Thermal Agent Extinguishment of Two Types of Diffusion Flames

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ABSTRACT

The extinguishment of diffusion flames on two types of burners—an opposed-flow Tsuji burner and an axisymmetric burner with a surrounding coflow—by thermal agents has been investigated. Thermal agents are those that act primarily by extracting heat and diluting the flame. In this study nitrogen, argon, helium, and carbon dioxide have been used as thermal agents. Both methane and propane have been used as fuels. Extinguishing concentrations are found to depend on the agent, type of burner, and on the fuel used. Propane flames are found to be more difficult to extinguish than methane flames on the same burner, while the Tsuji-type burner requires much higher concentrations of thermal agents for extinguishment than the coflow burner. Possible explanations for the observed differences are discussed.

1.   INTRODUCTION

The use of halons for fire fighting is being phased out due to their deleterious effects on stratospheric ozone. This paper describes the findings of a portion of a study designed to characterize and identify super-effective thermal fire-fighting agents as possible replacements for these effective compounds. The full report will be available shortly. [1] "Thermal" agents refer to compounds that act simply by extracting heat from a flame zone and lowering the temperature to a point where combustion can no longer be sustained. These types of agents should be contrasted with "chemical" agents that generate active chemical species (e.g., the bromine atoms generated by halons) that interfere with the radical chain branching mechanisms required to sustain combustion.

This work is focused on buoyancy-dominated diffusion flames since most fires fall into this category. Some of the earliest work for diffusion flames was associated with the development of the concept of the limiting oxygen index (LOI) that is often used to characterize the flammability of a fuel. The LOI is defined to be the minimum concentration of oxygen in a mixture of air and nitrogen that is just sufficient to sustain combustion. Simmons and Wolfhard recorded LOI for a wide range of gaseous and liquid fuels using a slow flow of fuel from a hemispherical porous burner into an opposed flow of air diluted with nitrogen. [2] These authors also introduced the concept of a limit flame temperature, which they defined as the adiabatic flame temperature calculated for a stoichiometric mixture of fuel and air at the extinguishing condition.

Simmons and Wolfhard found that the limit flame temperature varied with fuel. [2] For the C1 to C10 normal alkanes the range was 1636 K to 1791 K. Interestingly, the values for methane and the fuels having more than five carbons were all within 20 K of 1791 K. Starting with pentane, the limit flame temperatures fell rapidly as the number of carbons in the fuel was reduced, reaching a minimum value at ethane, before increasing sharply once again for methane. One interpretation of these results is that the smaller multi carbon hydrocarbons, particularly ethane, are more flammable than methane and their longer

chain analogs. In 1979 Maæk considered these results and provided a convincing argument that, in general, the flammability of the smaller straight-chain hydrocarbons, including methane, should increase with decreasing carbon number. [3] This conclusion was based on the behavior of premixed flames and consideration of LOIs for the corresponding normal alcohols. On this basis, Maæk concluded that when methane is burned as a diffusion flame it has an unexpectedly low flammability.

One of the goals of the overall project on thermal agents was to develop approaches for using detailed chemical-kinetic models to better understand and predict the effectiveness of thermal agents for extinguishing buoyancy-dominated flames. Note that we are purposefully distinguishing between the meanings of flame "extinction" and "extinguishment". *Flame extinction* is used to describe a flame that goes out due to the local strain rate or other conditions causing the flame to become unstable. *Flame extinguishment* refers to the more specific conditions necessary to put out the buoyancy-dominated flames that are expected to be characteristic of most fires.

In order to define an extinguishing condition for the addition of thermal agents to the oxidizer it is necessary to relate the calculations to an experimental result. For the methane and propane flames of interest here we wished to use the LOI for this purpose. Somewhat surprisingly, only a limited number of LOI values have been published for these flames.

For methane, Simmons and Wolfhard reported a LOI value of 0.139 using a hemispherical burner located in a slow oxidizer counter flow. [2] This corresponds to an added N_2 volume fraction of 33.8 %. Measurements by Ishizuka and Tsuji in a similar burner yielded a value of 31.9 %. [4] Puri and Seshadri reported that a 28.6 % N_2 volume fraction was sufficient to extinguish an opposed-jet methane/air diffusion flame. [5] In a recent, as yet unpublished, study, researchers at NIST made measurements in a similar low strain-rate flame and measured a value of 30.0 % for the maximum N_2 volume fraction at extinguishment. [6] At the 1999 HOTWC meeting, Ural reported a study of extinguishment of a methane flame in a cup burner apparatus. [7] The extinguishing volume fraction of N_2 over a relatively wide range of fuel and oxidizer velocities was 27.1 %.

As for methane, there are only a limited number of LOI values reported for propane/air diffusion flames. Simmons and Wolfhard measured a LOI of 0.127 using their porous hemispherical burner, corresponding to a nitrogen volume fraction for extinguishment of 39.5 %. [2] Note that that the measured extinguishing concentration is roughly 17 % greater than observed for a methane flame. For an opposed-jet diffusion flame, Puri and Seshadri recorded an extinguishing volume fraction of 34.8 % nitrogen. [5] This value is nearly 22 % higher than found for methane by the same authors. Note that for a given fuel, the nitrogen extinguishing volume fraction is significantly lower for the opposed-jet burner than for the porous burner.

Several values of nitrogen extinguishing concentration are available for propane flames burning in a cup burner configuration. Hamins et al. reported an extinguishing volume fraction of 32.5 %. [8] Babb et al. measured a value of 33 %. [9] The results of Ural also yield a value of roughly 33 %. [7] These results are all very close together, suggesting that lab-to-lab variations are not responsible for the differences observed between different burners and fuels. Comparison of the results of Babb et al. for methane and propane indicates that a propane flame again required a higher concentration for extinguishment (roughly 22 %).

The range of extinguishing concentrations for methane and propane flames burning in air for different types of burners reported in the various investigations cited above is much larger than can be explained by uncertainty in the measurements and suggests that different types of diffusion flames yield different results. This raises the important question of what type of burner is appropriate for determining a characteristic extinguishing nitrogen volume fraction (or LOI) for buoyancy-dominated diffusion flames.

Due to the limited data available and the wide range of values reported, it was decided to carry out additional measurements of extinguishing concentrations for known thermal agents using two diffusion flame burners available at NIST. The first was a modified version of an apparatus, the Dispersed Liquid Agent Fire Suppression Screen (DLAFSS), developed at NIST to screen liquid fire-suppression agents. This system incorporates a Tsuji-type opposed-flow cylindrical porous burner. The second was a Santoro-type burner (a coflow diffusion flame) previously used at NIST for investigations of diffusion flame structure. These burners have been used to investigate extinguishment by nitrogen, carbon dioxide, argon, and helium.

2. Experimental

A. Dispersed Liquid Agent Fire Suppression Screen

The DLAFSS was designed for screening the effectiveness of liquid fire-fighting agents. It is described in a published report. [10] A more detailed description of the apparatus and the experimental procedure is available in a National Institute of Standards and Technology Internal Report [11]. Figure 1 shows a schematic for the DLAFSS. Briefly described, the apparatus consists of a small vertical wind tunnel, a porous cylindrical burner located at the test section, and a small nebulizer located in the settling chamber of the tunnel. Even though designed primarily for evaluating liquid fire suppression agents, the system can also be used for gaseous agents. [10,11] The injection point for gases is at the bottom of the system as can be seen in Figure 1.

The goal of these measurements was to identify extinction conditions for thermal agents added to the oxidizer flow for porous-burner-stabilized opposed-flow diffusion flames under the relatively low strain rates characteristic of buoyancy-dominated flames. Typically, the Tsuji burner is operated at considerably higher oxidizer flow velocities than required here, and the resulting strain rates at the flame are much greater than found in buoyancy-dominated flames. In order to generate the required low oxidizer velocities, the blower used to induce the flow in the DLAFSS was operated at the lowest setting possible. The thermal agents were then added to the induced air flow. Note that the oxidizer flow velocity is expected to vary as the agent volume fraction increases.

The flow rate of agent was controlled using a needle valve, and the volume flow rate was measured using a rotameter (Fischer Porter, Model 10A1755[*]). Even though the agent volume flow rate was known, it was found that it was not possible to predict the agent volume fraction using only the assumed airflow rate. This observation was attributed to variations in the total flow volume due to changes in the blower efficiency as agent was added. An alternate approach was adopted to estimate the total flow rate and thus the local flow velocity at the flame. The agent concentration was estimated by measuring the oxygen volume fraction in the oxidizer stream at the center of the settling chamber of the wind tunnel (see Figure 1). This was accomplished using a paramagnetic oxygen meter (Servomex Oxygen Analyzer Model 570A) in conjunction with a small sampling pump (Gilian Hi Flow Sampler, Model HFS 513A). The oxygen analyzer was zeroed and spanned using nitrogen and room air. Since the volume flow rate for the agent was known, knowledge of the degree of air dilution allowed the total flow rate to be calculated assuming complete mixing.

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[*]Certain commercial equipment, instruments, or material are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment are necessarily the best available for the purpose.
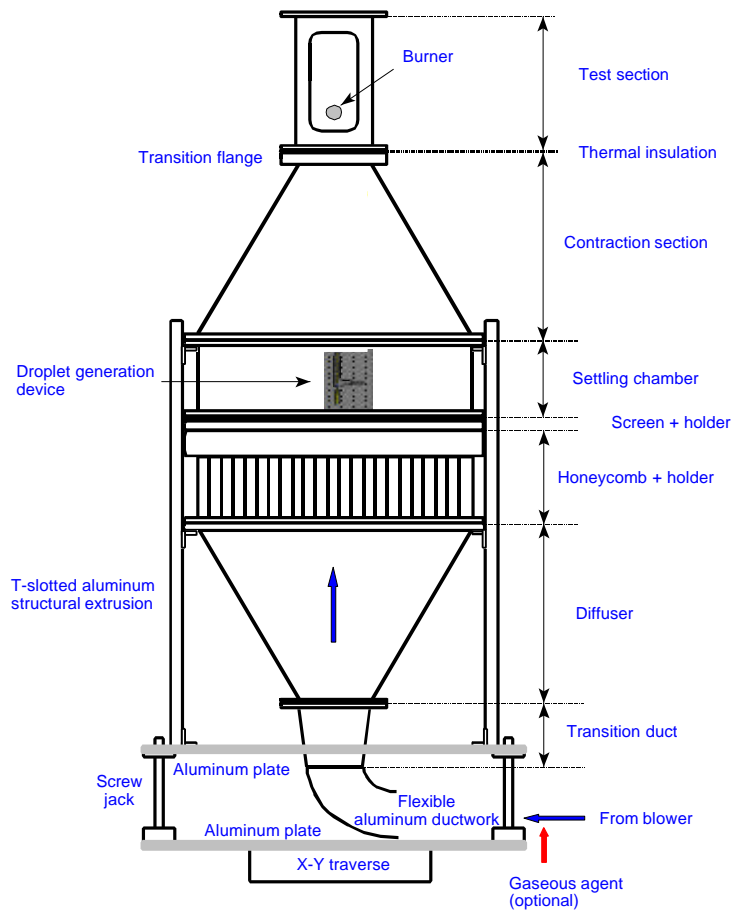
Figure 1. A schematic of the dispersed liquid agent fire suppression screen (DLAFSS) apparatus is shown.

In a typical DLAFSS experiment, extinction is defined to occur when the flame on the upstream side of the burner blows out. For high strain-rate conditions, it is generally found that a flame stabilized in the wake of the cylinder continues to burn following blow out of the upstream flame. During the current experiments, it was observed that when sufficient agent was added to the air flow to induce extinction of the stretched flame on the upstream side of the cylinder, the downstream flame was either extinguished at the same time, or disappeared when the agent concentration was increased only slightly. Since the stabilized flame is essentially a buoyancy-dominated flame, this is taken as evidence that the measurements are actually recording flame extinguishment values.

Suppression tests were performed by gradually adding the gaseous inhibitor to the oxidizer (air) stream until blow-off occurred (abrupt transition from envelope to wake flame). The volumetric flow rates of the suppressant at blow-off were recorded. The oxygen concentration was then noted for the same flow conditions.
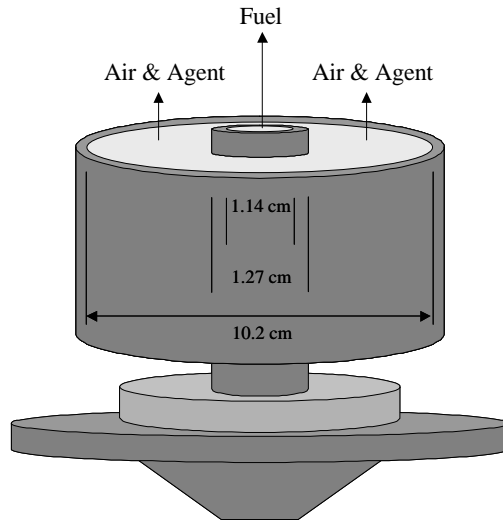
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Figure 2. A schematic of the modified Santoro burner is shown.
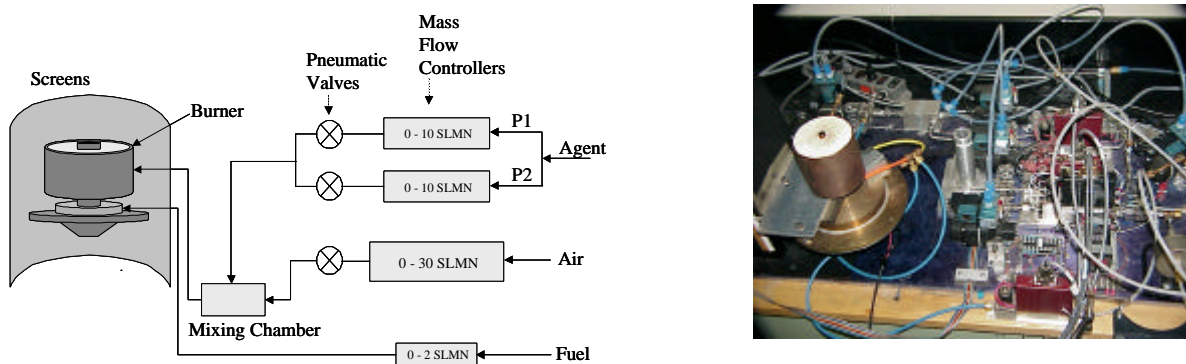

Figure 3. A schematic and photo of the Santoro burner and flow control system are shown.

B. Santoro Burner

An existing coflow burner and computer-controlled gas mixing system were modified to allow extinguishing concentrations of thermal agents to be determined for buoyancy-dominated laminar diffusion flames formed by a flow of gaseous fuel from a circular tube into a slow surrounding coflow of an air/agent mixture. The burner is based on a design originally developed by Santoro et al. that is commonly referred to as a "Santoro burner". [12] This type of burner has been employed for numerous flame studies at NIST. In a particularly relevant study, Smyth and Everest reported volume fractions of CF_3Br and CF_3I in air required to extinguish a propane flame on the Santoro burner. [13]

The actual burner used in this investigation is a modified Santoro burner that was originally employed to investigate acoustically forced, time-varying diffusion flames. [14] It has been employed for numerous studies. [15,16,17,18,19,20,21,22] A drawing of the burner is shown in Figure 2. It consists of an open 13.7 cm length of tubing with a 1.27 cm outer diameter that serves as the central fuel tube. The tube lip thickness is 0.065 cm, yielding an inner diameter of 1.14 cm. One end of the tube is attached to a

Table 1. Suppression Results Using the DLAFSS

Agent	Methane		Propane	
	Agent volume fraction at blow-off	$a_T = 2V_o/R$ (s^{-1})	Agent volume fraction at blow-off	$a_T = 2V_o/R$ (s^{-1})
Carbon Dioxide	0.240 ± 0.003* (n = 4)	39 ± 1	0.257 ± 0.008 (n = 3)	45 ± 2
Nitrogen	0.332 ± 0.004 (n = 5)	52	0.390 ± 0.004 (n = 5)	56
Helium	0.207 ± 0.003 (n = 5)	94	0.224 ± 0.003 (n = 5)	95 ± 1
Argon	0.468 ± 0.002 (n = 4)	44 ± 1	0.550 ± 0.005 (n = 5)	44
* mean ± standard deviation No. of samples = n				

plenum containing a loud speaker. The speaker, used to acoustically force the fuel flow, was not activated during this study. The open end of the fuel tube extends 0.4 cm above a surrounding 10.2 cm diameter ceramic honeycomb formed from 0.15 cm square cells and having an overall length of 2.5 cm. After passing through a chamber filled with glass beads and several screens, a flow of air and agent enters the honeycomb to form the surrounding coflow for the flame.

The flow velocities for the fuel and coflow streams were low and resulted in small buoyancy-dominated flames that were highly susceptible to room drafts. Screens were placed around the burner to minimize these disturbances. Flame products were removed from the area by an exhaust cone connected to the room exhaust by a flexible hose. The effect of the exhaust cone on the flames was judged to be negligible due to its low rate of suction and its location above the burner.

Fuel and the air/agent mixture were delivered to the burner using a system of thermal mass-flow controllers (MFC's). The flow-control system, shown in Figure 3, is a modification of a system developed at NIST for a previous investigation as described in detail by Pitts et al. [23] The flow system was software controlled by a desktop 486-DX personal computer. The air and agent streams were combined upstream of the burner in a mixing chamber designed to ensure a homogenous mixture. Pneumatic shut-off valves prevented unwanted backflow of gases and allowed for easy calibration of each MFC. Modifications for the current study included the addition of a 30 SLM (standard liter per minute) mass-flow controller for the air flow and moving the 10 SLM and 2 SLM mass-flow controllers to the agent and fuel streams, respectively. Air was supplied from an in-house high-pressure line, and its relative humidity was a consistent 4.5 %.

3. Results for Thermal Agent Extinction of Methane and Propane Diffusion Flames Burning on Tsuji and Santoro Burners

The extinguishment behaviors of flames stabilized on the Tsuji and Santoro burners were investigated using the gaseous thermal agents nitrogen, carbon dioxide, argon, and helium. The following two sections summarize the general observations and the results of extinguishment volume fraction measurements.

A. Tsuji Burner

Multiple extinguishment tests were run for each agent. Table 1 summarizes measured values of extinguishing volume fraction for the four thermal agents. The repeatability of the measurements is indicated by the magnitudes of the standard deviation. The actual number of repeated tests is denoted by the symbol *n*. The table also includes values of the stagnation velocity gradient, a_T, defined as $2V_o/R$,

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where V_o is the velocity based on the total volumetric flow rate of air and gaseous agent at blow-off and R is the burner radius. a_T represents the characteristic stagnation strain rate that is often used for Tsuji burners and has units of s^{-1}.

As already discussed, measurements of extinguishing volume fractions in the literature are limited for opposed-flow porous burners. Simmons and Wolfhard [2] reported values of 34 % and 39.5 % for the extinguishing volume fractions of methane and propane flames on a hemispherical porous burner, while Ishizuka and Tsuji [4] found a value of 31.9 % for a methane flame stabilized on a cylindrical porous burner. These values agree very well with those included in Table 1, (33.2 ± 0.4) % and (39.0 ± 0.4) % for methane and propane, respectively. This agreement is found even though two different types of porous burners were used. Recall that the extinguishing nitrogen volume fractions of Simmons and Wolfhard were the highest observed for the various types of diffusion flames discussed earlier. It must be concluded that a flame for a given fuel is more stable on an opposed-flow Tsuji-type or hemispherical porous burner than for the corresponding flames burning between two axisymmetric opposed-jet flows or in a coflow configuration. The reasons for these observations are currently unclear.

Note that in the case of helium included in Table 1, the values for $a_T = 2V_o/R$ are almost a factor of two higher than those obtained using nitrogen, carbon dioxide, and argon. Recall that the blower in the DLAFSS is set to operate at the lowest possible revolution rate. Even though the blower speed is nominally constant, when the density downstream of the blower is significantly reduced, the blower generates a higher volume flow rate. The net result is that the characteristic strain rate, a_T, at the flame is roughly a factor of two higher for the helium case than for the other agents, and it is to be expected that the observed extinguishing concentration will be somewhat lower than would be measured for a purely buoyancy-dominated flame.

B. Santoro Burner

The coflowing gas burner is a deceptively simple flame configuration. During the extinguishment studies summarized here a number of complex behaviors were observed that complicated what should have been, in principle, a simple measurement of extinguishing concentration. The behaviors are also shown to be fuel dependent, being different for methane and propane flames.

Consider first the methane base flame (i.e., fuel and air nominal velocities equal to 7 cm/s) burning in air diluted with N_2. With only air present, a blue flame was evident slightly below the exit and very close to the fuel tube. Further downstream the flame was yellow indicating the presence of soot. As the N_2 concentration in the oxidizer was increased, the base of the flame gradually moved downstream and away from the burner tube, but the flame still appeared to be attached. At the same time, the fraction of the flame that appeared yellow decreased. When the N_2 volume fraction reached 20.2 %, an up and down oscillation of the flame base suddenly appeared as indicated in Figure 4. This flame was entirely blue. The oscillating flame only existed over a narrow range of N_2 volume fraction. Similar oscillations for flames near extinction have been reported previously in the literature. [24,25]

When the N_2 volume fraction was increased to 20.5 %, the flame detached from the burner and moved downstream, where it became stable and floated lazily up and down 10 mm to 15 mm above the burner. With further increases in N_2 concentration, the flame moved further downstream, while becoming shorter and broader. These changes in appearance are shown in cartoon form in Figure 5. Similar lifted-flame structures have been observed in investigations with different fuels and burner configurations and are attributed to the presence of triple flames. [26,27,28,29] The presence of lifted flames has also been

Attached flame instability
$0.202 < X_{N_2} < 0.205$

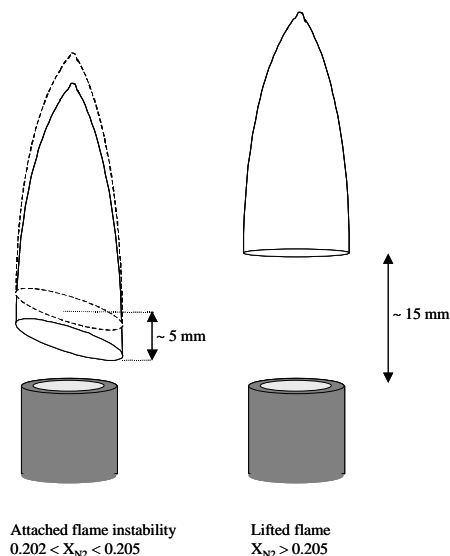Lifted flame
$X_{N_2} > 0.205$

~ 5 mm

~ 15 mm

Figure 4. Sketch of a methane flame showing the attached flame oscillation and subsequent stabilized lifted flame that result from the addition of nitrogen to the air co-flow.
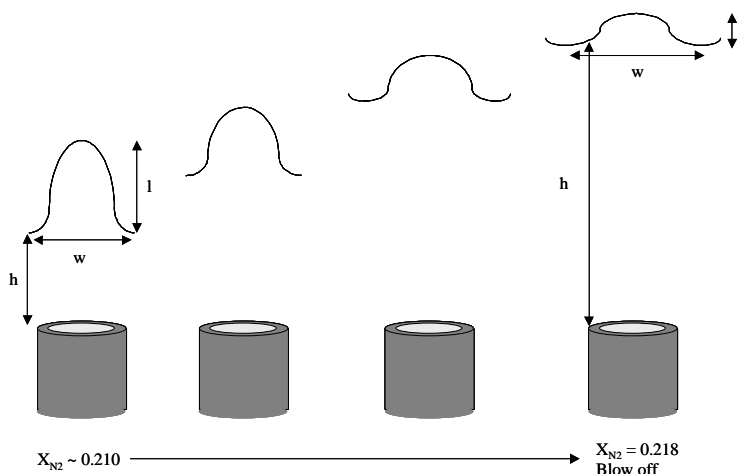

$X_{N_2} \sim 0.210$

$X_{N_2} = 0.218$
Blow off

Figure 5. The evolution of the methane diffusion flame structure as additional N_2 is added to the co-flow air stream is shown.

reported during cup burner experiments using gaseous fuels. [7,8,9] When the N_2 volume fraction reached 21.8 %, the lifted flame could no longer be stabilized, and it simply floated away, i.e., it was blown off.

Increasing N_2 dilution of the air resulted in three distinct behaviors—attached flame instability, lift off, and blow off. The N_2 volume fraction range where these processes occurred was narrow, ranging from 20.5 % to 21.9 %. It is difficult to define any of these processes as a true extinguishment, though blow off would seem to be the most appropriate. For reasons that will be clear shortly, the onset of the fluctuation behavior was used for the characteristic extinguishing concentration for methane flames burning in air diluted with thermal agents.

When CO_2, Ar, and He were used as diluents, the response of the baseline methane flame changed from that observed for N_2. For all three agents, the initial effect of increasing their concentration in air was the appearance of the attached flame instability. Similar to the results for N_2, additional small increases in the

volume fractions of CO_2 and Ar resulted in detachment of the flame from the burner, with stabilization further downstream. At first, these flames moved further downstream with additional increases in diluent concentration, but eventually the flames reached lift-off heights where further increases appeared to have little effect. The most likely reason for this observation is that the flames reached a downstream location where surrounding room air was able to diffuse through the oxidizer coflow and provide sufficient O_2 to sustain combustion. For these cases it is impossible to define the agent volume fraction required for flame blow off. The behavior of the flame burning in air diluted with He was quite different. After a few oscillations following the onset of the attached flame instability, the flame was extinguished without further increases in helium concentration. Apparently, the onset of the attached flame instability was sufficient to extinguish the methane burning in the He/air mixture. Since the appearance of the flame instability was the only common behavior for all four of the agents, its onset was used as the characteristic volume fraction for extinguishment.

When the baseline fuel and oxidizer volume flow rates for the methane case were used for propane, the resulting flame length was much greater than observed for methane. This observation is easily understood by considering the stoichiometries for complete combustion of the two fuels,

$$\text{Methane:} \qquad CH_4 + 2O_2 \rightarrow 2H_2O + CO_2$$

$$\text{Propane:} \qquad C_3H_8 + 5O_2 \rightarrow 4H_2O + 3CO_2 \;,$$
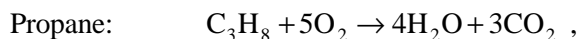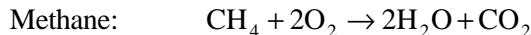
which indicate that combustion of a given volume of propane requires 2.5 times more oxidizer than the same volume of methane. Since the entrainment rate of oxidizer into laminar diffusion flames is roughly independent of the fuel flow rate, a longer flame length is required for the complete combustion of propane with the same fuel flow rate.

In order to have roughly comparable flame lengths for the two fuels, the nominal fuel velocity for propane was reduced to 40 % of that used for methane (i.e., a nominal velocity of 2.8 cm/s, volume flow rate of 0.171 SLM). With the oxidizer nominal velocity maintained at 7 cm/s, the propane flame length was comparable to that for the baseline methane flame. These flow velocities were adopted as the baseline conditions for the propane flame.

Similar to the baseline methane flame, the propane flame was attached to the fuel tube prior to the addition of nitrogen to the coflow. As the nitrogen volume flow rate was increased, the blue region at the base of the flame occupied a larger volume, as was also observed for the methane flame. However, unlike the methane flame, the base of the propane flame broadened substantially as it moved away from the burner tube with increasing nitrogen addition. When the nitrogen volume fraction reached 26.5 %, the flame base detached from the fuel tube and stabilized approximately 5 mm downstream. By the time the nitrogen volume fraction was increased to 27.6 %, the flame base was approximately 10 mm above the fuel tube, and began to oscillate with a combined vertical and radial motion. Further downstream the flame formed a necked-down region. With only an additional increase of 0.4 % nitrogen volume fraction, the flame suddenly extinguished by collapsing at the necked-down region. A cartoon of the nearly extinguished flame is shown in Figure 6. The extinguishment of the propane flame following lift off stands in sharp contrast to the methane flame that formed a stable lifted flame following detachment from the burner.

Unlike the baseline methane flame, the general response of the propane flame to dilution of the coflow air by CO_2, Ar, and He was the same as described above for nitrogen dilution. Since an easily characterized

a) t=t_1 b) t=t_2 c) t=t_3

Necked down region & extinguishment point
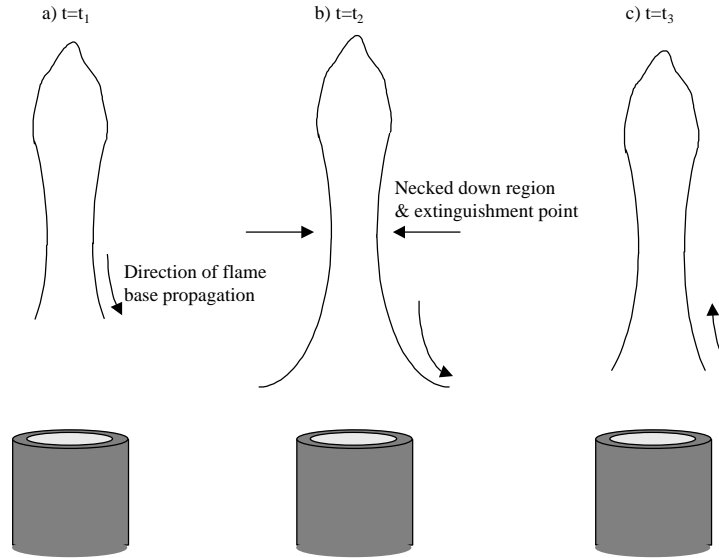
Direction of flame base propagation

Figure 6. A sketch of the time evolution of a nearly extinguished propane flame is shown for the case of nitrogen dilution of the co-flow air, $t_1 < t_3$.

Table 2. Measured Agent Volume Fractions at Onset of Flame-Base Instability (Osc) and for Flame Extinguishment (Ext) of Baseline Methane and Propane Diffusion Coflow Flames

	Methane		Propane	
	Osc	Ext	Osc	Ext
Carbon Dioxide	0.120 (s=±0.001)	-	0.169 (s=±0.004)	0.176 (s=±0.001)
Nitrogen	0.202 (s=±0.002)	0.218 (s=±0.002)	0.276 (s=±0.005)	0.280 (s=±0.008)
Helium	0.200 (s=±0.001)	0.200 (s=±0.001)	0.271 (s=±0.003)	0.273 (s=±0.002)
Argon	0.290 (s=±0.001)	-	0.356 (s=±0.002)	0.368 (s=±0.003)

s = Standard deviation
Number. of samples = 6

extinguishment was observed for each agent using propane, this event was designated as the characteristic flame extinguishment behavior.

The results of extinguishment studies for baseline methane and propane diffusion flames on a Santoro burner are summarized in Table 2. Agent volume fractions corresponding to the onset of flame fluctuation and flame extinguishment (if observed) are included. Uncertainties represent the standard deviation, s, for six repeats of each measurement. Extinguishment was not observed for the methane flame with CO_2 and Ar. The volume fraction of agent required to induce oscillation is taken as the characteristic extinguishing concentration for the methane flame, while the actual concentration at flame extinguishment is used for the propane flame. Note that the small differences observed between the two values for a given agent and fuel
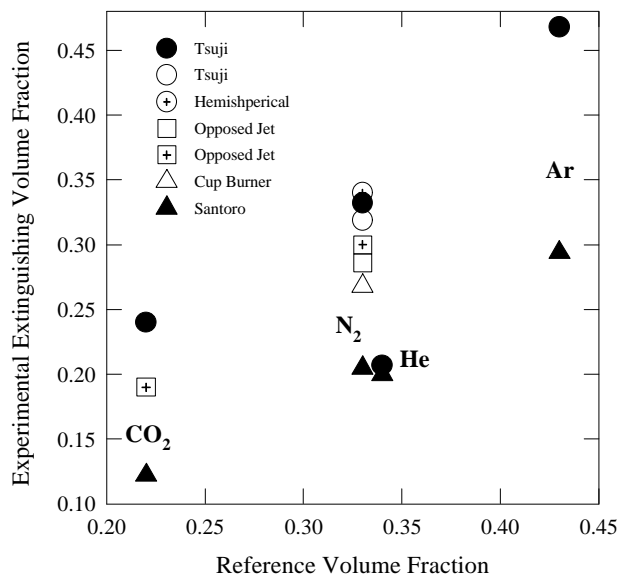
Figure 7.   Experimental measurements of extinguishing volume fractions for the indicated thermal agents are plotted as a function of a reference concentration for methane flames.   Solid symbols represent current results for Tsuji and Santoro burners, and open symbols are values taken from the following references (same order as symbols):   Tsuji cylindrical porous burner [4], hemispherical porous burner [2], opposed-jet burners [5,6], cup burner [7].   For clarity, the reference concentration for helium has been increased by 0.5 %.

suggests that only small differences will be introduced by the use of the different definitions for extinguishment.

4. Discussion

It is desirable to have some means of comparing the various experimental results graphically. For this purpose we have chosen to plot the results for the various gases as a function of the corresponding reference volume fraction predicted for extinguishment using detailed chemical-kinetic modeling and the assumption of a common maximum flame temperature for extinguishment.   Details concerning these calculations will be presented elsewhere. [1]

Figure 7 shows a plot of measured extinguishing volume fractions for thermal agents added to the air flows of the Tsuji and Santoro burners used in the current investigation (solid symbols).   For comparison purposes, a number of measurements taken from the literature for a variety of different diffusion flames are also included (open symbols). Even though all of the data are recorded for diffusion flames, it is obvious that significant variations are observed that seem to be burner dependent. With the exception of helium, the highest extinguishing concentrations in the current study were found for the Tsuji burner, i.e., a porous cylindrical burner in an oxidizer counterflow. For nitrogen the current value is in good agreement with two earlier measurements recorded using hemispherical [2] and cylindrical [4] porous burners in counterflow configurations.   Interestingly, the two sets of measurements recorded using opposed-jet diffusion flames yield extinguishing volume fractions that are significantly lower than those using porous burners.

Figure 7 also includes a cup burner result taken from Ural for nitrogen. [7] The cup burner consists of an axisymmetic burner surrounded by an enclosed coflow. It is typically used for liquid fuels, but has been
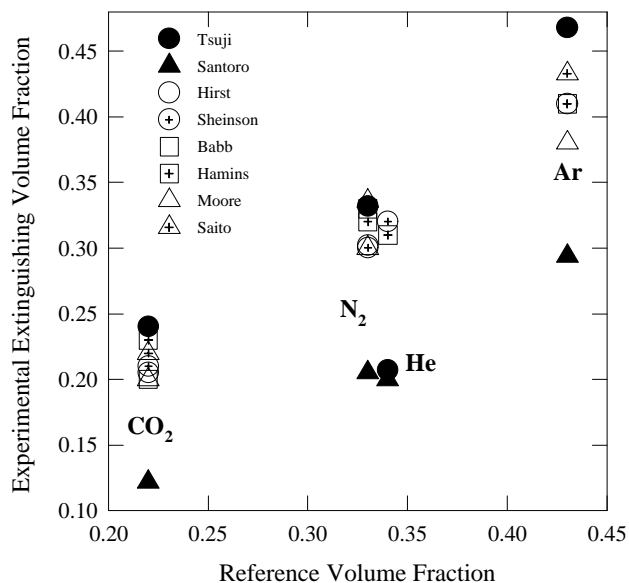
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Figure 8. Experimental extinguishing volume fractions for the indicated thermal agents are plotted as a function of a reference concentration for methane flames using the Tsuji and Santoro burners (solid symbols). These results are compared with cup burner measurements using heptane as fuel (open symbols) taken from the following references (same order as symbols): Hirst [30], Sheinson [31], Babb [9], Hamins [8], Moore [32], and Saito [33]. For clarity, the reference concentration for helium has been increased by 0.5 %.

modified for gaseous fuels. For standard configurations, the "cup" used as the burner has a greater diameter (roughly a factor of two) than the Santoro burner. The measured extinguishing volume fractions fall below those recorded for the opposed-flow burners, but lie well above the corresponding results for the Santoro burner.

All of the measurements recorded using the Santoro burner lie well below those recorded with the other types of burners, with the exception of the helium measurements using the DLAFSS. Recall that due to experimental problems, the global strain rate was roughly twice as high for helium as for the other agents. Even though the relative magnitudes differ significantly, extinguishing volume fractions, for the two burners used here, again with the exception of helium, vary in very similar manners for the different agents.

There are insufficient data in Figure 7 to allow a clear dependence of the extinguishing volume fraction on agent to be identified. A much larger number of measurements of extinguishment volume fractions using these thermal agents have been reported for heptane flames in cup-burner experiments. Figure 8 compares the current results with a number of cup burner results for heptane available in the literature. The results for N_2 and CO_2 tend to fall relatively close together and to lie just below the Tsuji burner results for methane. Even though the cup burner extinguishing volume fractions are considerably higher for a given agent, the relative variations with agent are similar to those for the Santoro burner. It is particularly noteworthy that both types of burners indicate that the extinguishing effectiveness of nitrogen and helium are very similar. As already noted, the results for helium using the Tsuji burner appear to be lower than expected. Similarly, there is an indication that the measured value for the Tsuji burner using argon may be slightly higher than expected.
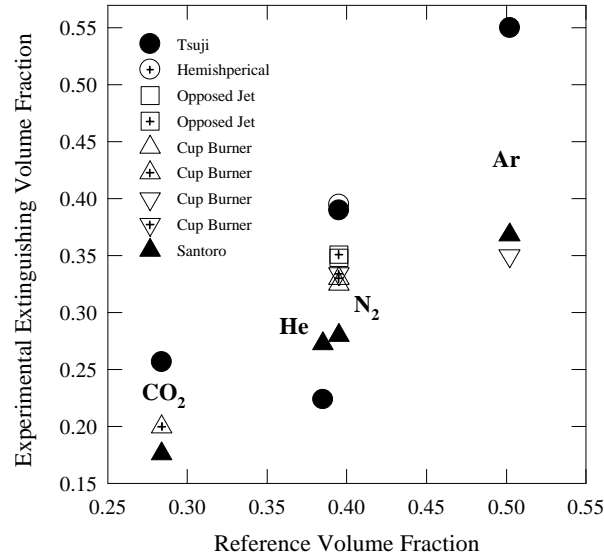
Figure 9.   Experimental measurements of extinguishing volume fractions for the indicated thermal agents are plotted as a function of a reference concentration for propane flames. Solid symbols represent current results for Tsuji and Santoro burners, and open symbols are values taken from the following references (same order as symbols): hemispherical porous burner [2], opposed-jet burners [5,6], and cup burners [7,8,9,32].

The current experimental results for the propane flames are plotted in Figure 9 in a similar manner as the methane results in Figure 7. Experimental values for various diffusion flames are also shown. The same general behaviors are found as were observed for methane. The porous burners require the highest concentrations of an agent for extinguishments, with the exception of helium. Opposed-jet burners require slightly lower concentrations, and the cup burner requires even less. Values for the Santoro burner are considerably lower still. There is an indication that the DLAFSS value for argon may be slightly highly than expected. The required extinguishing concentrations of helium and nitrogen are very similar for the Santoro burner.

Comparison of Figure 7 and Figure 9 suggests that extinguishing concentrations for a given agent are somewhat lower for methane than propane. This is confirmed by the data shown in Figure 10 that directly compares the results for methane and propane flame results. In each case, for a given agent and burner type, the required agent volume fraction to extinguish the flame is higher for a propane flame than for a methane flame.

While there are some inconsistencies in the current experimental results, the findings of this study in conjunction with earlier literature results support the following conclusions:

1. The amount of agent required to extinguish a buoyancy-dominated diffusion flame depends on the type of burner employed. The relative ordering of diffusion flame types based on difficulty of extinguishment is 1) porous burner in a counterflow, 2) opposed-jet, and 3) coflow.

2. Even though both burners use coflows of oxidizer and fuel, it is much easier to extinguish a Santoro burner than the corresponding cup burner flame. Previous researchers have noted that the flame stability in cup burners decreases with the cup diameter, which is consistent with the current observations. [34,35]
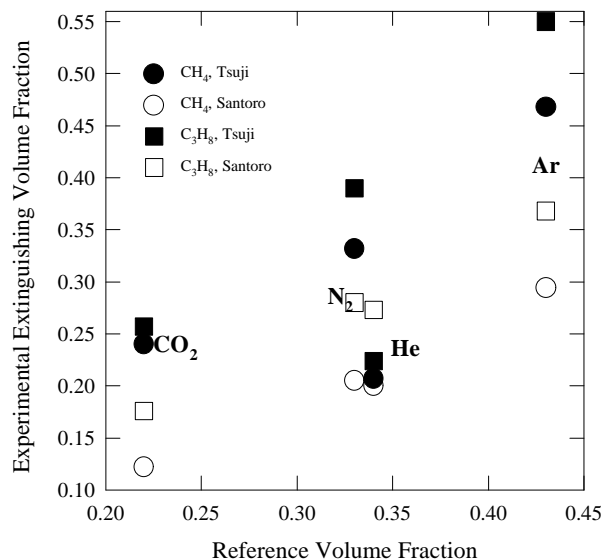
Figure 10. Experimental values from the current study for extinguishing concentrations of the indicated thermal agents are compared for methane and propane flames. Data are plotted as a function of the reference extinguishing concentration for methane. For clarity, the reference concentration for helium has been increased by 0.5 %.

3. Propane flames require higher concentrations of an agent to induce extinguishment than methane flames. This observation is consistent with the discussion of Maæk concerning flame stability variations with fuel. [3]

4. Even though the amount of a given agent required for extinguishment depends on the fuel, the relative effectiveness of different agents does not seem to change from fuel to fuel. This is consistent with recent conclusions reached in the literature. [36,37]

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6. References

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