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F. Takahashi and W. J. Schmoll
University of Dayton
Dayton, OH

V. M. Belovich
Air Force Research Laboratory
Wright-Patterson Air Force Base, OH

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SUPPRESSION OF BLUFF-BODY STABILIZED DIFFUSION FLAMES

Fumiaki Takahashi* and W. John Schmoll†
University of Dayton Research Institute
300 College Park, Dayton, Ohio 45469

Vincent M. Belovich‡
Air Force Research Laboratory
Wright-Patterson Air Force Base, Ohio 45433

ABSTRACT

The stabilization and suppression of a nonpremixed flame formed behind a backward-facing step in a small wind tunnel have been studies by impulsively injecting a gaseous fire-extinguishing agent (bromotrifluoromethane) into the airflow. Methane issued from a porous plate downstream of the step to simulate a pool fire in the aircraft engine nacelle. As the mean air velocity was increased, two distinct flame stabilization and suppression regimes were observed: rim-attached wrinkled laminar flame and wake-stabilized turbulent flame. In both regimes, as the agent injection period was increased at a fixed mean air velocity, the critical agent mole fraction at suppression decreased. In the rim-attached flame regime, the total agent mass at suppression was nearly constant at a fixed air velocity nearly independent of the agent mole fraction, injection period and step height. In the wake-stabilized flame regime, the turbulent mixing process of the agent into the recirculation zone behind the step essentially determined the critical agent mole fraction dependence on the injection period. The total agent mass required for suppression increased with the mean air velocity and then leveled off to a level proportional to the step height as the transition from the rim-attached to wake-stabilized flame regime occurred.

INTRODUCTION

Fires in the aircraft engine nacelle, which encases the engine compressor, combustors and turbine, can be stabilized by a recirculation zone formed behind a clutter (tubes and boxes, etc.) under over-ventilated conditions [1-7, 9, 10]. The fuel sources are leaking jet-fuel and hydraulic-fluid lines that can feed the fire in the form of a spray, puddle, or pool. Similar conditions may exist in fires in aircraft dry bays, ships, or land combat vehicle engine compartments. Suppression occurs when a critical concentration of agent is transported to the fire. After the fire is extinguished, re-ignition may occur as the fuel-air mixture makes contact with hot metal surfaces or sparks from damaged electrical circuits.

Because of its superior effectiveness, halon 1301 (bromotrifluoromethane, CF_3Br) has been used as a fire-extinguishing agent to protect aircraft engine nacelles and other compartments. As halon 1301 is replaced with a possibly less effective agent, the amount of replacement agent required for suppression over a range of operating conditions must be determined. Hence, it is not clearly known whether or not the flame extinguishing data [7, 12-14] using conventional methods such as a cup burner can effectively characterize bluff-body stabilized flames.

The broad objectives of this study are as follows:

(1) Determine difficult-to-extinguish cases by a parametric investigation using combinations of given geometric elements and experimental conditions. The parameters to be considered are (a) clutter configuration (backward-facing step, buffle plate, J-flange, cavity, and blockage ratio), (b) fuel and injection characteristics (fuel type: methane and JP-8; spray or pool), (c) air flow characteristics (velocity and temperature), (d) hot surface (roughness and temperature), and (e) suppression agents (agent type: CF_3Br, CF_3I, C_2HF_5 [HFC-125], C_3HF_7 [HFC-227ea]; temperature, supply vessel pressure and injection period).

(2) Gain a better understanding of the fundamental mechanisms of flame stabilization and identify the critical parameters that are important to suppressing bluff-body stabilized flames.

(3) Develop a phenomenological model that can be integrated into computational fluid dynamics models

* Research Engineer, Research Institute, Senior Member AIAA
† Associate Research Physicist, Research Institute
‡ Mechanical Engineer, Propulsion Sciences and Advanced Concept Division, Member AIAA

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for predicting bluff-body stabilized fires and their suppression.

In this paper, the initial experimental results are reported on the extinction limits of a methane flame stabilized behind a backward-facing step using halon 1301 as the baseline suppression agent.

EXPERIMENTAL TECHNIQUES

Figure 1 shows a schematic of the experimental apparatus for the model-fire suppression study. The apparatus consists of the fuel, air, and agent supply systems, a horizontal small-scale wind tunnel, and a combustion product scrubber. Methane issues upward at a mean velocity of 0.7 cm/s (flow rate: 10 l/min) from a porous plate (150 × 150 × 12.7-mm thickness, stainless steel) placed downstream of a backward-facing step (height [h_s]: 32 mm or 64 mm) in the test section (154 × 154-mm^2 cross-section, 77-cm length). The airflow is regulated by passing through honeycombs, a diffuser, mesh screens (#100), a contraction nozzle, and a turbulence generating perforated plate (33% opening, 2.4 mm-dia. 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.

The agent supply system, which is similar to that of Hamins et al. [7, 9], consists of a (liquid) agent reservoir (3.8 l), two connected gaseous agent storage vessels (38 l each), and a computer-controlled solenoid valve. The gaseous agent was injected impulsively into the air ~1 m upstream of the flame. Uniform agent dispersion into the airstream was achieved by injecting the agent radially into a reduced diameter (108 mm) section of the air passage through 16 6.4-mm-dia. holes in a 25.4-mm-o.d. closed-end tube. The mesh screens and a perforated plate downstream ensure complete agent-air mixing prior to entering the flame zone. The storage volume, including two pressure vessels and associated plumbing, is 79.9 l. The agent temperature and pressure in the second storage vessel are measured with a type-T thermocouple and a pressure transducer. The amount of injected agent is controlled by varying the initial pressure and the time period that the valve is open and 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 dividing the mean agent flow rate ([volume]/[injection period]) by the airflow rate.

The cyclone-type scrubber is attached to the exit of the test section to remove acidic gases (HF) by water sprays from eight pressure-swirl atomizers on the top plate. The gases are exhausted through the central tube and the water is collected in a drain tank. An air-driven ejector is attached to the scrubber exit to reduce the backpressure and adjust the pressure of the test section to atmospheric.

The extinction limit experiment is conducted as follows. First, a stable flame is established for a fixed mean airflow velocity, and then the agent is injected for a particular storage vessel pressure and an injection period. The agent injection test is repeated 20 times to

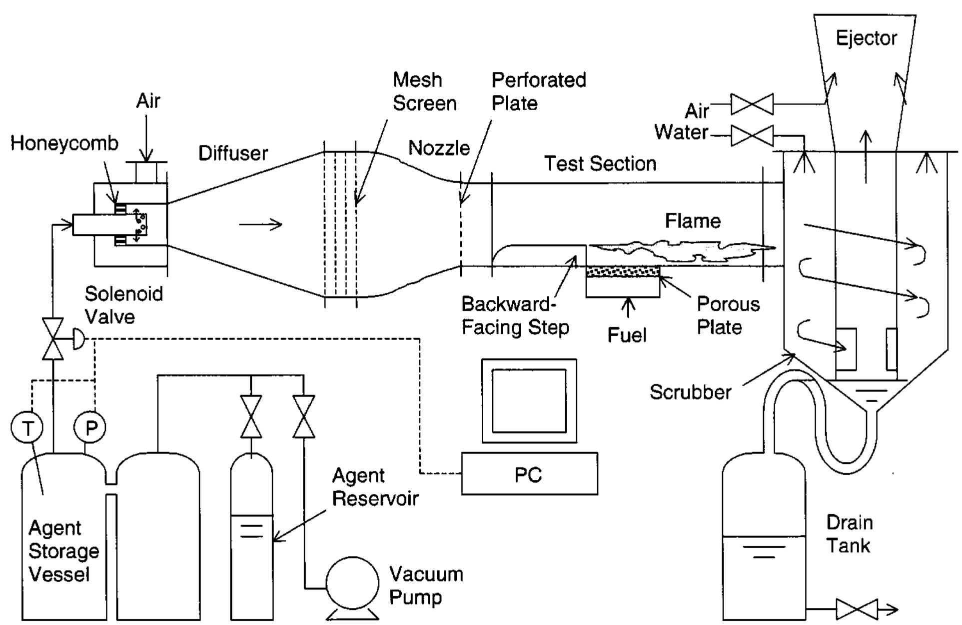

Fig. 1 Experimental apparatus.

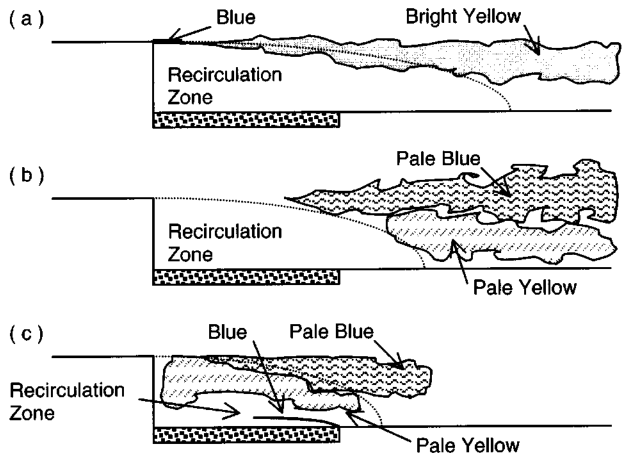

Fig. 2 Flame stabilization and suppression regimes. (a) Rim-attached wrinkled laminar flame at low air velocities, (b) transition flame, and (c) wake-stabilized turbulent flame at high air velocities.

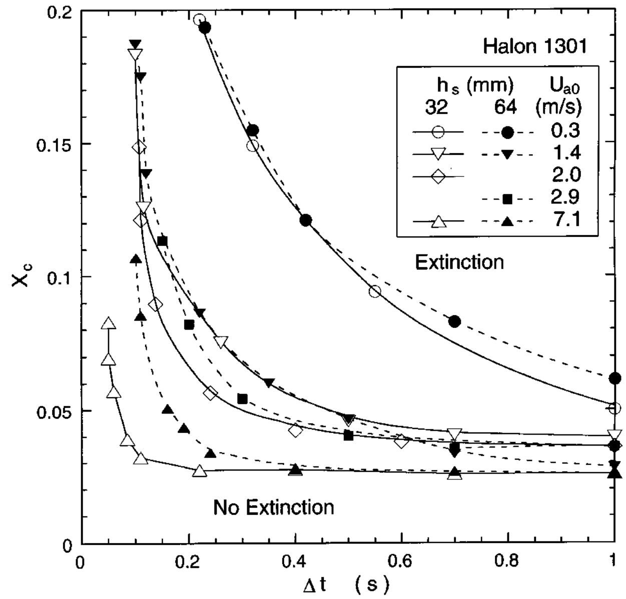

Fig. 3 The critical agent mole fraction at suppression as a function of agent injection period.

determine the probability of extinction. Then either the storage vessel pressure or injection period is varied step-wise and repeat the experiment. The extinction condition is confirmed at a probability of 90% chosen arbitrary.

RESULTS AND DISCUSSION

Figure 2 shows a schematic of the step-stabilized nonpremixed flames. Two distinct flame stabilization regimes were observed: rim-attached and wake. At low mean air velocities (U_{as} < approximately 3 m/s), a wrinkled laminar diffusion flame attached to the edges of the backward-facing step. There existed a short (~2 cm) blue flame zone, with a dark space (~1 mm) between the flame base and the rim, and a trailing long (~50 cm) bright-yellow flame, typical of hydrocarbon diffusion flames. On the other hand, at high mean air velocities (U_{as} > approximately 8 m/s for h_s = 64 mm or immediately after detachment at 3.3 m/s for h_s = 32 mm), a turbulent blue flame was stabilized approximately 1 cm downstream of the rim and yellowish flame zones were sporadically formed in the wake of the step. The flow in the wake appeared to be three-dimensional with a main recirculation zone in the central region of the wind tunnel, outward reverse flows near the side windows, and a small corner vortex in the inner corner of the step. At moderate mean air velocities between these two flame stabilization regimes, a highly unstationary transitional flame was observed for h_s = 64 mm with the flame base moving back and forth (5-15 cm from the step).

Figure 3 shows the critical agent mole fraction at suppression (X_c) as a function of agent injection period (Δt) at different mean air velocities for two different step heights. As Δt was increased for a given U_{a0}, X_c decreased monotonically. The extinction of diffusion flames is generally explained [15] by a critical Damköhler number (Da = τ_r/τ_c, τ_c: the chemical time and τ_r: the flow or diffusion time) below which extinction occurs. Increasing the agent concentration or injection period induces chemical inhibition (and heat losses), thus increases the chemical time, and decreases Da. On the other hand, increasing the air velocity decreases the flow time and, in turn, Da. Therefore, as these parameters were increased, the no-extinction region narrowed.

For a low U_{a0}, large X_c and Δt were required to suppress the flame. In fact, for U_{a0} = 0.3 m/s, the extinction limit curve exceeded the design condition for the current halon fire-extinguishing system in the engine nacelle, which requires to achieve 6% agent concentration everywhere for at least 0.5 s. At this air velocity, the extinction limit curves for two different step heights were nearly coincident. For higher air velocities, the minimum agent mole fraction below which no extinction occur even at long injection periods: for U_{a0} = 7.1 m/s, X_c =.0.025 for both step heights. This agent concentration threshold is roughly consistent with the minimum agent concentration of ~3 % obtained using a cup burner and counterflow diffusion flames at a low strain rate (50 s^{-1}) [7, 8]. Furthermore, there existed a minimum injection period, below which the flame could not be extinguished even at high agent concentrations: $\Delta t \approx$ 0.05 s for h_s = 32 mm and $\Delta t \approx$ 0.1 s for h_s = 64 mm.

Hamins et al [10] explained the extinction-limit curves for baffle-stabilized spray flames in terms of a phenomenological model for a well-stirred reactor developed by Longwell et al. [16]. It was assumed that the flame was stabilized in the recirculation zone downstream of the baffle. To extinguish the flame, the agent mole fraction in the recirculation zone had to obtain a critical value (X_∞). Complete mixing of the agent in the recirculation zone was instantaneous. By using the first-order differential equation describing mixing in a well-stirred reactor, the critical agent mole fraction in the free stream ($X_c[\Delta t]$) at extinction was related to the critical agent mole fraction in the free stream for long injection periods ($X_c[\Delta t >> \tau]$ or X_∞).

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

where τ is the characteristic mixing time for entrainment into the recirculation zone. For long injection period, $X_c \approx X_\infty$. For short injection period, large free stream agent concentrations are required to obtain extinction. A critical injection period (Δt_c) below which a flame cannot be extinguished regardless of agent concentration was further derived for $X_c = 1$.

$$\Delta t = -\tau \ln(1 - X_\infty) \qquad (2)$$

Figure 4 shows the extinction limits for $U_{a0} = 7.1$ m/s for two different step heights and theoretical curves using Eq. (1) with $X_\infty = 0.025$ for three different values of τ. The theoretical curves showed a general trend obtained experimentally; the curves for $\tau = 0.1$ and 0.2 generally follow the data points for $h_s = 32$ mm and 64 mm, respectively. For these conditions, Eq. (2) yields the critical injection period of 2.5 ms and 5 ms, respectively, for these step heights. However, the data points in Fig. 4 tend to deviate from the theoretical curves at high X_c values, suggesting that the critical values may be much higher than those calculated.

The factor-of-two increase in τ and h_s suggests that the characteristic mixing time is proportional to the step height or more generally h_s/U_{a0} as similar to the case for axisymmetric baffle plates [10]. Therefore, the data points in Fig. 4 are re-plotted in Fig 5, in which the abscissa is the non-dimensional agent injection period. The data points for two different step heights nearly corrupted into a single curve, showing the trend of $\tau \propto h_s/U_{a0}$. A parametric study of the characteristic mixing time is desirable to reveal the effects of blockage ratio as well as the step height and air velocity.

From a practical point of view, the total amount of agent delivered under a given air flow rate condition is important. Figure 6 shows a re-plot of the data, presented in Fig. 3, in which the total agent mass required to extinguish the flame (m_{total}) is plotted as a function of the critical agent mole fraction. For low mean air velocities (U_{a0} = 0.3 and 1.4 m/s), the total agent mass was nearly constant independent of the agent mole fraction, injection period, and step height. Under these low air velocity conditions, the flame drifted downstream of the

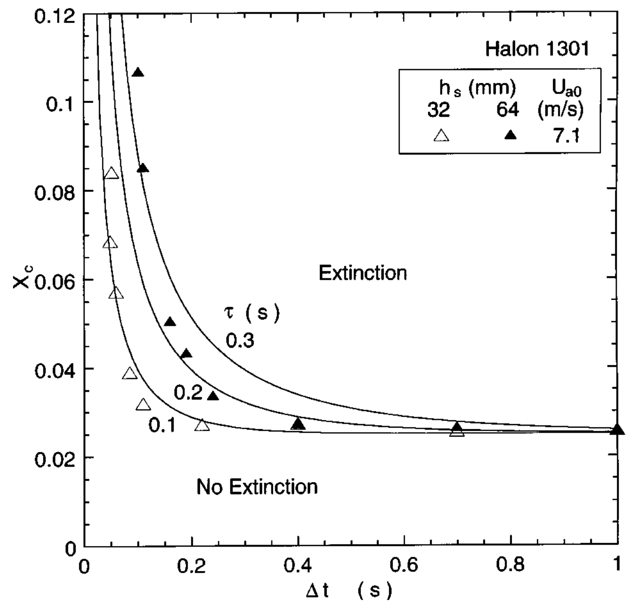

Fig. 4 The critical agent mole fraction at suppression as a function of agent injection period for a high air velocity with theoretical fitting curves for different characteristic mixing times.

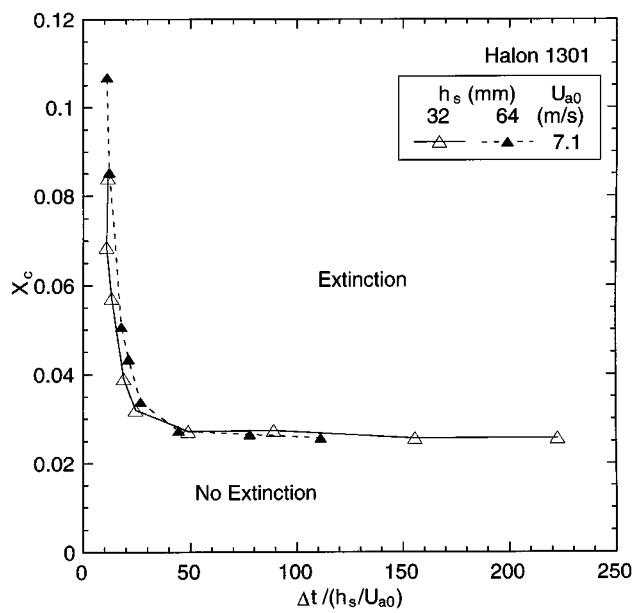

Fig. 5 The critical agent mole fraction at suppression as a function of non-dimensional agent injection period for a high air velocity

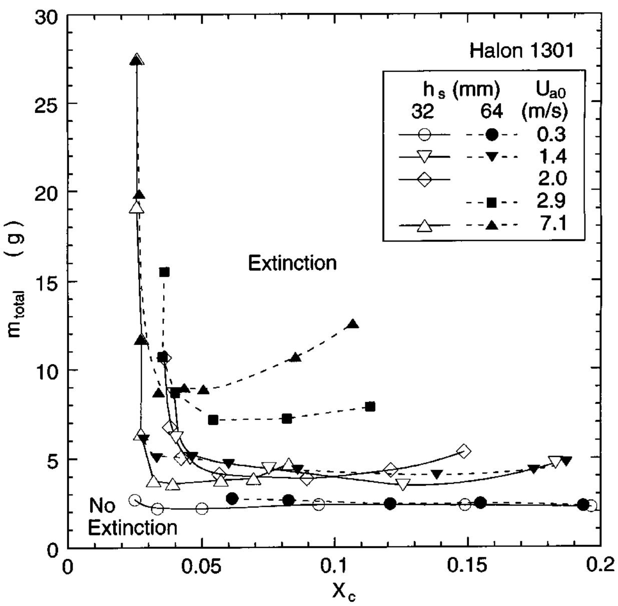

Fig. 6 The total agent mass at suppression as a function of the critical agent mole fraction.

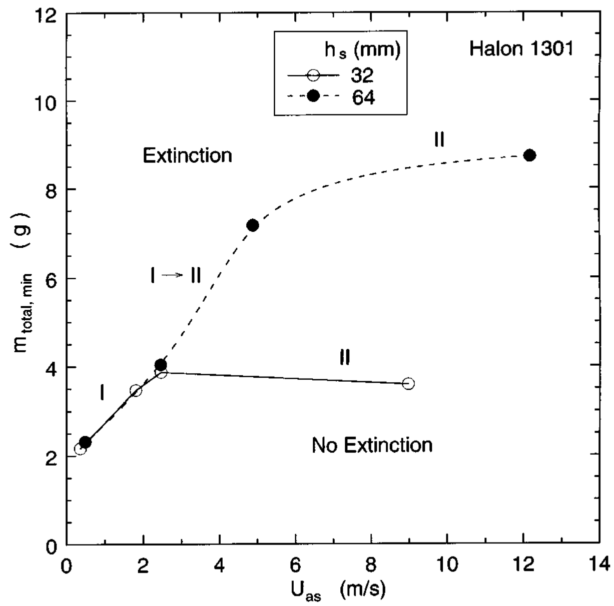

Fig. 7 The minimum total agent mass at suppression as a function of mean air velocity at the step with corresponding flame stabilization and suppression regimes.

recirculation zone as the agent was delivered and simply blew off or propagated along the lower part of the test section back to the step after the wave of high agent concentration passed. Competing processes of fuel-air mixing to promote partially premixed flame propagation and inhibition by the agent determined the extinction limit. Thus, the effect of the step height is relatively small. By contrast, for high mean air velocities, the turbulent mixing in the recirculation zone controls the extinction limit as described earlier. A larger step possessing a larger recirculation zone volume requires a larger agent mass to achieve the same agent concentration.

Figure 7 shows the minimum total agent mass ($m_{\text{total, min}}$), determined from Fig. 6, plotted against the mean air velocity at the step. Here, U_{as} was used because the flame detachment process was controlled by the local velocity rather than the global U_{a0}. As U_{as} was increased, $m_{\text{total, min}}$ increased proportionally and then leveled off. For h_s = 32 mm and 64 mm, the flame detached from the step at U_{as} = 3.3 m/s and 2.7 m/s, respectively, and the transition from regime I to II occurs (see Fig. 2). For regime I, the $m_{\text{total, min}}$ curves for two different h_s were identical, and for regime II, $m_{\text{total, min}}$ became nearly constant with its value nearly twice for h_s = 64 mm compared to that for 32 mm. Therefore, the agent mass require for suppression is roughly proportional to the step height.

CONCLUSIONS

The extinction limits of nonpremixed methane flames stabilized by a backward-facing step in an airstream were reported using a gaseous suppressant (halon 1301). Two distinct regimes of flame stabilization and, in turn, suppression mechanisms were observed: (I) rim-attached wrinkled laminar flame and (II) wake-stabilized turbulent flame. In general, as the agent injection period was increased, the critical agent mole fraction at extinction decreased. In regime I, the total agent mass at extinction was nearly constant at a given mean air velocity, independent of the agent concentration and injection period. In regime II, the turbulent mixing process in the recirculation zone dictated the extinction limit. The minimum total agent mass at extinction increased linearly with the air velocity independent of the step height in regime I and level off in regime II to a level roughly proportional to the step height.

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