# Extinction of Nonpremixed Flames with Halogenated Fire Suppressants

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An experimental, analytical, and numerical study was performed to elucidate the influence of eleven gaseous agents, considered to be substitutes for $CF_3Br$, on the structure and critical conditions of extinction of diffusion flames burning liquid hydrocarbon fuels. The effectiveness of these agents in quenching flames was compared to those of $CF_3Br$ and an inert diluent such as nitrogen. Experiments were performed on diffusion flames stabilized in the counterflowing as well as in the coflowing configuration. The fuels tested were heptane in the counterflowing configuration, and heptane, the jet fuels JP-8, and JP-5, and hydraulic fluids (military specifications 5606 and 83282) in the coflowing configuration. The oxidizing gas was a mixture of air and the agent. On a mass and mole basis $CF_3Br$ was found to be most effective in quenching the flames and the mass-based effectiveness of the other eleven agents was found to be nearly the same as that of nitrogen. Experimental results were interpreted using one-step, activation-energy asymptotic theories and the results were used to provide a rough indication of the thermal and chemical influence of these agents on the flame structure. To understand in some detail the influence of $CF_3Br$ on the structure and mechanisms of extinction of the flame, numerical calculations using detailed chemistry were performed. The calculated structure of counterflow heptane–air diffusion flames inhibited with $CF_3Br$ was found to consist of three distinct zones including a $CF_3Br$ consumption zone which appears to act as a sink for radicals. The calculated values of the critical conditions of extinction of counterflow heptane–air diffusion flames inhibited with $CF_3Br$ were found to agree fairly well with measurements. The study suggests the need for refinement of the inhibition chemistry.

## INTRODUCTION

Recent international agreements have called for restrictions on the production of bromotrifluoromethane ($CF_3Br$), a commonly used fire suppressant, due to its high potential for depleting the ozone in the stratosphere. The search for a suitable agent to replace $CF_3Br$ (Halon 1301) for in-flight fire protection by the U.S. Air Force identified eleven gaseous agents, and they are $CF_3CH_2CF_3$ (HFC-236), $CHFClCF_3$ (HCFC-124), $CHF_2CF_3$ (HFC-125), $C_3HF_7$ (HFC-227), $C_3F_8$ (FC-218), $CHF_2Cl$

(HCFC-22), $CH_2FCF_3$ (HFC-134a), $C_4F_{10}$ (FC-31-10), $CH_2F_2/CHF_2CF_3$ (60%/40% by volume) (HFC-32/HFC-125), cyclo-$C_4F_8$ (FC-318) and $C_2F_6$ (FC-116). To determine the effectiveness of these agents in quenching flames in comparison to the effectiveness of $CF_3Br$ and an inert diluent such as nitrogen, experiments were performed on laminar diffusion flames stabilized in the counterflowing as well as in the coflowing configuration. The fuel tested in the experiments performed in the counterflowing configuration was heptane and the fuels tested in the coflowing configuration were heptane, the jet fuels JP-8, and JP-5, and hydraulic fluids (military specifications 5606 and 83282). The oxidizing gas was a mixture of air and the agent. Experimental results were interpreted using one-step, activation-energy

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asymptotic theories. Although this is a poor approximation for the chemistry occurring in the reaction zone, it provides a rough indication of the thermal and chemical influence of these agents on the flame structure. To understand in some detail the influence of $CF_3Br$ on the structure and mechanisms of extinction of the flame, numerical calculations using detailed chemistry were performed and the resutls were compared with the measurements.

An excellent review of the literature relevant to chemical inhibition of flames has been recently completed by Pitts et al. [1]. The use of Halon 1301 in extinguishing fires has also been reviewed previously [2]. Counterflowing [3, 4] and coflowing [2, 5, 6] configurations have been used previously for studying the structure and mechanisms of extinction of diffusion flames. In the counterflowing configuration the diffusion flame is stablized in the stagnation point boundary layer formed by directing an oxidizing gas stream downward onto the surface of a liquid fuel. In the counterflowing configuration, at a given value of the strain rate $a$, which is inversely proportional to the characteristic residence time $\tau_f$, flame extinction is defined to occur when the concentration of the agent added to the oxidizer stream is high enough to cause the flame to abruptly extinguish. In the coflowing configuration the liquid fuel is fed to a cup and the oxidizer flows in the same direction concentric to the flow of the liquid. The flame is stabilized in the shear layer formed between the coflowing streams of the oxidizer and the gaseous fuel vaporized from the surface of the liquid. Test burners employing this coflowing configuration are referred to as the "cup burner" [2–4]. In the coflowing configuration flame extinction is defined to occur when the concentration of the agent added to the oxidizer stream is high enough to lift the flame off the surface of the liquid pool and blow it downstream away from the fuel cup.

Westbrook [7] has developed a detailed chemical-kinetic mechanism for describing the structure of premixed flames of hydrogen, methane, methanol and ethylene inhibited by $CF_3Br$. The predictions of this mechanism were found to agree fairly well with measurements [7]. This mechanism is used here to clarify the inhibiting effects of $CF_3Br$ on counterflow heptane–air flames. Although the mechanism proposed by Westbrook [7] was tested on flames burning fuels other than heptane, it is reasonable to use this mechanism here because $CF_3Br$ reacts primarily with the radicals and the consumption of $CF_3Br$ and heptane occur in different regions of the flame. The results of these calculations were compared with measurements of critical conditions of extinction. This part of the study was motivated by previous successful numerical investigations of the structure of uninhibited counterflow heptane–air diffusion flames using detailed chemistry [8, 9].

## DESCRIPTION OF THE EXPERIMENTAL APPARATUS

The counterflow burner used here is described in detail elsewhere [10]. It consists of a fuel-container that has a diameter of 50 mm and a depth of 18 mm, and an oxidizer duct with an inner diameter of 50.1 mm through which the oxidizing stream containing the gaseous agent to be tested is introduced into the flame. Experiments were performed with $L = 1$ cm, where $L$ is the separation distance between the surface of the liquid pool and the exit of the oxidizer duct. The cup burner employed here is essentially similar to that used by Booth et al. [5]. It consists of a fuel cup which has a diameter of 28 mm with a 45 degree ground edge. The fuel cup is located inside a Pyrex chimney which has an inner diameter of 9.6 cm and is 45 cm long. The surface of the liquid fuel in the cup was 25 cm below the top of the chimney. In the counterflow and cup burner studies the level of the liquid fuel in the cup was accurately controlled by a device similar to that designed by Bajpai [6]. The flowrates of air, nitrogen and the gaseous agent were measured by use of variable area flowmeters and the accuracy of the measurements are estimated to be around $\pm 3\%$. Experiments were performed in the counterflow and coflowing configurations at a value of pressure $p = 1$ atm, with the initial temperature of the oxidizer stream $T_x = 25°C$.

For experiments performed in the counterflow configuration the flowrate of air in the

oxidizer duct was maintained at some predetermined value and the liquid pool was ignited. The agent was then added gradually to the oxidizer stream until the flame was extinguished. The flowrates of air and the agent at extinction were recorded. The experiments were repeated for a different value of the flowrate of air. The velocity of the oxidizer stream at the exit of the oxidizer duct $U$ was presumed to be equal to the ratio of the total flow rate to the cross-sectional area of the duct. The characteristic strain rate at extinction was calculated using the expression $a = 2U/L$ [11]. In the coflowing configuration measurements were made with the flowrates of the oxidizer stream in excess of 20 l/min. The agent was added gradually to the oxidizer stream until the flame was observed to blowoff from the surface of the fuel cup. More details of the apparatus and the experimental procedure are given elsewhere [12].

## FORMULATION OF THE NUMERICAL PROBLEM

The governing equations, the boundary conditions, and the interface balance conditions for flames stabilized in the counterflow configuration over the surface of a liquid fuel are described elsewhere [8,9]. The chemical–kinetic mechanism and the rates of the elementary reactions describing the oxidation of heptane are the same as that used previously [8,9]. The elementary reactions involving $CF_3Br$ and its decomposition products are shown in Table II of Ref. 7. For simplicity the elementary reactions involving $C_2$ species, and $H_2O_2$ were omitted. The chemical kinetic mechanism now contains 82 reactions involving 35 species. Calculations are performed in an axisymmetrical configuration. The boundary conditions at the exit of the oxidizer duct and the interface balance conditions at the surface of the liquid pool were described in Ref. 9. At the surface of the liquid pool, the tangential component the gas velocity and the flux of all species except that of the fuel are set equal to zero. The flux of the gaseous fuel evaporating from the liquid fuel surface is presumed to be equal to the mass burning rate, and the heat flux into the liquid pool is presumed to be equal to the product of the mass burning rate and the heat of vaporization. The mass burning rate is unknown and is determined as part of the solution. The surface temperature of the liquid fuel $T_s$, was calculated using the Clausius–Clapeyron equation for liquid-vapor equilibrium. At the exit of the oxidizer duct the mass flow rate, the temperature of the oxidizer stream, and the mass fraction of $N_2$, $O_2$, and $CF_3Br$ are specified. If the outer flow is strictly irrotational then the strain rate $a$, defined as the axial gradient of the axial component of the flow velocity must also be specified. Alternatively, if the value of the tangential component of the flow velocity at the exit of the oxidizer duct is presumed to be zero then the outer flow is rotational, and the strain rate varies along the axis. Previous studies have shown that the outer flow-fields encountered in the experiments are neither strictly rotational nor irrotational [9,13]. For simplicity, the calculations were performed presuming that the outer flow is irrotational. All calculations were performed for $p = 1$ atm and $T_\infty = 298$ K. The heat of vaporization was set equal to 361 J/g which corresponds to the normal boiling point of heptane, and its variation with surface temperature was neglected.

## EXPERIMENTAL RESULTS OF FLAME EXTINCTION

### Counterflow Results

Figure 1 shows the mass fraction of the agents at extinction as a function of the characteristic strain rate $a$. For a given agent, the region below the curve represents flammable mixtures. In this configuration it was not possible to stabilize a steady flame for values of $a$ approximately below 40 s$^{-1}$. The results show that at any given value of $a$, the value of the mass fraction of $CF_3Br$ required to extinguish the flame is lower than the mass fraction of all the other agents. Therefore on a mass basis $CF_3Br$ is considerably more effective in extinguishing the flame than all the other agents tested even though it contains a heavy bromine atom. Comparison of the relative mass-based effectiveness of all the agents except $CF_3Br$ shows that at low strain rates HFC-236 is most
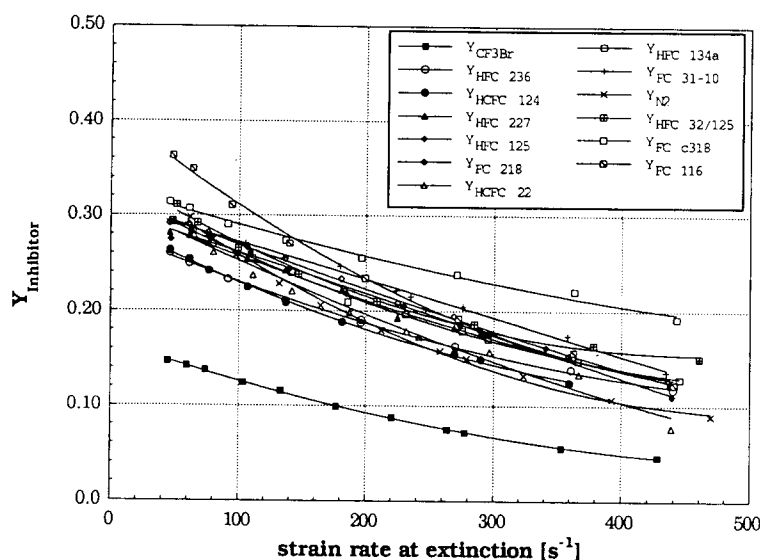
Fig. 1. Mass fraction of various agents as a function of the characteristic strain rate $(s^{-1})$ at extinction of counterflow diffusion flames burning heptane.

effective and FC-116 least effective in extinguishing the flame, whereas at high strain rates HCFC-22 is most effective and FC-318 least effective. In fact, at high strain rates only $CF_3Br$ and HCFC-22 are more effective than $N_2$ in extinguishing the flame. The results also show that with the exception of $CF_3Br$, the differences in the mass-based effectiveness of the various agents including that of $N_2$ are relatively small. If the results shown in Fig. 1 are plotted again showing the mole fraction of the agents at extinction, as a function of $a$, then the relative effectiveness of the agents ranked on a mole basis is found to be different from their mass-based effectiveness. On a mole basis $CF_3Br$ was found to be most effective and $N_2$ to be least effective in extinguishing the flame among all the agents tested.

## Coflow Results

Figure 2 shows the minimum mass fraction of the agents required in the oxidizer stream to blowoff flames burning heptane, jet fuels JP-8
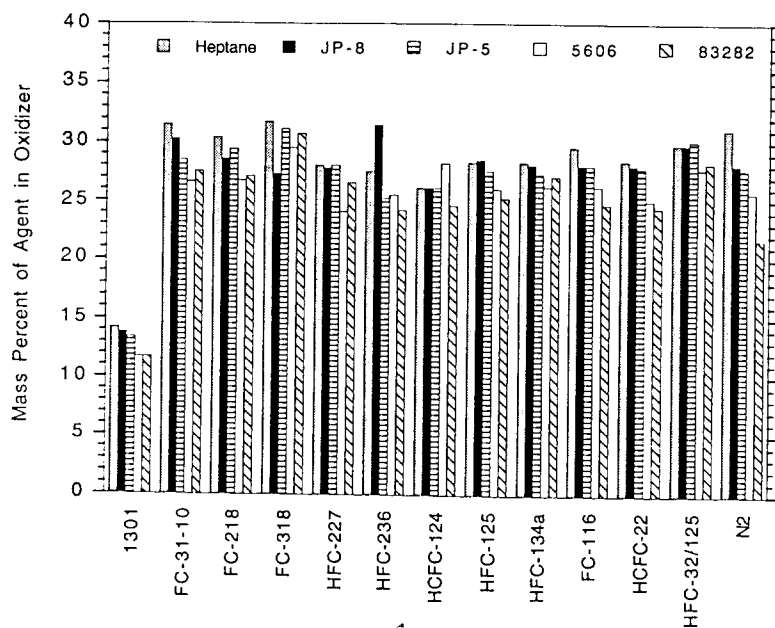


Fig. 2. Minimum mass fraction of various agents at blowoff of coflow diffusion flames burning various liquid fuels.

and JP-5, and hydraulic fluids 5606 and 83282 in the cup burner. Generally, heptane flames were most difficult to extinguish and flames burning the hydraulic fluids were the least difficult to extinguish. Figure 2 shows that $CF_3Br$ is considerably more effective in blowing off the flames than all the other agents tested. Consistent with the measurements in the counterflow configuration, the results also show that with the exception of $CF_3Br$, the differences in the mass-based effectiveness of the various agents including that of $N_2$ are relatively small.

## Comparison between Counterflow and Coflow Results

Figure 3 shows the comparison between the cup burner results for the minimum mole fraction of the various agents at blowoff of flames burning heptane and the counterflow results for the minimum mole fraction of various agents at flame extinction measured at $a = 50$ $s^{-1}$, and $a = 360$ $s^{-1}$. Comparison of the relative mole-based effectiveness of all the agents except $CF_3Br$ measured in both configurations show FC-31-10 to be most effective and HFC-32/125 to be least effective in extinguishing the flame. Also, the relative rankings of the various agents as well as the value of the mole fraction measured in the counterflow burner at

a low value of the strain rate correspond very closely to the cup burner results. This observation could be partly explained using recent results of Seshadri et al. [14], where it is shown that for flames stabilized in the coflowing configuration, the characteristic strain rate at the flamesheet decreases with the distance above the region where the fuel and oxidizer initially come into contact. Consequently, when the oxidizing gas stream does not contain any inhibitor, the flame can be expected to be stabilized in the cup burner at a position where the characteristic strain rate is roughly equal to the value of $a$ at extinction measured in the counterflow experiments. Since the results of counterflow experiments show the value of $a$ at extinction to decrease with increasing amounts of inhibitor in the oxidizing stream, the flame-standoff distance in the cup-burner can be expected to increase with increasing amounts of inhibitor in the oxidizing stream. This was in fact observed in the coflow experiments. When the amount of inhibitor in the oxidizing stream of the cup burner reaches a value at which the corresponding extinction value $a$ in the counterflow configuration is around or below 50 $s^{-1}$, the flame can be expected to blowoff from the surface of the liquid pool in the cup burner, because at these low values of the strain rate a steady flame cannot be stabilized in the counterflow burner.
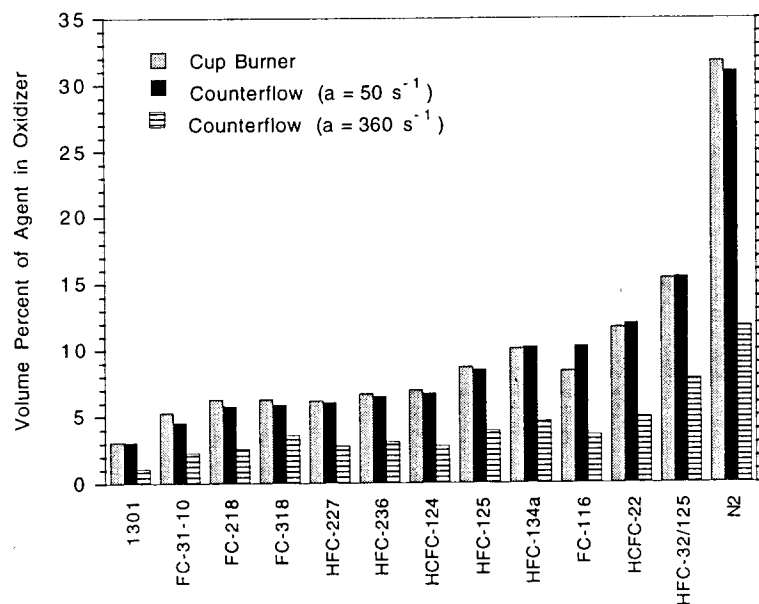


Fig. 3. Minimum mole fraction of various agents at blowoff of coflow diffusion flames burning heptane. For comparison the values of the mole fraction of these agents at extinction measured in counterflow diffusion flames at strain rates of 50 and 360 $s^{-1}$ are also shown.

This provides a plausible explanation for the observed correspondence between the coflow results and counterflow results at lower values of $a$. However, detailed flame structure measurements are needed to establish a fundamental correspondence between the measurements of extinction in the counterflow configuration and blowoff in the coflow configuration.

## INTERPRETATION OF THE EXPERIMENTAL RESULTS USING ACTIVATION-ENERGY ASYMPTOTIC THEORIES

Activation-energy asymptotic theories of flame extinction [15–17], where the gas-phase chemical reaction is approximated as a one-step process have predicted the value of the Damköhler Number at extinction $\delta_e$, which is defined as the ratio of $\tau_f$ to $\tau_c$, where $\tau_c$ is the characteristic chemical reaction time. For a given chemical system, the value of $\tau_c$ will depend on the relative concentrations of the various reactants including that of the agent and the local gas temperature, and the value of $\tau_f$ will depend on the strain rate $a$. For a given fuel-oxidizer system, the effectiveness of an agent in interfering in the chemical reaction between the fuel and oxygen can be roughly estimated by examining the value of $\delta_e$. For a given value of $\tau_f$, the value of $\tau_c$ at extinction can be expected to decrease and the corresponding value

of $\delta_e$ to increase with increasing chemical inhibition of the agent. In the absence of temperature measurements in the flame at conditions close to flame extinction, the calculated adiabatic flame temperature $T_f$, provides a rough measure of the value of $\tau_c$.

Measurements of the critical conditions of extinction of heptane flames with some selected agents shown in Fig. 1 were used to calculate the adiabatic flame temperatures and the results are plotted in Fig. 4. In the calculations the agent was presumed to be inert, preferential diffusion was neglected and the gas-phase chemical reaction was presumed to occur as a one-step overall process with stoichiometric amounts of fuel reacting with oxygen to form the products $CO_2$ and $H_2O$. Figure 4 shows that for any given value of the strain rate $a$, the value of $T_f$ calculated for flames inhibited with $CF_3Br$ is higher than the value of $T_f$ calculated for flames inhibited with the other agents. Therefore for any value of $\tau_f$, the critical conditions of extinction measured with $CF_3Br$ yield smaller values of $\tau_c$ or larger values of $\delta_e$ than those measured with the other agents. Therefore $CF_3Br$ appears to interfere more with the flame chemistry than the other agents and therefore cannot be presumed to be inert. Also, except for $CF_3Br$ the values of $T_f$ calculated using the measured mass fractions of the other agents at extinction do not differ much from those calculated using the measured mass fractions of $N_2$ at extinc-
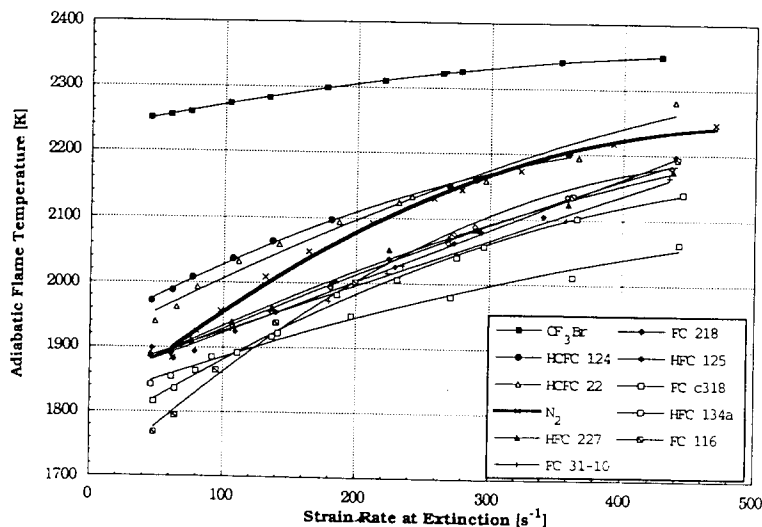


Fig. 4. Calculated adiabatic flame temperature as a function of the strain rate ($s^{-1}$) at extinction. The data shown in Fig. 1 were used in the calculations. The agents were considered to be inert.

tion. Since the influence of $N_2$ on the flame is primarily thermal, it appears that with the exception of $CF_3Br$, all the other agents have a significant thermal influence on the flame. However, it is difficult to distinguish between the chemical and thermal influences of these agents on the flame. The differences in the calculated values of $T_f$ can be partly attributed to preferential diffusion.

The calculated values of $T_f$ are used to interpret the extinction measurements using predictions of activation-energy asymptotic analysis [15–17] with the agents including $CF_3Br$ presumed to be chemically inert. The rate constant of the gas-phase chemical reaction between the fuel and oxygen is represented by the Arrhenius expression $k = B \exp(-E_0/(RT))$, where $B$ is the frequency factor, $E_0$ the activation-energy, $R$ the gas constant, and $T$ the gas temperature. The characteristic activation-energy of the chemical reaction is presumed to be large in comparison to the thermal energy in the flame. Results of activation-energy asymptotic analysis predict that at flame extinction [17]

$$Fa/T_f^2 = \rho_x T_x B_0 R^3 \exp\left(-E_0/(RT_f)\right)/$$

$$(2W_F E_0^3),$$

where $\rho_x$ represents the density of the oxidizer stream at the exit of the gas duct, $W_F$ the molecular weight of the fuel, and $B_0$ the frequency factor for molar rate of consumption of oxygen. The value of the quantity $F$ depends

on the flowfield, and Krishnamurthy et al. [16] have outlined methods for estimating $F$ for the counterflow geometry. It follows that a plot of $\ln(Fa/T_f^2)$ vs. $1/T_f$ represents an Arrhenius type plot, and the slope of this plot can be used to deduce the activation-energy of the chemical reaction between the fuel and oxygen. Figure 5 shows Arrhenius diagrams plotted using the measurements of critical conditions of extinction of heptane flames with some selected agents shown in Fig. 1. The value of $E_0$ in kJ/mol deduced from this plot for flame extinction with the agents $CF_3Br$, FC-318, HCFC-124, FC-31-10, HCFC-22, HFC-227, FC-218, HFC-125, HFC-134a, $N_2$ and FC-116 are 899, 311, 294, 244, 231, 227, 218, 214, 189, 168, and 143 respectively. Since the influence of $N_2$ on the flame is primarily thermal, deviations of the value of $E_0$ calculated using the extinction data obtained with other agents from 168 kJ/mol is a rough measure of the chemical influence of these agents. Since the value of $E_0$ calculated using extinction data with $CF_3Br$ is unrealistically high, clearly the one-step approximation is not valid, and $CF_3Br$ appears to have a significant influence on the flame chemistry. Therefore a numerical study with complex chemistry and detailed transport was made to examine in detail the influence of $CF_3Br$ on the flame structure and its extinction characteristics. However in comparison to $CF_3Br$, the other agents appear to have considerably less influence on the flame chemistry.
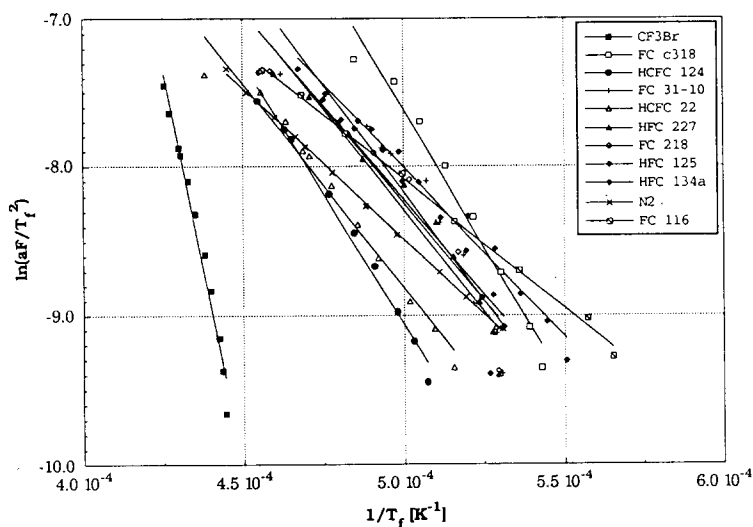


Fig. 5. Arrhenius plots obtained using the extinction data shown in Fig. 1. The agents were considered to be chemically inert.

## NUMERICAL PREDICTIONS OF FLAME STRUCTURE AND CRITICAL CONDITIONS OF EXTINCTION

Figure 6 shows the values of the mole fractions of $C_7H_{16}$, $O_2$, $CO_2$, $CF_3Br$, $H_2$, CO, HF, HBr, Br and H and $T$ as a function of the axial coordinate $y$, calculated for values of $a = 61.4$ $s^{-1}$, with $X_{O_2,\infty} = 0.204$ and $X_{CF_3Br,\infty} = 0.022$, where $X_i$ is the mole fraction of species $i$. In the calculations the surface of the liquid fuel was presumed to be located at $y = 0.0$ cm and the oxidizer jet at $y = 1.0$ cm. The profiles clearly show the concentration of $CF_3Br$ and $C_7H_{16}$ to approach zero at different regions in the flow-field and the peak values of the flame temperature and the mole fraction of $H_2O$, $CO_2$, and H to occur between these regions. These observations are consistent with previous measurements [4]. For convenience, the regions where $C_7H_{16}$ and $CF_3Br$ approach zero will be referred to as the "fuel-consumption zone," and the "$CF_3Br$-consumption zone" respectively. The region between these zones will be referred to as the "product-formation zone." Figure 6 shows that the peak value of $X_H$ occurs in the product-formation zone, and its

value decreases to zero on either side of this peak. The peak values of $X_{CO}$ and $X_{H_2}$ occur in the fuel-consumption zone. The profiles of H and $C_7H_{16}$ exhibit a classical diffusion flamelike structure in the fuel-consumption zone, therefore this zone acts as a sink for the radicals and in this zone the predominant reactions appear to be between the fuel and the radicals to form primarily CO and $H_2$. The structure of the fuel-consumption zone of the inhibited heptane-air diffusion flame appears to be similar to the structure of the fuel-consumption zone of the uninhibited heptane-air diffusion flame examined previously [8]. The profiles of H and $CF_3Br$ in the $CF_3Br$-consumption zone also exhibit a classical diffusion flamelike structure. Hence, in the inhibited flame there appears an additional sink for radicals and this could be responsible for flame inhibition. Figure 6 shows that the concentration of HBr is small in the $CF_3Br$-consumption zone and the peak value of Br is reached in this zone. This could be due to the reaction $H + HBr \rightarrow H_2 + Br$, which consumes HBr and forms Br. Asymptotic analyses using reduced chemistry can be useful in resolving the influence of this additional radical sink on the flame structure and on the critical conditions of flame extinction.

Finally, for heptane–air flames Figure 7 shows that for both numerical prediction and measurements, the values of the flow velocity at extinction $U$ increases with decreasing amounts of the mass fraction of $CF_3Br$ in the oxidizer stream. However, at high values of $U$ the predicted value of the mass fraction of $CF_3Br$ is higher than the measured value, whereas at low values of $U$ the predicted value of the mass fraction of $CF_3Br$ is lower than the measured value. This implies that with increasing amounts of $CF_3Br$ the chemical-kinetic mechanism employed here predicts an increasingly stronger inhibition effect of $CF_3Br$ than that shown by the measurements. Therefore, there is a need to refine the inhibition chemistry particularly at high concentrations of $CF_3Br$ in the air stream.

Figure 7 also shows that the calculated values of the maximum flame temperature at extinction $T_{max}$, is a strong function of $U$ and the mass fraction of $CF_3Br$ in the oxidizer
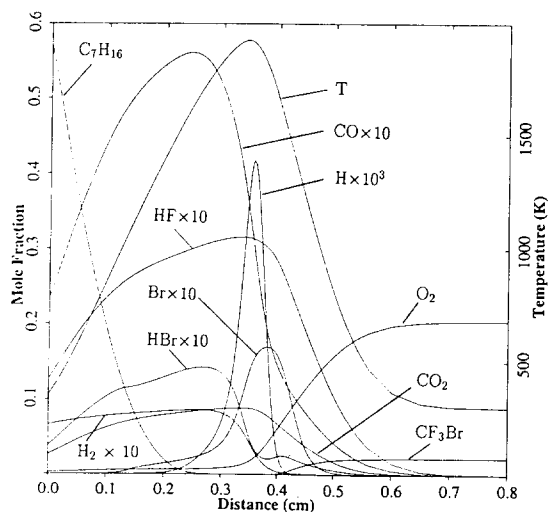


Fig. 6. Calculated values of the temperature and the values of the mole fractions of $C_7H_{16}$, $O_2$, $CO_2$, $CF_3Br$, $H_2$, CO, HF, HBr, Br and H as a function of the axial coordinate $y$, for values of $a = 50.7\,s^{-1}$, with $X_{O_2,\infty} = 0.204$, $X_{CF_3Br,\infty} = 0.022$, and $U = 37.68$ cm/s. The liquid fuel was presumed to be located at $y = 0.0$ cm and the oxidizer jet at $y = 1.0$ cm.
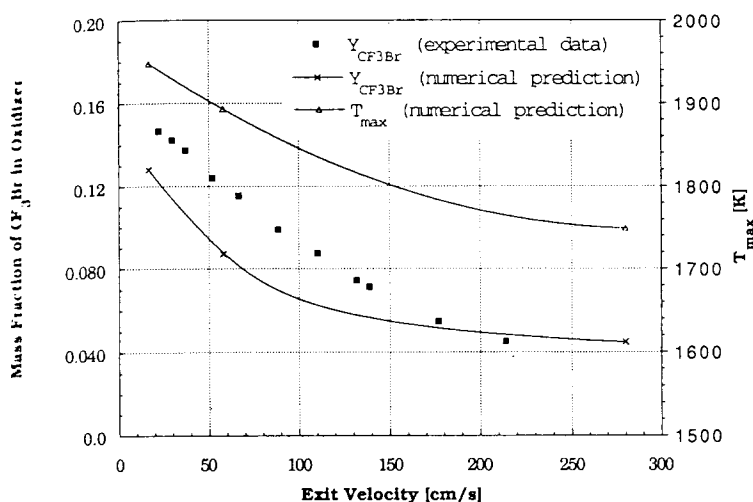
Fig. 7. Comparison between the calculated and the measured values of the mass fraction of $CF_3Br$ as a function of the flow velocity $U$ in cm/s at extinction of counterflow heptane–air flames. Also shown are the calculated vaues of the maximum flame temperature $T_{max}$.

stream. Comparison of Fig. 7 with Figs. 1 and 4 shows that with increasing amounts of $CF_3Br$ in the oxidizer stream, the values of the maximum flame temperature and the adiabatic flame temperature at extinction increase. These observations suggest significant chemical inhibition of the flame by $CF_3Br$. Using the knowledge obtained from the numerical study of flames inhibited by $CF_3Br$, it is instructive to speculate on the influence of the other agents on the flame structure and their extinction characteristics. The inhibition effect of $CF_3Br$ is possibly due to the presence of a strong radical sink at the $CF_3Br$-consumption layer shown in Fig. 6. Since Figs. 4 and 5 show that the other agents tested here have a significant thermal influence on the flame, the structure of flames inhibited by these agents may not exhibit a strong radical sink similar to the $CF_3Br$-consumption layer shown in Fig. 6. Therefore consumpton of these other agents is likely to be distributed in the product-formation layer. Detailed numerical studies of flame structure are necessary to clarify the influence of these other agents on the flame structure. Such calculations can be performed only after improved knowledge of the fluorine chemistry in the flame structure becomes available.

## SUMMARY AND CONCLUSIONS

An experimental, analytical and numerical study was performed to elucidate the influence of various agents on the structure and critical conditions of extinction of counterflow diffusion flames and on the critical conditions of blowoff of coflow diffusion flames burning liquid hydrocarbon fuels. The following remarks summarize the major conclusions of this study:

1. Both on a mass and on a mole basis $CF_3Br$ is considerably more effective in extinguishing the flame than all the other agents tested. With the exception of $CF_3Br$, on a mass basis the effectiveness of all the other agents in extinguishing diffusion flames was nearly the same as that of nitrogen.

2. The relative rankings of the effectiveness of various agents measured in the counterflow configuration at low strain rates agree with the cup-burner measurements.

3. Interpretation of the results based on one-step activation-energy asymptotic theories shows that $CF_3Br$ has a significant influence on the flame chemistry. The other agents tested here appear to have a significant thermal and some chemical influence on the flame.

4. The structure of heptane–air flames inhibited by $CF_3Br$ exhibits three zones, namely a fuel-consumption zone, a product-formation zone, and a $CF_3Br$-consumption zone. The inhibiting influence of $CF_3Br$ may be due to the presence of a radical sink in the $CF_3Br$-consumption zone.

5. The differences between the predicted and measured strain rates at extinction for hep-

tane–air flames inhibited by $CF_3Br$ increase with increasing concentrations of $CF_3Br$ in the oxidizer stream. Further research is needed to refine the inhibition chemistry.

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