was measured by the sodium D-line emission method [16,18,19]. **A** fine-mist spray of a saturated NaCl-aqueous solution is injected impulsively (~1 sec) into the air supply plenum before a honeycomb flow straightener using an artist's airbrush. The emission of sodium D-line (589 nm) by flame reactions in the high-temperature recirculation zone saturates at a maximum value during the pulsed injection period and then decays. The first-order differential equation for the mole fraction of species (X) in the recirculation zone is

$$X = \tau(dX/dt) \quad (1)$$

where t is the elapsed time and τ is the characteristic mixing time. The solution for the equation describing decay in response to a falling step function ($X_0 \rightarrow 0$) is

$$(X/X_0) = exp(-t/\tau) \tag{2}$$

where X_0 is the initial mole fraction of the seed species. By assuming that the measured sodium emission intensity is proportional to the concentration of the seed species. the mean characteristic mixing (or residence) time (τ_{exp}) in the recirculation zone is determined by averaging the values over ~20 repetitions.

RESULTS AND DISCUSSION

Figure 2 shows the critical agent mole fraction at extinction (X_c) as a function of the agent injection period (Δt) for JP-8 pool flames. The varied experimental parameters include the agent type (Halon 1301 and HFC-125), obstacle shape (step and J-flange), step height, and mean initial air velocity. In general, as Δt was increased for a given U_{a0}, X_c decreased monotonically and approached a minimum value (X_∞) below which no extinction occurred even at long injection periods; $X_\infty = 0.04$ and 0.087 for Halon 1301 and HFC-125, respectively, for all cases except for a J-flange at $U_{a0} = 2.9$ m/sec, for which $X_\infty = 0.11$. These minimum agent mole fractions were comparable to the values for heptane and JP-8 fuel (~0.03-0.035 and ~0.086 for Halon 1301 and HFC-125, respectively) obtained using conventional steady-state cup-burner and counterflow-diffusion-flame methods at relatively low strain rates (25-50 sec^{-1}) [8-13]. The trend of the higher minimum value for HFC-125 at a lower air velocity was also observed by Hamins et al. [14] for an axisymmetric 35 mm diameter. baffle-stabilized JP-8 spray flame ($X_\infty = 0.078$ and 0.10 at the air velocities of 7.5 and 3.0 m/sec, respectively). On the other hand, as the agent injection period was decreased, there was a minimum injection period below which the flame could not be extinguished even at high agent concentrations.

Based on a phenomenological model for a well-stirred reactor developed by Longwell et al. [20], Hamins et al. [14] developed a mixing model that characterizes the rate of agent entrainment into the recirculation zone. It is assumed that extinction of the flame occurs when the agent mole fraction in the recirculation zone reaches a critical value (X_∞) and that complete mixing of the agent in the recirculation zone is instantaneous. By using the first-order differential equation describing mixing in a well-stirred reactor. which is identical to Equation 1, the critical agent mole fraction in the free stream (X_c) at extinction is related to the critical agent mole fraction in the free stream for long injection periods (X_∞).

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

Hence, τ is the Characteristic mixing time for entrainment into the recirculation zone. For a long injection period, Equation 3 becomes $X_c \approx X_\infty$. For a short injection period, large free stream, agent concentrations are required to obtain extinction.

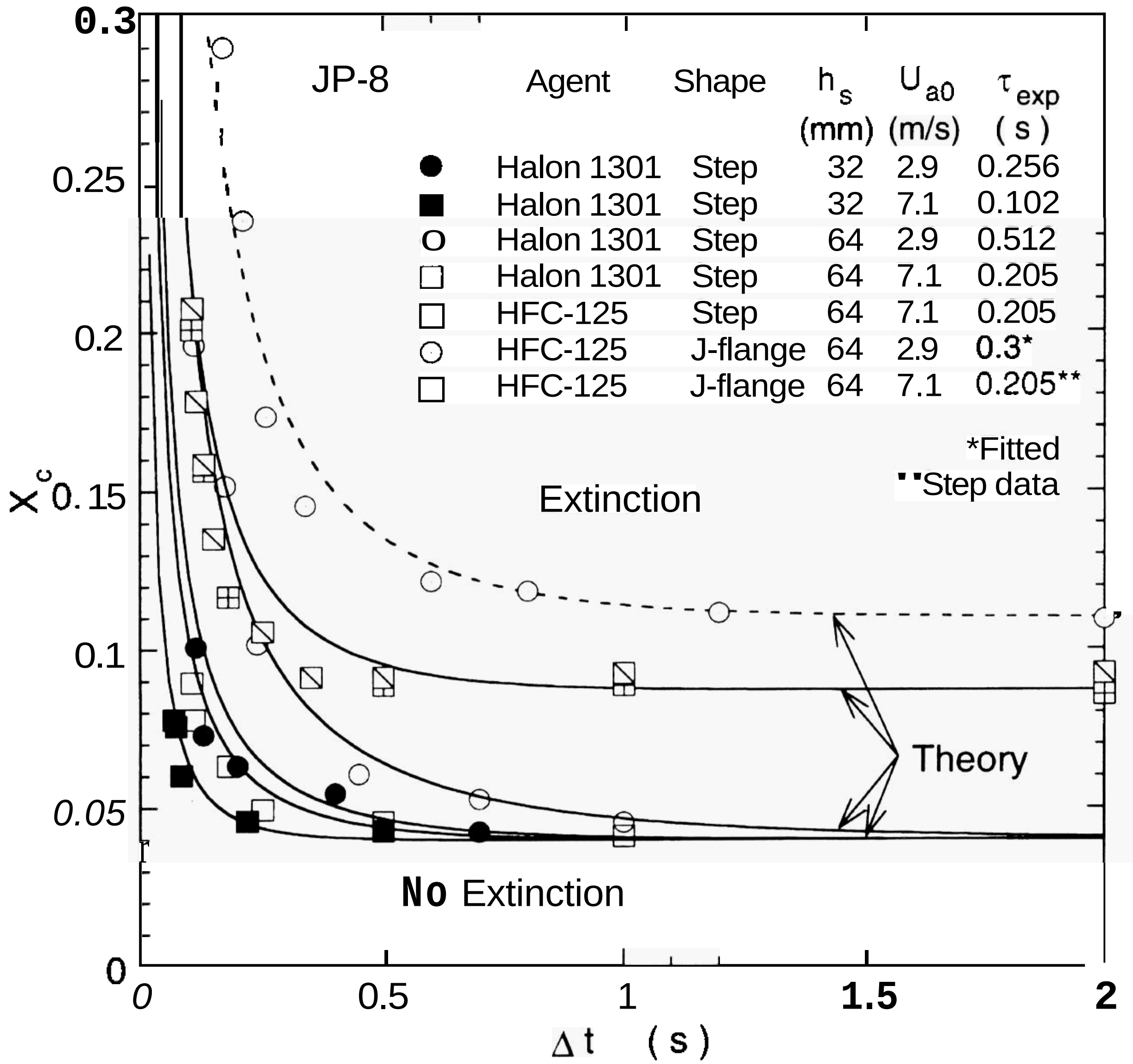
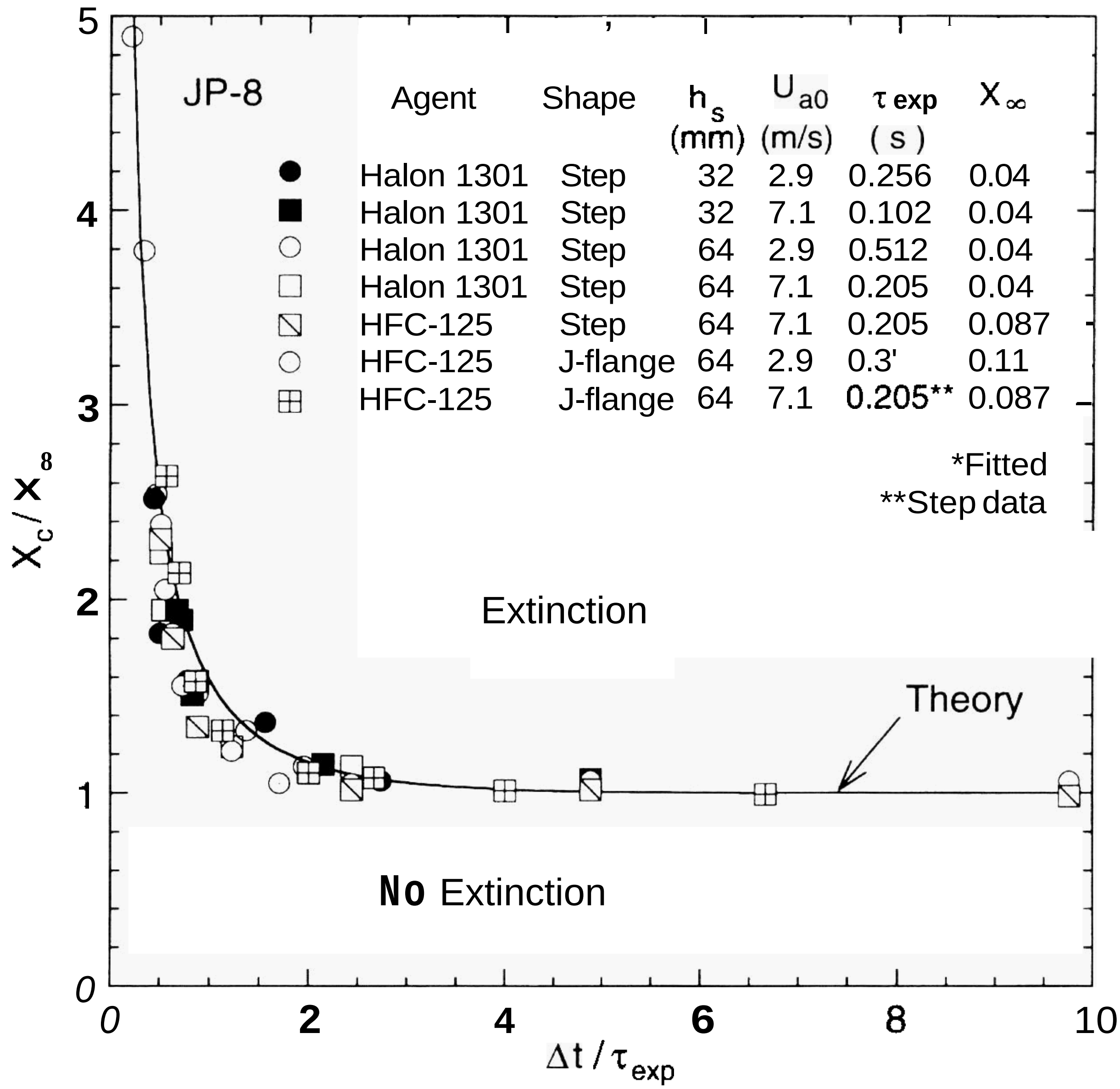


Figure 2. Measured critical agent mole fraction at extinction and theoretical curves as **a** function of the agent injection period.

Figure 2 also shows the theoretical extinction-limit curves using Equation ***3*** with X_∞ described above and the characteristic mixing time (τ_{exp} = 22.79 $[h_s/U_{a0}]$) determined previously [16,181 for the hackward-facing steps. The theoretical curves followed the data points fairly well and showed the general trend of the experimental results **very** well. Therefore, the data points in Figure 2 are replotted in Figure **3** in a nondimensional form: the critical agent mole fraction at extinction normalized by the minimum value (X_c/X_∞) vs. the agent injection period normalized by the characteristic mixing time in the recirculation zone ($\Delta t/\tau_{exp}$) with a theoretical curve by Equation ***3*.**



Figurc 3. Measured critical agent mole fraction at extinction normalized by the minimum value at long injection periods and theoretical curves as a function of the agent injection period normalized by the characteristic mixing time.

The data points for different agents, obstacles. step heights, and mean initial air velocities nearly collapsed into a single curve, thus supporting the physical processes described hy Equation 3. The similar results were also obtained for step-stabilized methane flames for various step heights and air velocities [16,18]. The nondimensional representation of the results revealed that the critical agent mole fraction at extinction dramatically increased as the agent injection period decreased below the characteristic mixing time ($\Delta t < \tau_{exp}$). Because the minimum agent mole fraction can be approximated by the value obtained hy the conventional steady-state methods and the characteristic mixing time is correlated to the experimental conditions (the step height and mean initial air velocity), the extinction limit of obstacle-stabilized flames can be predicted theoretically. The current results of the obstruction effects on suppression obtained for a simple geometry revealed an underlying physical process, thus serving as a building block for founding a basis for flame suppression mechanisms in more complex clutter configurations.

CONCLUSIONS

The extinction limits of JP-8 pool flames stabilized by a backward-facing step or J-flange in an airstream were measured as the critical agent mole fraction at extinction by varying the unsteady injection period of a gaseous fire-extinguishing agent (Halon 1301 or HFC-125) for various air velocities and step heights. The measured extinction-limit data points collapsed into a single curve, when plotting the critical agent mole fraction at extinction normalized by its minimum value obtained at long injection periods as a function of the agent injection period normalized by the measured characteristic mixing (residence) time. The data trend can be predicted by a theoretical expression using the minimum agent mole fraction and the measured characteristic mixing time. The effect of obstruction on the extinction limits is significant only when the agent injection period is less than the characteristic mixing time.

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