Near-limit laminar burning velocities of microgravity premixed hydrogen flames with chemically-passive fire suppressants

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Abstract

Effects of chemically-passive fire suppressants on laminar premixed hydrogen flames were investigated by combined use of microgravity experiments and computations. The experiments used a short-drop free-fall laboratory facility that provides at least 450 ms of $10^{-2}$ g. Near-limit laminar burning velocities were measured for outwardly propagating spherical stoichiometric hydrogen-air flames with varying concentrations of He, Ar, N$_2$, and CO$_2$ as suppressants. Burning velocities were also computed using the steady, one-dimensional laminar premixed flame code PREMIX. Both measured and computed results showed the suppressants to increase in effectiveness in the order He, Ar, N$_2$, to CO$_2$. The differences in effectiveness are shown to result from increased quenching of reactions by the increased specific heat due to the suppressant and from changes in the transport rates near the flame. The concentration needed for each suppressant to prevent flame propagation was also determined. Far from this flammability limit, agreement between measured and computed laminar burning velocities was good, but for near-limit flames the computed velocities were significantly lower than measured values. These near-limit differences may be due to third-body recombination rates for $\text{H} + \text{O}_2 + \text{M} = \text{HO}_2 + \text{M}$ reactions, and in particular to the third-body chaperon efficacy of various species M.

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Keywords: Extinction; Chemically passive suppressants; Hydrogen flames; Microgravity

1. Introduction

Long-duration space missions, including trips to the Moon and Mars, present substantially increased risks of accidental fires, and as a result the development of effective fire-safety systems for spacecraft environments will be critical to such missions. Although chemically-active flame suppressants such as Halons are known to be highly effective, they generate reaction products that can be dangerous to health and life-support systems. Consequently, chemically-passive suppressants are potentially more suitable for such long-duration missions. The present study thus examines the effectiveness of various chemically-passive suppressants on premixed flame
propagation under microgravity conditions and spacecraft environments.

Low-gravity effects dominate fire behavior and control in spacecraft. Previous studies [1–3] have shown low-gravity flames to have broader flammability limits than do comparable flames in normal gravity. The reduction of buoyancy with reduced gravity makes weak near-limit flames in microgravity more difficult to extinguish, and for this reason conventional normal-gravity tests cannot provide effective guidelines for suppressant effectiveness on flammability limits in microgravity environments.

Here, we present results for suppressant effects on flames by studying outwardly-propagating spherical laminar premixed hydrogen flames in microgravity. Although realistic flames are not usually fully premixed, the behavior of premixed flames presents a worst-case limit for naturally occurring fires. In addition, modeling nonpremixed flames in complex fluid dynamics scenarios often requires laminar flame speeds, such as determined here, as input into the flame propagation submodel. Premixed flames also develop sufficiently fast that their propagation characteristics can be measured in the laboratory using a small, short-drop, free-fall microgravity facility. Moreover, hydrogen–oxygen chemical kinetics play a fundamental role for combustion of all hydrocarbons in air, and numerical solutions of the underlying kinetic mechanism are considered relatively reliable. Furthermore, results from the hydrogen–oxygen system provide conservative estimates for suppressant effectiveness, since such flames are the most difficult to extinguish among combustibles of practical interest. Additionally, outwardly-propagating spherical flames are advantageous for this study because they allow comparatively straightforward determination of the unstretched laminar burning velocities.

A previous study [4] has reported results for the effectiveness of various agents as chemically-passive flame suppressants under normal-gravity conditions. The agents considered were inert gases, specifically He, Ar, N2, and CO2, chosen to allow separate identification of the relative effects of dilution, heat capacity, and transport properties on suppressant effectiveness. That study examined flame propagation velocities in normal gravity for suppressant concentrations below 40% volume fraction in the reactant mixture. For such comparatively low suppressant concentrations, the resulting flames were sufficiently fast that gravity had a negligible effect on the flame propagation. However, as the suppressant volume fraction is increased above 40% and the extinction limit is approached, normal-gravity flames become greatly affected by buoyant distortion. As a result, conducting near-limit flame-suppression experiments under microgravity conditions is essential for determining the true flammability limits of suppressed flames for spacecraft environments.

The present study extends previous work by investigating the effects of chemically-passive suppressants on the near-limit properties of laminar premixed hydrogen flames in microgravity. Using a new short-drop free-fall facility that allows measurement of near-limit flame properties without the disruptive effects of buoyancy, laminar burning velocities are measured for diluted stoichiometric hydrogen-air flames at atmospheric pressure using He, Ar, N2, and CO2 as suppressants. Corresponding results are also obtained for suppression of stoichiometric hydrogen flames in an atmosphere consisting of 30% oxygen and 70% nitrogen by volume at a pressure of 0.7 atm, which is the prescribed spacecraft environment for crew conditioning prior to external vehicular activities (EVA). The near-limit laminar burning velocities measured in both normal-air and EVA atmospheres are extrapolated to zero stretch to allow comparisons with corresponding computed values for unstretched laminar burning velocities. For each suppressant and both atmospheres, measured and computed values of the suppressant volume fraction needed to extinguish the flames are determined.

2. Experiment description

2.1. Apparatus

Figure 1 shows key components of the short-drop free-fall facility assembled for this investigation in the Microgravity Combustion Laboratory at the University of Michigan. The facility consists of a support tower, a free-falling spherical combustion chamber, a deceleration box, and shadowgraph optics that record the flame propagation as the chamber falls. The free-fall chamber, which has an inside diameter of 360 mm and can be operated at pressures from vacuum to 34 atm, is held at the top of the tower by an electromagnet before being dropped. As the chamber is released, a Hall-effect sensor detects the motion and sends a trigger pulse to a timer. After a short delay to allow oscillations from the chamber release to decay to required levels, a timer pulse triggers a high-voltage spark generator connected to electrodes that ignite the mixture. A second pulse triggers a high-speed digital video camera that records the flame propagation within the free-falling chamber. The free-fall duration can be made as long as 750 ms by setting the vertical position of a deceleration box below the chamber. In the present experiments, a 1-m free-fall distance is used to provide 450 ms of 10−2 g reduced gravity. After each experiment, the combustion chamber is vented and purged with air to cool it down prior to
being recharged with the desired atmosphere and hoisted up the tower for the next test.

A high-speed shadowgraph system records the flame during the fall. As indicated in Fig. 1, light from a continuous 100 W short arc-length mercury lamp is reduced by a neutral density filter and reflected from a concave mirror to form a parallel beam. Using three first surface mirrors, one fixed on the drop tower and two attached on either side of the free-fall chamber, the parallel light beam propagates through two 100 mm diameter quartz windows mounted on the each side of the chamber, and then back up the tower toward the video camera. The beam passes through a lens that directs the image onto a Phantom high-speed digital camera. The beam is reflected from a concave mirror to form a parallel beam. Using three first surface mirrors, one fixed on the drop tower and two attached on either side of the free-fall chamber, the parallel light beam propagates through two 100 mm diameter quartz windows mounted on the each side of the chamber, and then back up the tower toward the video camera. The beam passes through a lens that directs the image onto a Phantom high-speed digital video camera that records 1000 images per second.

The reactant mixture is prepared in the spherical combustion chamber by adding gases at appropriate partial pressures to reach the desired reactant mixture and test pressure. The reactants are mixed for 5–10 min using a small metal fan in the chamber, and the fan-induced motion is allowed to decay for at least 30 min before ignition. The flame is ignited by a spark at the center of the chamber from two electrodes consisting of 250 μm diameter tungsten wires having free lengths of 40 mm. The spark gap is adjusted from 0.5–3.0 mm, with larger gaps used to ignite flames having relatively small laminar burning velocities that require larger ignition energies. The spark energy is supplied by a high-voltage capacitive discharge circuit with an adjustable 0–30 kV voltage and a discharge time of roughly 5 μs. The spark gap and spark energy are adjusted be to as close as possible to the minimum ignition energies.

2.2. Data reduction

Present measurements were restricted to flames with diameters 10 mm < d < 60 mm, with the upper limit imposed so that the volume of burned gas is always less than 0.5% of the total chamber volume. As a result, the chamber pressure remains constant within 0.7% throughout the observation period, consistent with previous measurements of laminar premixed flame properties [4–6]. The lower limit on flame diameter avoids ignition disturbances and ensures that the characteristic flame thickness δD and flame radius r_f satisfy δD/r_f << 1, so that effects of curvature and transient phenomena associated with flame thicknesses were small. This is also consistent with previous measurements [4–6]. Under these assumptions, quasi-steady expressions for the laminar burning velocity and flame stretch are given [7] by

\[ S_L = \frac{\rho_b}{\rho_a} \frac{d r_f}{d t} \quad K = \frac{2}{r_f} \frac{d r_f}{d t} \quad (1a, b) \]

Here \( S_L \) is the observed flame propagation speed into the unburned gas and \( K \) is the flame stretch. Both are related to the change in flame radius \( r_f \) with time \( t \). The density ratio \( \rho_b/\rho_a \) was obtained from CET93 assuming adiabatic constant-pressure combustion with chemical equilibrium in the combustion products [8] and the same volume fractions of elements in the unburned and burned gases [4–6]. The flame radius \( r_f (t) \) was measured from the shadowgraph images along the direction perpendicular to the spark electrodes, where disturbances of the flame surface by the electrodes are minimal. Final results were averaged over measurements from three to five tests at each condition, with 95% confidence intervals characterizing uncertainties in the reported values.

2.3. Unstretched laminar burning velocities

From Markstein [9] and Clavin [10], the laminar burning velocity \( S_L \) is related to the flame stretch \( K \) for small to moderate values of curvature and stretch as

\[ S_L = S_{L\infty} - L K, \quad (2) \]

where \( S_{L\infty} \) is the laminar burning velocity for an unstretched planar flame. The Markstein length \( L \) is a measure of the flame response to the stretch rate \( K \), and can be either positive (preferential-diffusion stable) or negative (preferential-diffusion unstable), depending on the reactants. The unstretched laminar burning velocities \( S_{L\infty} \) were
obtained by extrapolating the measured stretched laminar burning velocities $S_L(K)$ from Eq. (1a, b) to zero stretch. Since this study only involves suppressed stoichiometric hydrogen flames (the neutral preferential-diffusion condition of hydrogen/air flames is at fuel equivalence ratio of 0.8–0.9 [5]), the effects of stretch are relatively weak compared to fuel-rich or fuel-lean conditions. All measurements reported herein were made before any flame instabilities were observed. The resulting uncertainty in the measured $S_L(1)$ values based on the 95% confidence intervals is typically below 10%, with the largest uncertainties corresponding to extremely slow thick flames, for which the radius is more difficult to measure.

3. Laminar burning velocity calculations

Numerical calculations of unstretched flame speeds were carried out using the steady, one-dimensional laminar premixed flame code PREMIX, with the updated comprehensive kinetic model for hydrogen combustion due to Li et al. [11]. CHEMKIN was used as a preprocessor to determine thermochemical and transport properties from the database of Kee et al. [12], except for HO$_2$, for which the recommendations of Kim et al. [13] were used. An optically thin model was used to calculate the radiative heat loss from CO$_2$ and H$_2$O. Planck absorption coefficients were taken from Kuznetsov and Sabelnikov [14]. The resulting computed unstretched burning velocities $S_L(1)$ were compared for each suppressant type and concentration with the corresponding measured values obtained as described above.

4. Results and discussions

4.1. Effects of gravity

In previous 1-g experiments [4], for undiluted or moderately-diluted mixtures corresponding to $S_L(1) > 20$ cm/s, the observed flame front remained spherical throughout the measurement. In such cases, the laminar burning velocities obtained in 1-g and μ-g experiments are essentially the same. However for more highly-diluted slower-burning mixtures, flames in 1-g become noticeably buoyant, with the flame reaching the top of the chamber before the bottom. At very high dilution levels corresponding to slowly-burning near-limit mixtures, a flame at 1-g cannot even propagate downward against the flow induced by buoyancy. As a result, experiments in microgravity become essential for measuring the near-limit flame properties. A typical example is shown in Fig. 2, corresponding to 1-g and μ-g realizations of a stoichiometric hydrogen-air mixture with 64% N$_2$ dilution. At 1-g the burned gases are seen to move upward to form a classical mushroom shape, while in μ-g the flame remains smooth and spherical. The present microgravity experiments thus permit accurate measurements of the flame radius $r_f(t)$ up to the extinction limit. This in turn allows accurate determination of the laminar burning velocity $S_L$ and the flame stretch $K$ via Eq. (1a,b) and the unstretched laminar burning velocity $S_L(1)$ via Eq. (2).

4.2. Burning velocities

The short-drop free-fall facility was used to measure the unstretched laminar burning veloci-

![Fig. 2. Burning sequences of stoichiometric H$_2$/air/64% N$_2$ flames (H$_2$:O$_2$:N$_2$ = 2:1:15.78) at 1 atm after ignition: (a), 1-g; (b), μ-g.](image-url)
ties $S_{L\infty}$ of stoichiometric hydrogen-air flames for each suppressant type and concentration as described above. The $S_{L\infty}$ values measured at atmospheric pressure are shown in Fig. 3, with corresponding results for the EVA atmosphere shown in Fig. 4. Results are given as functions of the suppressant volume fraction, with the corresponding computed values shown for comparison. The oxygen index, also shown in the lower axis, is the volume fraction of oxygen in the reactant mixture as a percentage of the non-fuel gases. The measured values of $S_{L\infty}$ for suppressant volume fractions below 40% are from previous 1-g experiments [4]. Since the burning velocities in those cases generally exceed 20 cm/s, gravity effects can be neglected and direct comparisons with the present $\mu$-g results can be made. For suppressant volume fractions above 40%, in most cases the 1-g flame was not sufficiently spherical to obtain meaningful values of the flame radius $r_f(t)$ and thus laminar burning velocities are reported only from the $\mu$-g measurements. The uncertainties in the measured $S_{L\infty}$ values are shown by 95% confidence intervals.

The results in Fig. 3 show that all suppressants cause $S_{L\infty}$ to decrease as the suppressant concentration is increased. The relative effectiveness for the suppressants, defined by the reduction of the unstretched laminar burning velocity at any fixed suppressant concentration, increases in order
from helium to argon, nitrogen, and carbon dioxide, with the latter being most effective. For argon, nitrogen, and carbon dioxide the observed trend can be explained by the simple increase in the specific heat of the non-fuel gases per unit oxygen concentration [15]. This causes a corresponding reduction in the reaction zone temperatures of these flames, and an associated reduction in their laminar burning velocities [16]. However helium represents an exception, since its specific heat is identical to that of argon, and thus demonstrates that the simple specific-heat effect alone cannot account for the observed relative suppressant effectiveness. For helium, the reduction in flame speed produced by the specific-heat effect is partly offset by the increase in heat and mass transfer rates into the reactant mixture from the substantially higher diffusivity of helium, which act to increase $S_{L\infty}$ when helium is present. The specific-heat effect is dominant, since the suppressant effectiveness still increases with increasing helium concentration, but the net result is to render helium less effective than argon. We were not able to measure near-limit velocities for helium dilution. These slow flames require a much higher ignition energy and the flame shape is not spherical, which may be due to fast diffusion of helium atoms. This topic requires further study.

For the EVA atmosphere in Fig. 4, the higher suppressant effectiveness of CO$_2$ relative to N$_2$, is consistent with the simple specific-heat effect noted above. As expected, the higher oxygen concentration (30%) in the EVA atmosphere increases the resulting $S_{L\infty}$ values relative to the corresponding cases in Fig. 3. However the lower pressure in the EVA atmosphere reduces the mass-burning rate at the same $S_{L\infty}$ value. The net result is that, for the same suppressant type and concentration, the mass-burning rates are only about 10% larger in the EVA atmosphere in Fig. 4 than for the air atmosphere in Fig. 3.

4.3. Flammability limits

Figures 3 and 4 show that for each suppressant there is a maximum concentration above which no flame will propagate in the present experiments. Previous computations [17] suggested that there is no purely chemical flammability limit for unstretched laminar flames without heat losses, and that $S_{L\infty}$ will instead decrease asymptotically to zero as the dilution by an inert suppressant increases. Other calculations, including radiation heat loss [18,19] suggested heat loss could play a significant role in flame extinction and showed a limiting flame speed of 2 cm/s. In addition, practically all experimental studies of flammability limits have suggested that the laminar burning velocity at the flammability limit, here denoted by $S_{L\infty, \text{lim}}$, is not zero and instead is on the order of a few cm/s. The present results in Figs. 3 and 4 are consistent with this.

Despite many studies to date, there is no agreement on the true value of $S_{L\infty, \text{lim}}$. If for the moment we accept the computational [18] and experimental [1] results that suggest $S_{L\infty, \text{lim}} \approx 2$ cm/s, then we can use the measured $S_{L\infty}$ values in Figs. 3 and 4 to estimate the concentration of each suppressant needed to extinguish a hydrogen flame in air and EVA atmospheres. This is done by extrapolating the measured near-limit laminar burning velocities to determine where $S_{L\infty}$ would reach 2 cm/s. The resulting extrapolated limits for stoichiometric H$_2$/air and H$_2$/EVA flames are given in Table 1 in terms of the suppressant volume fraction in the reactant mixture, as well as the corresponding suppressant volume fraction in the non-fuel gases and the limiting oxygen index. Although the extrapolation is based on a flammability limit criterion about which there remains some uncertainty, the purpose is to estimate the amount of suppressant needed to extinguish a hydrogen flame. Table 1 also gives the flammability limits of stoichiometric hydrogen in air diluted with nitrogen or carbon dioxide, as measured by Coward and Jones [20], for upward propagation in a closed vertical tube. These limits are only slightly lower than those we measured.

The practical significance of the above estimate demonstrates the fundamental importance of accurately determining the true nature of the extinction limit for laminar premixed flames.

Table 1

| Flammability limits of hydrogen flames ($\phi=1.0$): suppressant volume fraction at $S_{L\infty} \approx 2$ cm/s |
|-----------------|-----------------|-----------------|-----------------|
| Supp            | $X_{\text{Supp}}^a$ | $X_{\text{Supp}}^b$ | Oxygen index |
| H$_2$ in air    |                 |                 |               |
| Ar              | 75              | 81              | 4.1           |
| N$_2$           | 67              | 74              | 5.5           |
| CO$_2$          | 52              | 61              | 8.4           |
| H$_2$ in EVA    |                 |                 |               |
| N$_2$           | 75              | 82              | 5.3           |
| CO$_2$          | 62              | 72              | 8.4           |

$X_{\text{Supp}}^a$ denotes suppressant volume fraction in the reactant mixture in this work.

$X_{\text{Supp}}^b$ denotes suppressant volume fraction in the non-fuel gases in this work.

$X_{\text{Supp}}$ denotes suppressant volume fraction in the non-fuel gases by Coward and Jones [20].
As noted above, computational results [18] and experimental results [1,2] including those in Figs. 3 and 4 suggest that the flammability limit corresponds to a non-zero value of $S_{L,\infty,\lim}$. In any given experiment, near the flammability limit it is likely that small disturbances produced by buoyant convection or hydrodynamic strain could potentially account for the observed non-zero extinction limits. Additionally, heat losses in most experiments due to radiation or conduction could also cause the observed non-zero extinction limits [21]. However in the present microgravity experiments, buoyant convection and hydrodynamic strain have been essentially eliminated, as noted above. Moreover, the 180 mm radius of the present spherical chamber is sufficiently large in comparison with the $r_f < 30$ mm flames for heat losses by conduction to the walls or to the 250 $\mu$m tungsten electrodes to also be negligible. This suggests that, in the present experiments, radiative heat loss to the chamber wall is likely to be the sole remaining experimental factor that could realistically account for the observed non-zero values of $S_{L,\infty,\lim}$ in Figs. 3 and 4.

4.4. Discrepancies in computed burning velocities

There is evidence that shortcomings in the chemical kinetic mechanism may be at least partly responsible for differences between the measured and computed results in Figs. 3 and 4. The respective $S_{L,\infty}$ values are seen to agree reasonably well at low suppressant concentration, but to diverge at higher concentrations as the observed extinction limits are approach. For the hydrogen-air flame with 56% $N_2$ dilution, the computed $S_{L,\infty}$ is only about half of the measured value. Consistent with this, Wu and Ronney [22] have previously found that standard chemical kinetic mechanisms yield smaller flame balls, lower flame speeds, and richer flammability limits than do measurements. Egolfopoulos and Law [23,24] also found that the standard kinetic mechanisms underpredict the flame speed for strained pre-mixed hydrogen-air flames as the fuel equivalence ratio is decreased. Now we use sensitivity analysis to examine whether improvements in the chemical mechanism are needed to obtain more accurate computed results for near-limit flames. Other relevant processes could be molecular transport mechanisms and radiation heat losses of near-limit flames, both of which will be considered in future work.

To identify the most important elementary reactions of hydrogen flames at various degrees of dilution, a sensitivity analysis of $S_{L,\infty}$ respect to reaction rate coefficients was performed for stoichiometric $H_2/EVA$ flames diluted with 40%, 60%, and 66% $N_2$ by volume. The results, shown in Fig. 5, indicate that the chain-propagation and chain-branching reactions have positive sensitivities on $S_{L,\infty}$ while the chain-termination reactions have negative sensitivities. Increasing the $N_2$ volume fraction increases the corresponding sensitivities, yielding the largest sensitivities at the largest $N_2$ volume fraction. For the 40% $N_2$ flame, two-body chain branching reactions are dominant. For the near-limit 66% $N_2$ flame, the sensitivity to the three-body chain-termination reaction $H + O_2 + M = H_2O_2 + M$ becomes comparable with the sensitivity to the chain-branching reactions. This indicates that, as the extinction limit is approached, this chain-termination reaction increasingly controls the flame.

Figure 5 suggests the possibility that a substantial part of the discrepancy between the measured and computed $S_{L,\infty}$ values in Figs. 3 and 4 may be due to the three-body recombination rates for $H + O_2 + M = HO_2 + M$ reactions, and in particular to the third-body chaperon efficiency of various species M. This is made even more likely by the fact that for the present measured values considerable care has been taken to reduce imperfections in the experiments that might otherwise be relied on to account for this difference. The $H + O_2 + M = HO_2 + M$ recombination reactions are extremely important for highly-diluted near-limit flames, due to the competition between chain-branching and chain-terminating reactions near the flammability limit. However, it is less important far away from the limits. This is consistent with the increasing discrepancies in Figs. 3 and 4 between measured and computed $S_{L,\infty}$ values as the suppressant concentrations are increased, and suggests poten-
tial value in measurements and computations to better define the third-body efficiencies in this key reaction.

5. Conclusions

A short-drop free-fall microgravity facility at the University of Michigan has been used to accurately measure near-limit unstretched laminar burning velocities for varying concentrations of several inert diluents in stoichiometric hydrogen-air and hydrogen-EVA flames. Results show that these chemically-passive flame suppressants perform in order of increasing effectiveness from helium, to argon, nitrogen, and carbon dioxide. This is consistent with their effects on the specific heat and transport properties of the reactant mixture. The volume fraction of each suppressant required to extinguish stoichiometric H₂/air or H₂/EVA flames, estimated by extrapolating the measured near-limit laminar burning velocities to 2 cm/s, was found to be 75% Ar, 67% N₂ or 52% CO₂ by volume in the reactant mixture for the H₂/air flame, and 75% N₂ or 62% CO₂ for the H₂/EVA flame.

Computed values for the unstretched laminar burning velocities using current chemical kinetic mechanisms were found to be in good agreement with corresponding measured values far from the extinction limit. However the computed values become substantially lower than the measured values at large suppressant concentrations as the flammability limit is approached, even though considerable care has been taken to reduce imperfections in the present experiments that might otherwise account for these differences. The increasing sensitivity of the burning velocity to the three-body chain-termination reactions H + O₂ + M = HO₂ + M as the extinction limits is approached suggests that possible improvements in the third-body chaperon efficiencies may be needed to reconcile computed flammability limits with the present measured values.

Acknowledgment

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References


Comments

James W. Fleming, Naval Research Laboratory, USA. While the precision may be quite good, the accuracy (absolute value) of an experimentally determined burning velocity depends on the measurement approach. Can the disagreement you show in your modeling and experimental burning velocity results be attributed to your measurement method?

Reply. Laminar burning velocity was defined in the same way for both experiments and simulations, as the velocity of the flame front with respect to the unburned...
gas. For a spherically propagating flame in a closed chamber, the laminar burning velocity follows Eq. (1a) \([7]\) in the paper, under the assumption of a thin flame. Accordingly, measurements of flame speed were limited to conditions where the flame radius was much larger than the characteristic flame thickness, so the different definitions of the flame front should have negligible impact on the flame speed. Consequently, we believe other factors such as chemical kinetics and transport properties contribute more to the observed near-limit discrepancies.

Ronald S. Sheinson, Naval Research Laboratory, USA. Our experimental extinction studies on \(n\)-heptane cup burner diffusion flames \([1]\) observed suppressant efficiency increased from argon to neon to helium, in accordance with increasing thermal conductivity/diffusion. Atomic helium was approximately as efficient as diatomic nitrogen. Molar efficiency of polyatomic suppressants did scale with heat capacity, as modeled in our paper.

In our flame extinction modeling of 1-D premixed stoichiometric hydrogen/air plus suppressant, we determined that while heat capacity was the major suppressant factor for polyatomics, for nitrogen it contributed 50%, and for helium \(C_p\) contributed only 15%. Dilution and thermal conductivity were the dominant flame extinction factors for helium.

As helium near-limit flames are very diffuse and slow, I propose you would have seen extinction at lower helium concentrations if the experimental drop tower times were longer. It can be similarly difficult to define clear extinction criteria for modeling without excessively long computation time simulations. Flame propagation merges smoothly into slow oxidation. Assigning arbitrary minimum flame propagation velocity criteria is artificial, but useful with proper sensitivity considerations.

Reference


Reply. This is consistent with our results. As shown in Fig. 3, for a given suppressant mole fraction, helium flames have higher burning velocities than argon flames due to the higher thermal conductivity and mass diffusivity of helium, even though they have the same specific heat. However, the results in Fig. 3 also show that stoichiometric hydrogen/air flames at NTP can be ignited and propagate spherically for argon mole fractions up to 73%, while the helium flames could not be ignited at helium mole fractions above 66%, suggesting that the extinction limit for helium is lower than for argon. This is consistent with the commenter’s 1-D modeling results.