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The Effect of Hydrogen Addition on Flammability Limit and NOx Emission in Lean Counterflow CH₄/Air Premixed Flames

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Abstract

The effect of hydrogen addition to lean counterflow CH₄/air premixed flames on the extinction limits and the characteristics of NOx emission was investigated by numerical simulation. The detailed chemistry and complex thermal and transport properties were employed. The results show that the addition of hydrogen can significantly enlarge the flammable region and extend the flammability limit to a lower equivalence ratio. If the equivalence ratio is kept constant, the addition of hydrogen increases the emission of NO in a flame, due to the enhancement in the rate of the NNH or N₂O intermediate NO formation route. When the equivalence ratio is relatively higher, the addition of hydrogen causes a monotonously decrease in the formation of NO₂ and
N$_2$O. However for relatively lower equivalence ratio flames, the emission of NO$_2$ and N$_2$O first increases, and then decreases with the increase in the fraction of hydrogen.

*Key words:* Hydrogen enrichment, NOx, extinction limit, premixed flame.
1. Introduction

The addition of hydrogen to a hydrocarbon flame is of great interest for combustion scientists and engineers. It can improve the burning stability for extra lean combustion and reduce the greenhouse gas and pollutant emission, such as CO₂, CO, unburned hydrocarbon and soot particles. The development of hydrogen enrichment technology has motivated studies in understanding the effect of hydrogen addition on extinction and NOx emission characteristics in extra lean premixed flames.

The extinction characteristics of stretched methane and hydrogen premixed flames have been extensively studied [1-5]. The influence of hydrogen addition on the response of lean premixed CH₄ flames to high strained flows was recently investigated by Jackson et al. [6]. It is showed that the addition of hydrogen to methane extended the stretch extinction limit and thus could improve the lean premixed flame stability. Another extinction limit at lower stretch rate, known as radiation extinction limit [2-5], was not investigated in [6]. Many researchers have studied NOx emission in various hydrocarbon and hydrogen flames, such as [7-12]. Rørtveit et al. [13] reported a comparison of low-NOx burners for combustion of methane and hydrogen mixtures. They indicated that the addition of hydrogen to natural gas or methane resulted in an increase in NOx for most burners, and a slight decrease in NOx for one burner. Therefore further studies are required to understand the detailed effect of hydrogen addition to hydrocarbon flames on the extinction limits and the characteristics of NOx emission.

Theoretically the addition of hydrogen to a hydrocarbon fuel may reduce the prompt NO due to the decrease in hydrocarbon radicals in a flame, if the flame temperature is
keeping constant. However the thermal NO may be increased because of the rise in flame temperature. In addition, the NO from NNH mechanism [12] also may increase compared to a pure hydrocarbon flames. The combined effects of these factors determine the net influence of hydrogen addition on NOx emission in lean hydrocarbon premixed flames.

In this paper, the effect of hydrogen addition on the characteristics of extinction and NOx emission in lean counterflow CH$_4$ premixed flames is investigated by numerical simulation. Detailed chemistry and complex thermal and transport properties were used. Following the numerical model section, we first present and simply discuss the effect of hydrogen addition on the flammable region and flammability limit of lean counterflow methane/air premixed flames. Then detailed discussion is provided on NOx emission characteristics in hydrogen enriched lean methane premixed flames. Finally conclusions are given.

2. Numerical Model

The studied flame configuration is an axisymmetric laminar counterflow premixed flame, stabilized near the stagnation plane of two opposed-jets.

The simulations assumed the stagnation point flow approximation. The governing equations can be found elsewhere [14]. The potential boundary conditions were used. The calculations were carried out with a code revised from that of Kee et al. [15]. Upwind and center difference schemes were respectively used for the convective and diffusion terms in all the governing equations. Adaptive refinement of meshes was done. The arc-length
continuation method [16] was employed to obtain the extinction limits. The pressure and the fresh mixture temperature were, respectively, 1 atm and 300 K.

The previous investigation [17] using an improved radiation model, in which the radiation reabsorption was taken into account, showed that the resorption has little influence on the extinction limits and temperatures of lean counterflow CH₄/air premixed flames. To simplify the calculation, the optically thin radiation model, employed in the previous study [3], was used in the present calculation to save the computation time.

The chemical reaction mechanism used is essentially from GRI-Mech 3.0 [18]. The thermal and transport properties were obtained by using the database of GRI-Mech 3.0 and the algorithms given in [19, 20]. The thermal diffusion velocity of H₂ and H was accounted for, while that of other species was ignored.

It has been known that NO can be formed through thermal, N₂O intermediate, and prompt routes [7-11], based on the initiation reactions by which molecular nitrogen is converted to atom nitrogen or other intermediate species containing element nitrogen. The thermal NO formation is comprised of the three reactions: \( N + NO = N₂ + O \), \( N + O₂ = NO + O \) and \( N + OH = NO + H \), of which the first one is the initiation reaction. The N₂O intermediate route is initiated by the reactions: \( N₂O (+M) = N₂ + O (+M) \), \( N₂O + H = N₂ + OH \), \( N₂O + O = N₂ + O₂ \) and \( N₂O + OH = N₂ + HO₂ \), and then the formed N₂O is partially converted to NO. The prompt NO in hydrocarbon flames is initiated by the rapid reactions of hydrocarbon radicals with molecular nitrogen [7]. In addition, NO formation can also be initiated by the reactions of molecular nitrogen with other hydrocarbon free radicals, such as H, OH, H₂. These reactions include: \( NH + N = N₂ + H \), \( NH + NO = N₂ + OH \), \( NNH = N₂ + H \), \( NNH + M = N₂ + H + M \), \( NNH + O₂ = HO₂ + N₂ \), \( NNH + O = OH \).
+ N₂, NNH + H = H₂ + N₂, NNH + OH = H₂O + N₂, and NNH + CH₃ = CH₄ + N₂. Please note that although the last reaction is initiated by CH₄, we also attribute it to this route due to NNH. This route to form NO is called NNH intermediate route [12]. To identify the relative importance of the four routes to NO formation in current study, four simulations were carried out for each flame. The first simulation (SIM1) was conducted by the full chemistry (GRI-Mech 3.0), while the second simulation (SIM2) was carried out by removing the initiation reactions of the prompt routes. In the third simulation (SIM3), the initiation reactions of both the prompt and NNH intermediate routes were removed. All the initiation reactions of the prompt, N₂O and NNH intermediate routes were removed in the forth simulation (SIM4). Consequently NO obtained from SIM4 can be attributed to from the thermal mechanism. The difference in NO between SIM1 and SIM2 is attributed to from the prompt route, and the difference between SIM2 and SIM3 is due to the NNH intermediate route. The NO contributed by the N₂O intermediate route is the difference between SIM3 and SIM4.

3. Results and Discussions

A stretch rate of 30 1/s was used for all the flames. This choice was arbitrary. The fuel used is a mixture of methane and hydrogen, with \( \alpha_{H_2} \) being the fraction of hydrogen, i.e. \( \alpha_{H_2} = \frac{V_{H_2}}{V_{H_2} + V_{CH_4}} \), where \( V_{H_2} \) and \( V_{CH_4} \) are the volume flow rates of hydrogen and methane, respectively. The variable \( \phi \) represents the equivalence ratio in all the plots. Since the objective of this paper is to study the effect of hydrogen enrichment in extra lean premixed flames, the equivalence ratio investigated was limited
less than 0.7 and the fraction of hydrogen was up to 0.4 for most cases. However for the sake of comparison, the hydrogen fraction of 1.0 (pure H\textsubscript{2}/air premixed flame) was reached in some cases. Unless explicitly indicated, the results were obtained by the full Gri-Mech 3.0 chemistry.

3.1. Effect of Hydrogen Addition on Extinction Limits

It has been well known that for a given equivalence ratio lean CH\textsubscript{4}/air or H\textsubscript{2}/air mixture, there are two extinction limits when the stretch rate varies. One is caused by an extra high stretch rate due to the shortened residence time, and the other is caused by an extra low stretch rate because of the radiation heat loss. The former is usually called “stretch extinction limit”, and the latter is named as “radiation extinction limit”. If all the extinction limits and the corresponding equivalence ratios are plotted in a stretch rate – equivalence ratio plane, a C-shaped curve can be formed [3]. The upper branch of the curve is the stretch extinction limit branch, and the lower branch is the radiation extinction limit branch. The region bounded by the two extinction limit branches is the flammable region of counterflow lean premixed flames. At a critical equivalence ratio, the two branches merge at one point. This critical equivalence ratio is the flammability limit of counterflow lean premixed flame. If the equivalence ratio is lower than the flammability limit, a steady counterflow premixed flame cannot exist regardless of the values of the stretch rate.

The effect of hydrogen addition to lean methane/air counterflow premixed flames was investigated in this paper. Since the NOx chemistry usually has negligible effect on
flame temperature and structure, the reactions and species related NOx formation were removed (except N\textsubscript{2}) in the calculations of extinction limits to simplify the calculation.

Figure 1 shows the C-shaped curves of the flames with four different hydrogen fractions being 0.0, 0.1, 0.2 and 0.4, respectively. It should be pointed out that although the reaction schemes used in this paper and in the previous study [3] are different, the same flammability limit (0.42) was obtained for the pure counterflow CH\textsubscript{4}/air lean premixed flame. It is observed from Fig.1 that the addition of hydrogen increases the stretch extinction limit and reduce the radiation extinction limit for a given equivalence ratio lean counterflow CH\textsubscript{4}/air premixed flame. The effect of hydrogen addition is enhanced with the increase in the fraction of hydrogen. With the fraction of hydrogen is increased from 0.0 to 0.4, the flammability limit is extended from 0.42 to 0.335. Two reasons cause the phenomenon. The first reason is that hydrogen has a higher flame speed and a lower flammability limit than CH\textsubscript{4}. Secondly, the Lewis number of a H\textsubscript{2}/air mixture is lower than that of a CH\textsubscript{4}/air mixture. The preferential diffusion of H\textsubscript{2} results in the higher combustion intensity in a H\textsubscript{2}/CH\textsubscript{4}/air flame than in a CH\textsubscript{4}/air flame for a given equivalence ratio. As a result, the flammable region of a flame is enlarged and the flammability limit is extended to a lower equivalence ratio, with the addition of hydrogen. These observations are qualitatively consistent with the results by Jackson et al. [6] who however did not studied the radiation extinction limit.

Therefore we can conclude that the addition of hydrogen to a CH\textsubscript{4}/air premixed flame can significantly improve the combustion stability. This is the biggest advantage of the hydrogen enrichment technology. It allows a combustor to operate under extra lean condition, and thus reduce the emission of green house gas, such as CO\textsubscript{2}. For example,
the stretch extinction limit of the flame with the equivalence ratio of 0.5 and the hydrogen fraction of 0.4 is even higher than that of the pure CH₄/air premixed flame with the equivalence ratio of 0.65, as shown in Fig.1.

The two stable flame phenomenon found in [4, 5] was not investigated in this paper, since it is beyond the current objective.

### 3.2. NO Emission

Figure 2 shows the distributions of NO mole fractions in counterflow premixed flames with equivalence ratios of 0.47 and 0.55, when the fraction of hydrogen varies from 0.0 to 1.0 (from pure CH₄/air to pure H₂/air premixed flame). It is clearly indicated that the addition of hydrogen increases the emission of NO in a counterflow premixed CH₄/air premixed flame if the equivalence ratio is kept constant. With the increase of the hydrogen fraction, NO concentration rises. The flames of other equivalence ratios have qualitatively similar results.

Figure 3 displays the variations of NO emission indices in the flames of equivalence ratios of 0.47 and 0.55, obtained by the four simulations (SIM1 to SIM4), when the fraction of hydrogen varies from 0 to 1.0. Being different from the conventional definition, the emission index in this paper is defined based on the consumption of oxygen, i.e. $EI_{NO} = \frac{\text{the ratio of the formed NO mass to the consumed molecular oxygen mass}}{\text{rather than the consumption of fuel. The reason is that hydrogen is not only the parent fuel, but also an intermediate species in this study. It is observed that the contributions of the thermal and prompt routes to the total NO emission are very small in}}$
these flames. This is because these flames are extra lean and the temperatures are very low. The two significant routes of NO formation in the pure CH$_4$/air premixed flames ($\alpha_{H_2} = 0.0$) are the N$_2$O and the NNH intermediate routes. However, with the increase of the hydrogen fraction, the contribution of the NNH intermediate route quickly rises, while those of other three routes change very slowly, except for the flames with the equivalence ratio of 0.47 at lower hydrogen fraction ($\alpha_{H_2} < 0.2$). When the pure H$_2$/air premixed flames ($\alpha_{H_2} = 1.0$) are reached, the contribution of the prompt route disappears, and the NNH intermediate route dominates the NO formation. For the flame with the equivalence ratio of 0.47, when the fraction increases from 0.0 to 0.2, the contribution of the N$_2$O intermediate route rises much faster than the other three routes.

Figure 4 displays the NO emission indices of the flames with the equivalence ratio of 0.7, when the fraction of hydrogen varies from 0.0 to 0.4. Being different from the flames with the equivalence ratios of 0.47 and 0.55, it is found that the contributions of the thermal and prompt routes to NO formation in these flames relatively increase. It is because the increase in the flame temperatures and methane concentrations. Due to the flame temperature increase, the contribution of the thermal route slowly increases with the rise of the hydrogen fraction. Similar to the flames with the equivalence ratios of 0.47 and 0.55, it is also observed that the contribution of the NNH intermediate route to the total NO formation rises faster than the three other routes, when the fraction of hydrogen increases.

From the above results we can conclude that the rise of NO formation rate with the increase of the added hydrogen fraction is mainly caused by the rise of the NNH
intermediate route, except for the flame with very low equivalence ratio and at lower hydrogen fraction.

A sensitivity analysis indicates that the two most significant initiation reactions of the NNH intermediate NO formation route are \( \text{NNH} = \text{N}_2 + \text{H} \) and \( \text{NNH} + \text{M} = \text{N}_2 + \text{H} + \text{M} \), and the most important NNH destruction reaction is \( \text{NNH} + \text{O}_2 = \text{HO}_2 + \text{N}_2 \). With the increase of the hydrogen fraction, the concentration of H and the temperature in a flame increase if the equivalence ratio is kept constant. As an example, this is shown in Fig.5 for the flames with the equivalence ratio of 0.55. Therefore the NO formation rate by the NNH intermediate route quickly increases. Later we'll show that the \( \text{N}_2\text{O} \) concentration actually decreases with the increase of the hydrogen fraction in the flames with the equivalence ratio of 0.55, which cause the NO from the \( \text{N}_2\text{O} \) intermediate route varies little. As a result, the increase of total NO emission in the flame with the equivalence ratio of 0.55 is mainly due to the NNH intermediate route, when the hydrogen fraction is increased. The flames with higher equivalence ratios are qualitatively similar to the flame with the equivalence ratio of 0.55.

When the equivalence ratio is 0.47, the flame temperature reduces and the concentration of oxygen increases. The formed NNH is quickly converted back to molecular nitrogen by the reaction \( \text{NNH} + \text{O}_2 = \text{HO}_2 + \text{N}_2 \). Consequently the contribution of the NNH intermediate route to the total NO formation varies little, when the fraction of hydrogen begins to increase from zero to a lower value. On the other hand, the \( \text{N}_2\text{O} \) intermediate route dominates the NO formation in this kind of flames. With the increase of the hydrogen fraction from zero to a lower value, the increase in the \( \text{N}_2\text{O} \) formation rate is greater than that of its destruction rate, as we shall discuss later. Therefore the
contribution of the N₂O intermediate route quickly increases, which cause the total NO emission increases. With the further increase in the fraction of hydrogen, both the temperature and the concentration of H rise to relatively higher levels. The rate of the NNH formation reaction exceeds that of its destruction reaction, and the situation for N₂O formation and destructions reverses. Consequently the NNH intermediate route dominates the NO formation and causes the rise of NO formation rate as the fraction of hydrogen is further increased, like the flames with the equivalence ratio of 0.55.

The above results and discussions conclude that the addition of hydrogen to a lean counterflow CH₄/air premixed flame causes the NO formation increases, because the contribution from the NNH (usually) or N₂O (at very low equivalence ratio and hydrogen fraction) intermediate route rises. However we should point out that this conclusion does not mean that the hydrogen enrichment technology has no advantage in terms of NO emission. As indicated before, since the addition of hydrogen can extend the flammability limit to lower equivalence ratio and enlarge the flammable region, the hydrogen enrichment technology allows a combustor to operate at lower equivalence ratio. Fig. 6 shows the NO emission indices for flames with the equivalence ratio varying from 0.47 to 0.70 and the hydrogen fraction being 0.0, 0.2 and 0.4. It is illustrated that the decrease in the equivalence ratio can significantly reduce the emission of NO. If the operating equivalence ratio of a combustor is decreased from 0.65 to 0.5 by 40% hydrogen enrichment, the NO emission index is reduced from 0.025 to 0.007 g-No/kg-O₂. From this viewpoint, we can say that the hydrogen enrichment can significantly reduce the emission of NO.
3.3. \textit{NO}_2 \textit{Formation}

Figure 7 displays the distributions of NO\(_2\) mole fractions in the flames with the equivalence ratios of 0.47 and 0.55, when the fraction of hydrogen is increased from 0.0 to 1.0. Different phenomena are observed for the flames with these two equivalence ratios. When the equivalence ratio equals 0.55, the concentration of NO\(_2\) monotonously decreases with the increase in the fraction of hydrogen. However, the NO\(_2\) concentration first increases when the fraction of hydrogen is raised from 0.0 to 0.2, and then decreases with the further increase in the fraction of hydrogen for the flames with the equivalence ratio of 0.47.

The main NO\(_2\) formation and destruction reactions are HO\(_2\) + NO = NO\(_2\) + OH and NO\(_2\) + H = NO + OH, respectively. The activation energy of the former one is negative, and the latter one is positive. When the equivalence ratio equals 0.55, with the increase in the fraction of hydrogen, both the flame temperature and the concentration of NO increase, Figs. 2a and 5. As a result of a negative activation energy, the rate of the NO\(_2\) formation reaction HO\(_2\) + NO = NO\(_2\) + OH changes very slowly, in spite of the increase in the concentration of NO. On the other hand, the increase in both the concentration of H and the temperature causes the rate of the NO\(_2\) destruction reaction relatively quickly raises when the fraction of hydrogen is increased. The combined variations in the rates of the formation and destruction reactions lead to the monotonous decrease in NO\(_2\) concentration with the increase in the fraction of hydrogen.

For the flames with the equivalence ratio of 0.47, the flame temperature is too low. When the fraction is increased from 0.0 to 0.2, the increase in the concentration of H and
the temperature is very limited. However the concentration of NO rises relatively quickly due to the N₂O intermediate route, as shown in Figs. 2b and 3b. Therefore the NO₂ concentration first increases. With the further increase in the fraction of hydrogen, the situation similar to the flames with the equivalence ratio of 0.55 occurs, because of the increased flame temperature and concentration of H.

Figure 8 illustrates the peak NO₂ mole fractions in flames with the equivalence ratios from 0.47 to 0.7 and the hydrogen fractions of 0.0, 0.1, 0.2 and 0.4. It is found that for the flames with equivalence ratio greater than 0.50, the NO₂ concentration monotonously decreases with the increase in the fraction of hydrogen. The flames with the equivalence ratio less or equal to 0.5 have the phenomenon similar to the flames of the equivalence ratio of 0.47, but the different transition hydrogen fraction value.

3.4. N₂O Emission

The distributions of N₂O mole fractions in the flames with the equivalence ratios of 0.47 and 0.55 are shown in Fig.9. We can find that the concentration of N₂O monotonously decreases with the increase in the fraction of hydrogen, if the equivalence ratio is kept at 0.55. Similar to the phenomenon for NO₂, when the equivalence is reduced to 0.47, the concentration of N₂O first rises with the increase of the hydrogen fraction from 0.0 to 0.4. With the further increase of the hydrogen fraction, the N₂O concentration decreases. This is also because of the combined effects of flame temperature, concentrations of H and O.
The most important formation and destruction reactions of N₂O are N₂O (+M) = N₂ + O (+M) and N₂O + H = N₂ + OH, respectively. When the equivalence ratio equals 0.55, the increase in the fraction of hydrogen causes the concentration of H to rise quickly, as in Fig.5, which results in the increase in the rate of N₂O destruction reaction to be greater than that of the formation reaction. Therefore the concentration of N₂O monotonously decreases with the increase of the hydrogen fraction.

As the equivalence ratio is 0.47, the flame temperature is lower and the concentrations of nitrogen and oxygen are relatively higher. When the fraction of hydrogen is raised from 0.0 to 0.4, the increase in the rate of the formation reaction is greater than that of the destruction reaction, because of the rise in flame temperature but very limited increase in H concentration. With the further increase in the fraction of hydrogen, the higher concentration of H causes increase in the destruction rate to exceed that of the formation reaction. Therefore the concentration of N₂O first increases, and then decreases with the rise in the fraction of hydrogen, when the equivalence ratio is 0.47.

Figure 10 shows the peak N₂O mole fractions for the flames with the equivalence ratios from 0.47 to 0.7 and the fractions from 0.0 to 0.4. Like for NO₂, we find that when the equivalence ratio is greater than 0.5, the concentration of N₂O monotonously decrease with the increase in the fraction of hydrogen. If the equivalence ratio is less or equal to 0.5, the concentration of N₂O first increases, and then decreases, when the fraction of hydrogen is increased.
It is also noted that the \( \text{N}_2\text{O} \) concentration actually increases with the reduction of the equivalence ratio for a given hydrogen enrichment fraction, except at very low equivalence ratio. This is a side effect of the extra lean combustion technology.

**Conclusions**

The effect of hydrogen addition to lean counterflow \( \text{CH}_4/\text{air} \) premixed flames on the extinction limits and the characteristics of NOx emission has been investigated by numerical simulation. The results show that the addition of hydrogen can significantly enlarge the flammable region and extend the flammability limit to a lower equivalence ratio. If the equivalence ratio is kept constant, the addition of hydrogen increases the emission of NO in a flame, due to the enhancement in the rate of the NNH or \( \text{N}_2\text{O} \) intermediate NO formation route. The hydrogen enrichment technology can reduce the NO emission from a combustor by allowing it to operate under extra lean condition. When the equivalence ratio is relatively higher, the addition of hydrogen causes a monotonously decrease in the formation of NO\(_2\) and \( \text{N}_2\text{O} \). However for extra low equivalence ratio flames, the emission of NO\(_2\) and \( \text{N}_2\text{O} \) first increases, and then decreases with the increase in the fraction of hydrogen.

**References**


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   [http://www.me.berkeley.edu/gri_mech/](http://www.me.berkeley.edu/gri_mech/).


Figure Captions:

Fig.1 C-shaped curves of lean counterflow premixed CH₄/H₂/air flames with four different hydrogen fractions.

Fig.2 Mole fractions of NO in flames with the equivalence ratios of 0.47 and 0.55 and varied hydrogen fraction.

Fig.3 NO emission indices in flames with the equivalence ratios of 0.47 and 0.55 and varied hydrogen fraction.

Fig.4 NO emission indices of the flame with the equivalence ratio of 0.70.

Fig.5 Temperatures and mole fractions of H in flames with the equivalence ratio of 0.55.

Fig.6 NO emission index variation with the equivalence ratio.

Fig.7 Mole fractions of NO₂ in flames with the equivalence ratios of 0.47 and 0.55.

Fig.8 Peak NO₂ mole fraction variation with the equivalence ratio from 0.47 to 0.7 and hydrogen fractions of 0.0, 0.1, 0.2 and 0.4.

Fig.9 Mole fractions of N₂O in flames with the equivalence ratios of 0.47 and 0.55.

Fig.10 Peak N₂O mole fractions of the flames with the equivalence ratios from 0.47 to 0.7 and hydrogen fractions of 0.0, 0.1, 0.2 and 0.4.
Fig. 1

Equivalence ratio

Extinction stretch rate, 1/s

α_{H2} = 0.0
α_{H2} = 0.1
α_{H2} = 0.2
α_{H2} = 0.4

(0.50, 484)
(0.65, 437)
Fig. 2
Fig. 3

(a) \( \phi = 0.55 \)
- Full NO
- \( \text{NO}_{\text{thermal}} + \text{N}_2\text{O} + \text{NNH} \)
- \( \text{NO}_{\text{thermal}} + \text{N}_2\text{O} \)
- Thermal NO

(b) \( \phi = 0.47 \)
- Full NO
- \( \text{NO}_{\text{thermal}} + \text{N}_2\text{O} + \text{NNH} \)
- \( \text{NO}_{\text{thermal}} + \text{N}_2\text{O} \)
- Thermal NO

Fraction of \( H_2 \):

<table>
<thead>
<tr>
<th>NO emission index, g-NO/Kg-O_2</th>
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<tbody>
<tr>
<td>0.000</td>
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<tr>
<td>0.005</td>
</tr>
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<td>0.020</td>
</tr>
<tr>
<td>0.025</td>
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<td>0.030</td>
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Prompt NO
- NO from NNH route
- NO from \( N_2O \) route

Fraction of \( H_2 \):

0.0 0.2 0.4 0.6 0.8 1.0
Fig. 4

Fraction of H$_2$

NO emission index, g-NO/Kg-NO

$\phi = 0.70$

- Full NO
- NO$_{\text{thermal + N}_2O + NNH}$
- NO$_{\text{thermal + N}_2O}$
- Thermal NO
\[ \phi = 0.55 \]

Distance from stagnation plane, cm

Temperature, K

Mole fraction of H

\[ \alpha = \begin{cases} 0.0 \\ 0.2 \\ 0.4 \\ 0.6 \\ 1.0 \end{cases} \]

H mole fraction

Fig. 5
Fig. 6

Distance from stagnation plane, cm

NO emission index, g-NO/Kg-O₂

α₁H₂ = 0.0
α₁H₂ = 0.2
α₁H₂ = 0.4

(0.50, 0.007)
(0.65, 0.025)
Fig. 8

Equivalence ratio

Peak NO₂ mole fraction

$\alpha_{H2} = 0.0$

$\alpha_{H2} = 0.1$

$\alpha_{H2} = 0.2$

$\alpha_{H2} = 0.4$
Fig. 9

(a) $\phi = 0.55$

- $\alpha_{H_2} = 0.0$
- $\alpha_{H_2} = 0.2$
- $\alpha_{H_2} = 0.4$
- $\alpha_{H_2} = 0.6$
- $\alpha_{H_2} = 1.0$

(b) $\phi = 0.47$

- $\alpha_{H_2} = 0.0$
- $\alpha_{H_2} = 0.2$
- $\alpha_{H_2} = 0.4$
- $\alpha_{H_2} = 0.6$
- $\alpha_{H_2} = 1.0$

Distance from stagnation plane, cm

Mole fraction of N$_2$O
Fig. 10

Peak $N_2O$ mole fraction vs. equivalence ratio for different $\alpha_{H_2}$ values.

- $\alpha_{H_2} = 0.0$
- $\alpha_{H_2} = 0.1$
- $\alpha_{H_2} = 0.2$
- $\alpha_{H_2} = 0.4$