Laminar Flame Speeds and Markstein Lengths of n-Decane/Air, n-Decane/O$_2$/He and MCH/Air Flames

Deepti Singh, Takayuki Nishiie, and Li Qiao*
School of Aeronautics and Astronautics,
Purdue University,
West Lafayette, IN, 47907, USA

Abstract

Laminar flame speeds and Markstein lengths of premixed n-Decane/air, n-Decane/O$_2$/He, Methylcyclohexane (MCH)/air were measured at fuel equivalence ratios ranging from 0.7 to 1.6, at an initial temperature of 400K and a pressure of 1 atm using spherically-expanding flames. Two fuel vaporization methods were used to ensure accuracy in determination of fuel-air equivalence ratios. Both linear and nonlinear extrapolation methods were considered to extract unstretched flame speed. The experimental results were compared with numerical simulations using the 1-D laminar premixed flame code PREMIX with several detailed reaction mechanisms. Three mechanisms were used for n-decane/air flames, the JetSurf 1.1, the mechanism of Zhao et al., and the mechanism of Honnet et al. For MCH, two mechanisms were used, the JetSurf 1.1 and the mechanism of Ranzi et al. The results show that the present measured flame speeds are in general lower than previous measurements using counterflow flames at most fuel equivalence ratios for both fuels. This could be due to the difference in experimental setup, spherically-expanding flames v.s. counterflow flames. The measured Markstein lengths for the two flames decreases with increase in equivalence ratio and the transition from stable flames to unstable flames occurs at a fuel equivalence ratio of 1.2 for n-decane and 1.3 for MCH. This trend is consistent with other large hydrocarbon fuels and is opposite to that of light fuels such as hydrogen and methane. Substituting nitrogen in air with helium resulted in a four-fold increase in flame speed of n-decane and an approximately three-fold increase in the Markstein lengths.

Introduction

Reliable design and optimization of jet engines will rely on a complete understanding of the chemical and physical properties of aviation fuels. Significant efforts recently have been directed towards jet fuel surrogates, which, when combined properly, can represent the physical and chemical properties of real fuels 1-18.

n-Decane has been suggested as a major surrogate for jet fuels and has been included in several surrogate models. Several kinetic models exist to represent n-decane oxidation, ignition and burning. In 1997, Doute et al. 4,5 validated a chemistry model containing 62 species and 467 reactions using a flat-flame burner stabilized premixed n-decane/air flames. Zerrieri et al. 19 developed a chemical kinetic scheme for n-decane based on high temperature data from flow reactor, jet stirred reactor, shock tube ignition delay times and burner-stabilized flame experiments. Bikas and Peters 20 presented a semi-detailed chemical kinetic model containing 67 species and 600 reactions for the combustion and auto-ignition of n-decane. Zhao et al. 21 revised the scheme of Zerrieri et al. to include high temperature data using flame speed data from stagnation jet-wall experiments. n-Decane models are also included in lumped mechanisms developed to represent the combustion chemistry of several straight chain alkanes. These include the JetSurf 0.2 by Sirjean et al. 22 containing 194 species and 1459 reactions for alkanes containing upto 10 carbon atoms, a scheme by Ranzi et al. 23 composed of 310 species and 8335 reactions for hydrocarbons with upto 16 C atoms, another mechanism by Westbrook et al. 24 to describe the combustion of n-alkanes from n-octane to n-hexadecane, and a detailed kinetic model for autoignition delay times of hydrocarbons from C$_4$-C$_{10}$ 25. These schemes have been validated by experimental data in premixed flames 4, shock tubes 26-28, pressure flow reactors 19, and jet stirred reactors 1, 9. Recently laminar flame speed data for n-decane has been published by Skjøth et al. 29, Zhao et al. 21, Kumar et al. 30, and Ji et al. 31.

Methylcyclohexane is one of cycloalkanes and has been considered as one of the major components of jet fuel surrogates. Its oxidation mechanisms, especially at low and intermediate temperatures, however, are not well understood yet. This is reflected by large discrepancies among the predictions using different mechanisms. Several experiments have been conducted using shock tubes, compression machines, and flow reactor for MCH/air flames 32-37, which provided measurements of ignition delay and species profiles and comparisons to numerical simulations. Few experimental data of flame speed, however, are
available for MCH flames except the recent study of Kumar and Sung\textsuperscript{38}.

In order to validate the accuracy of kinetics and models, it is important that the models be compared with experimental data of high fidelity, such as the flame structure and flame speed. A widely used parameter is the laminar burning speed that describes the propagation of the one-dimensional, planar, premixed flame in the doubly infinite domain. The laminar burning speed contains the fundamental information on the diffusivity, reactivity, and exothermicity of a given mixture and has been extensively used to validate kinetics and models. If a proposed model could not reproduce the laminar burning speed, its comprehensiveness and utility would require further examination. Therefore, an accurate knowledge of laminar burning speed is important in any combustion study, especially for practical fuels.

The purpose of this study is to measure unstretched laminar flame speeds and Markstein length for two fuels, n-decane and MCH, using spherically expanding flames. As discussed earlier, a few flame speed data exist for these fuels most from counterflow flame experiments\textsuperscript{39-40}. Discrepancies in measured flame speeds were observed even using the same counterflow flame configuration, indicating the complexity associated with the liquid fuel experiments, e.g., fuel vaporization, determination of fuel-air equivalence ratio, methods to correct the effect of flame stretch, linear or nonlinear extrapolation, etc. Here we used spherically expanding flames, which has its own advantages in determination of flame speed and Markstein length, and may provide additional insights on the chemistry of these fuels. The paper discusses details of the experimental methodology employed. In particular, two fuel vaporization methods were used to ensure accuracy in determination of fuel-air equivalence ratio. Additionally, both linear and nonlinear extrapolation methods were used and the results were compared. The 1-D, freely-propagating planar flames were simulated using PREMIX with several detailed kinetics mechanisms. The present measurements were compared with numerical simulations as well as previous measurements in literature.

**Experimental Method**

1. **Apparatus**

The experimental facility, as shown in Fig. 1, consists of a spherical combustion chamber placed inside a customized oven, an electrode spark ignition system, a liquid fuel vaporization system, and a high-speed shadowgraph system. The spherical combustion speed here is based on the assumption of flame propagation at constant pressure, thus the relatively large volume of the combustion chamber allows us to use a wider range of flame radius for data extraction. The chamber is fitted with two diametrically opposed electrodes made of tungsten wires to achieve ignition at the center of the chamber. The position of the upper electrode is fixed, while the position of the lower electrode can be adjusted to change the distance of the gap between the two electrodes. The ignition energy is supplied from a high voltage power supply and adjusted to be close to minimum ignition energy in order to minimize ignition disturbances. The chamber has four ports on the top which provide connections for tubings, hoses, wires, and fuel line. Two 10 cm diameter and 1 cm thick quartz windows are mounted on diametrically opposite ends of the chamber to allow for viewing and recording the flame propagation inside the chamber. The chamber can withstand a maximum pressure of up to 34 atm.

The combustion chamber was placed inside a customized oven and can be preheated to a maximum temperature of 650° F with a precise temperature controller. The oven has two large glass windows installed on the front and rear doors for optical access to which the windows on the chamber are aligned. Two K-type thermocouples were installed to monitor the temperature inside the oven and the temperature inside the chamber respectively. The advantage of using an oven, instead of wrapping the combustion chamber with a heating jacket, is that a uniform temperature field within the chamber can be achieved. Furthermore, with the preheated oven, liquid fuels can be vaporized and the initial temperature of the fuel/oxidizer mixture can be changed to provide more data on a wide range of initial temperatures.

A shadowgraph imaging system was set up to visualize flame propagation using a high-speed digital camera with a capture rate up to 10,000 frames-per-second. The light source is a 100-W Mercury lamp with a condensing lens and a small pinhole. This provides a sharp and intense illumination throughout the whole system. Two concave mirrors with a focal length of 1143 mm are placed on two sides of the oven.
2. Liquid fuel vaporization

The most challenging part of the experiment was to vaporize liquid fuels and to determine fuel/air equivalence ratios accurately. To achieve these goals, we used two different methods for fuel injection, which later were proved to produce almost the same results. The first method was to vaporize liquid fuels in a small fuel tank which has a volume of 30 ml. A stainless steel tubing with ¼ inch outer diameter, which connects the fuel tank and the combustion chamber, was wrapped with tape heaters. Several K-type thermocouples were installed in the fuel tank and on the surface of the fuel line to monitor the temperature and to ensure uniform temperature distribution along the line. Using a temperature controller the heater will stop heating once the temperature reaches the desired value. The fuel vapor was then transported to the combustion chamber using a precise valve, which will shut off when the desired partial pressure of fuel vapor is achieved. The partial pressures of fuel vapor and oxidizer were monitored using two different Kulite high-temperature pressure gauges. We chose a high accuracy gauge which has a measurement range of 0-2 psi (XTEH-10L-190/S-1A) for the fuel due to its low partial pressure. The other gauge has a relatively large measurement range of 0-50 psi (XTEH-7L-190-50A) and was used for monitoring the pressure of air or fuel-air mixtures. Both pressure gauges can be operated at temperatures up to 1000 °F with an accuracy of 0.1% of the upper limit.

For heavier fuels, the partial pressures of fuel vapor are typically low under the present experimental conditions, e.g., the lowest partial pressure of n-decane is 0.1579 psi among all the tests at atmospheric pressure. This put significant challenge on accurate determination of fuel-air equivalence ratio, even though a high-accuracy pressure gauge was used. This is because a little deviation of partial pressure could cause significant change in fuel-air equivalence ratio. Due to this consideration, we also tried another fuel injection method, which was based on the volume of the liquid fuel, rather than the partial pressure of the fuel vapor. Liquid fuels were injected to the combustion chamber directly using a 25 ml syringe (SGE Analytical Science) along with a syringe pump (KD Scientific, Model 1000 series). The syringe pump was programmed to deliver the required amount of fuel in terms of volume with an accuracy of ±<1%. The syringe, along with a luer lock valve and a 1/16” diameter, 24” long needle, was used to deliver the fuel to the combustion chamber. The injection rate can be adjusted and a low rate of 5 ml/hr was chose to enhance evaporation after a few trials. We observed that the droplets started to evaporate right after falling down from the tip of the needle and got completely evaporated when they hit the hot combustion chamber wall. The partial pressure of fuel vapor was also measured as a second check for the equivalence ratio.

The advantage of the first method is that the liquid fuel was pre-vaporized in a separate tank. Also, the fuel line and the combustion chamber were pre-heated to the desired temperature, thus fuel condensation was not a concern. However, the challenge was that the partial pressure of fuel vapor is typically low for heavier fuels and a little deviation could result in big change in fuel equivalence ratio. In the second method, the fuel equivalence ratio was determined based on the volume of the liquid fuel using a high accuracy syringe pump. However, the challenge was to completely vaporize the liquid fuel, which depends on the injection process. The two methods, however, produced almost the same results, as will be discussed in the following.

The test procedure began by heating the oven until the temperature inside the oven and chamber reaches the target temperature. Then the combustion chamber and the fuel vaporization system were evacuated using a vacuum pump. A small amount of air was added before adding the fuel vapor to the chamber to avoid fuel condensation and ensure mixing. After filling the fuel vapor either based on its partial pressure or based on its volume, preheated air was added until the pressure reached the target. The fuel-air mixture was allowed to stand for a period of 10-30 minutes for any disturbances to settle. The temperature and pressure inside of the chamber were monitored during this period and any drop in pressure was recorded. After each experiment, the chamber was flushed thoroughly with high pressure air.

3. Data processing
Similar to previous measurements of flame speed\textsuperscript{44} using a spherical combustion chamber of the same size, flame radius measurements have been limited to a range of 10-30 mm. The lower limit was to avoid disturbances caused by the transient ignition process and the upper limit was to ensure pressure increases inside the chamber were negligible. Under these assumptions, the local stretched flame speed and flame stretch are given by the following quasi-steady expressions due to Strehlow and Savage\textsuperscript{52}:

\begin{equation}
S_t = \frac{\rho_b}{\rho_u} \frac{dr}{dt}
\end{equation}

where \( S_t \) is the unburned gas speed and \( K \) is the flame stretch. The ratio of the burned gases to the unburned gases was computed using the NASA Chemical Equilibrium Applications code making the assumption of adiabatic constant pressure combustion \textsuperscript{44}. For small stretch rates, the linear extrapolation to zero stretch to obtain unstretched laminar flame speed, \( S_{\infty} \), is as follows, proposed by Markstein \textsuperscript{44} and Clavin \textsuperscript{45}:

\begin{equation}
S_L = S_{\infty} - L_u K
\end{equation}

where \( L \) is the Markstein Length.

The linear relation (Eq. 3), which is subject to the limitation of small stretch rate, may not apply to heavier fuels such as those studied here due to the small diffusivity of heavier fuels and high stretch rate\textsuperscript{46}. And non-linear extrapolation method may be needed. Due to this consideration, we also used a non-linear relation based on a model developed by Ronney and Sivashinsky\textsuperscript{47} specifically for quasi-steady, outwardly propagating spherical flames. The unstretched laminar flame speed was obtained by the following equation

\begin{equation}
\left( \frac{S_b}{S_{\infty}} \right)^2 \ln \left( \frac{S_b}{S_{\infty}} \right)^2 = - \frac{2L_u \kappa}{K_b}
\end{equation}

where \( S_{\infty} \) and \( S_b \) are the unstretched and stretched flame speed relative to burned gases respectively. \( L_u \) is the burned gas Markstein length, and \( \kappa \) is the stretch rate. The unstretched flame speed relative to unburned gases (\( S_{L_u} \)) is related to \( S_{b\infty} \) by the ratio of the burned and unburned gas density. The advantage of this model is that is valid over a large range of flame radius, including the initial stage of flame evolution where stretch rates are relatively high. This model has been used by Kelly and Law\textsuperscript{48} in the determination of laminar flame speeds of n-butane/air flames.

1.1 Uncertainty analysis

Uncertainties in the pressure measurements of the fuel vapor and air are less than 0.1\%. Additionally, with the 2.5\% accuracy in measuring radius, flame speed measurements were estimated to have an uncertainty of less than 5\%. For each condition, 5-7 tests were conducted to get an average of laminar flame speeds and Markstein lengths. n-Decane and MCH were tested at an initial temperature of 400 K, a pressure of 1 atm, and over equivalence ratios varying from 0.7 to 1.6. Additionally, n-Decane/O\textsubscript{2}/He flames were considered by replacing nitrogen in air with helium.

Computational Method

Numerical simulations of the steady, laminar, freely propagating 1-D premixed flames were carried out using the PREMIX\textsuperscript{48} module of the CHEMKIN\textsuperscript{49} software. The code provides multi-component diffusion approximation along with consideration of variable thermo-chemical and transport properties. The PREMIX algorithm provides an automatic grid refinement in regions of high property gradients resulting in better convergence properties for the final solution. Number of points in the computational grid and grid tolerance parameters were varied to ensure accuracy.

For n-decane, three kinetic mechanisms were used, including JetSurF \textsuperscript{1.1}\textsuperscript{22} being developed for jet fuel surrogates by a multi-university research collaboration, the mechanism by Zhao et al.\textsuperscript{21} (2005) specific to combustion behavior of n-Decane, and the mechanism of Honnet et al.\textsuperscript{16} representing combustion of kerosene. For MCH, two kinetic mechanisms were used, including JetSurf \textsuperscript{1.1}\textsuperscript{22} and a mechanism developed by Ranzi et al.\textsuperscript{23} for C\textsubscript{16}-C\textsubscript{22} hydrocarbons at low and high temperatures.

Results and Discussions

1. Comparison of the two fuel vaporization methods

As discussed earlier, we used two different methods to vaporize liquid fuels. In the first method, fuel was pre-vaporized in a separate tank and fuel-air equivalence ratio was determined by the partial pressure of fuel vapor. In the second method, liquid fuels were directly injected into the pre-heated combustion chamber using a syringe pump system and the fuel-air equivalence ratio was determined by the volume of the liquid being delivered. Both methods have pros and cons. Figure 1 is a comparison of the measured flame speed of n-decane/air flames using the two methods. The data shown are for an initial
temperature of 400 K and a pressure of 1 atm, and equivalence ratios of 0.8, 1.0 and 1.2. It can be seen that the difference in flame speed from the two methods are negligible for all fuel equivalence ratios. Therefore, we can conclude that both the partial pressure method and the volume method resulted in complete fuel vaporization and yielded accurate determination of fuel-air equivalence ratio for the low vapor pressure, high boiling point liquid fuels studied here.

Motivated by this, we used both linear and nonlinear extrapolation methods to determine unstretched flame speed and the results were compared. The nonlinear method (Eq. 4) was based on the theoretical model of Ronney and Sivashinsky\textsuperscript{47} specifically developed for outwardly propagating flames, which is not subject to the small stretch limitation and also accounts for density variation. This method has been used by Kelly and Law\textsuperscript{46} in determine flame speed of n-butane/air flames using spherical flames. Figure 3 shows a comparison of flame speeds obtained by linear and nonlinear extrapolation for stoichiometric n-decane/air flames at three equivalence ratios of 0.8, 1.0, and 1.2, respectively. The symbols are measured stretched flame speed. The solid curves represent nonlinear relation between stretched flame speed $S_b$ and stretch rate $K$. The dashed straight lines represent linear extrapolation to zero stretch. The difference in the unstretched flame speeds obtained by linear and nonlinear extrapolation is within 1 cm/s for the three equivalence ratios, with the maximum difference (approximately 1 cm) occurring at $\phi = 0.8$. The difference increases as $\phi$ increases and the linear extrapolation method overestimates flame speed in all three cases.

2. Linear and nonlinear extrapolation methods

To account for the effect of flame stretch and to obtain unstretched flame speed, linear extrapolation to zero stretch has been extensively used in laminar flames, e.g., counterflow flames and spherically expanding flames. Linear extrapolation, limited to small stretch rate, may not be accurate enough for heavier fuels due to the small diffusivity of heavier fuels and high stretch rate. Wang et al.\textsuperscript{30} have shown that there is a nonlinear variation in stretched burning velocity as stretch rate approaches zero for counterflow flames. The authors proposed and implemented a new nonlinear extrapolation method by utilizing numerical simulations and found that linear extrapolation can result in a significant over-prediction of unstretched burning velocity. Kelley and Law\textsuperscript{46} recently studied the nonlinear effects in extraction of laminar flame speed from expanding spherical flames. Their results show strong nonlinearity in the flame response as a consequence of the small diffusivity of the heavier liquid fuels and thus non-linear extrapolation method must be considered. They also suggest that the accuracy of the extrapolation can be enhanced by using larger combustion chambers and smaller ignition energies.

These findings are consistent with the Ref 46, which also used spherical flames. They found that the difference between linearly extracted and nonlinearly extracted flame speeds is between 1.4 – 3.4 cm/s for n-butane/air flames. The differences in flame speed and Markstein length with linear and nonlinear extraction in the present study is smaller comparing to those in Ref 46. This could be partially due to the fact that a
relatively larger combustion chamber was used in the present study, which can reduce the nonlinear nature of flame response to stretch for the range of measurements being made. In the present experiment, flame radius was measured in the range of 1.3-3 cm, while flame radius measurement was made in the range of 1.0-1.7 cm in Ref. 46, with the upper limit corresponding to a flame radius that is roughly 40% of the radius of the inner chamber.

3. n-Decane/air flames

n-Decane is one of the major straight-chain components of kerosene. It has been suggested as a major component in various surrogate models for jet fuels, e.g., Surrogate A, B [14], Surrogate D [51] and the Aachen surrogate model [15]. Figure 4 shows the measured and computed laminar flame speeds of n-decane/air flames as a function of equivalence ratio for a range of 0.7 to 1.4 at 400 K and 1 atm. The computed flame speeds were obtained using three mechanisms, the mechanism of Zhao et al. [21], the mechanism of Honnet et al. [16] and the JetSurF 1.1 [22] respectively. Also shown in Fig. 2 are the measured flame speeds by Kumar and Sung [30] and Ji et al. [31], both using counterflow flames.

The present measured flame speeds are lower than the two previous experiments using counterflow flames [30-31] at most fuel equivalence ratios. The present data have better agreement with Ji et al.’s data on the fuel-lean and fuel-rich side. And the largest discrepancy occurs at near-stoichiometric conditions, with our data about 3-5 cm/s lower. The flame speed measured by Kumar and Sung [30] deviate increasingly from the data of Ji et al. [31] at fuel-rich conditions. The former used linear-extrapolation in determination of unstretched flame speed and the latter used a new nonlinear extrapolation method based on numerical simulation experiments of opposed-jet flames, which was claimed to be responsible for the discrepancies at fuel-rich conditions as discussed by Wang et al. [50]. Overall, our data being slightly lower than those obtained with counterflow flames at most fuel equivalence ratios, along with the fact that we have used two fuel vaporization methods and have validated the accuracy of fuel-air equivalence ratio, make us believe that the discrepancies are likely to due to difference in flame configurations when testing heavier fuels, i.e., spherically-expanding flames v.s. counterflow flames.

It can be seen that there is considerable deviation between the predictions by the three mechanisms. Predicted flame speeds using the mechanism by Honnet et al. [16] have the lowest values and the predictions using JetSurF 1.1 are in between those of Honnet et al. [16] and Zhao et al. [21]. The present measured flame speeds agree best with the simulations using the JetSurF 1.1 mechanism. And the experimental results by Ji et al. [31] validate the JetSurF 1.1 model predictions very closely over the entire range of equivalence ratios.

4. MCH/Air flames

MCH (methylcyclohexane) has been considered as one of the major components of jet fuel surrogates. Its oxidation mechanisms, especially at low and intermediate temperatures, however, are not well understood. There are large discrepancies among different mechanisms. Few flame speed data are available for MCH flames. Figure 5 shows the measured and computed laminar flame speeds of MCH/air flames as a function of fuel equivalence ratio for a range of 0.7 to 1.4 at an initial temperature of 400 K and a pressure of 1 atm. The numerical simulations were conducted using PREMIX considering two kinetic mechanisms, the mechanism of Ranzi et al. [23] and the JetSurF 1.1 [22]. Also shown in Fig. 5 are the measured flame speeds by Kumar and Sung [38] using counterflow flames.

The present measured flame speeds are lower than those by Kumar and Sung at all fuel equivalence ratios, about 3-7 cm/s lower. Both experiments show that the maximum flame speed occurs at a fuel equivalence ratio of 1.1. The mechanism by Frassoldati predicted higher flame speeds than the JetSurF 1.1 mechanism at all fuel equivalence ratios. Both mechanisms overpredicted flame speeds at most fuel equivalence
ratios as the computed flame speeds are higher than the measured values for both experiments, except that Kumar and Sung’s data agree well with the predictions of JetSurf 1.1 at fuel-rich conditions. Again, the deviations between the present measurements and those of Kumar and Sung are likely to be caused by the difference in experimental setup, i.e., spherically expanding flames and counterflow flames.

5. Effect of helium dilution

For spherical expanding flames, preferential diffusion effects result in the creation of wrinkled flame surface for heavy (or light) fuel molecules such as n-Decane (or hydrogen) at fuel-rich (or lean) conditions. To delay the development of preferential-diffusion instabilities, N$_2$ was replaced by helium which has a much smaller molecular mass. This was helpful because it extended the range of equivalence ratios over which the un-stretched laminar burning speeds could be measured. The result of these experiments is discussed below.

The flame speeds of n-Decane/O$_2$/He were examined at an initial temperature of 400 K and pressure of 1.0 atm for the equivalence ratio of 0.8-1.6, as shown in Fig. 6. The O$_2$ and He were mixed in the ratio of O$_2$: He=1:3.76. The present experimental results were compared with the computational results using the mechanism by Zhao et al. and the JetSurF 1.1. Figure 6 shows that the Zhao’s mechanism and the JetSurF 1.1 are in good agreement with the flame speed for n-Decane/O$_2$/He over all the equivalence ratios. The experimental results show that as the equivalence ratio increases above unity, the flame speed decreases almost linearly at fuel rich conditions. Compared to the n-Decane/air flame, the flame speeds of n-Decane/O$_2$/He were almost four times higher, which is mainly due to the much lower heat capacity of helium as compared with N$_2$.

Also it was observed in the experiments, that relatively high ignition energy was required to ignite the helium diluted flames. Early development of flame instabilities were not observed in these flames and flame speed measurements could be made easily over a larger range of equivalence ratios on the fuel rich side.

6. Markstein length

Use of a spherical flame configuration has the advantage of easy measurement of flame speed, and stretch rate as compared to other flame configurations. Therefore, the Markstein length can be easily obtained. Markstein length is a direct measure of the flame response to stretch and an important parameter to assess the stability of the flames to preferential diffusion effects. The fuels considered here have large molecular weights and present results are different from those of lighter hydrocarbons studied previously due to different transport properties. H$_2$/Air and CH$_4$/Air flames have increasing Markstein length values with increasing equivalence ratio. However, for higher hydrocarbons such as ethane, ethylene and propane, Markstein length decreases with increasing equivalence ratio. A similar behavior is observed for the fuels considered here and the results are discussed below.

Figure 7 shows the Markstein lengths for n-decane/air and MCH/air mixtures at 1 atm and 400K. Here the Markstein lengths were obtained using nonlinear extrapolation based on Eq. 2. A decrease in Markstein lengths is observed for both fuels with increase in equivalence ratios and transition to negative values occurs at an equivalence ratio of 1.2 for n-decane/air and approximately 1.32 for MCH/air flames.
This trend of Markstein lengths is opposite to observations made for H₂/Air flames. In the case of H₂/Air flames, fuel lean flames are unstable and with increase in fuel equivalence ratio, there is an increase in flame stability and Markstein length. These observed differences can be explained on the basis of their transport properties. For a given equivalence ratio, the Markstein length of MCH/air flames is larger than that of n-decane/air flames.

Markstein lengths of n-decane/O₂/He were compared with n-decane/O₂/N₂ in Fig. 8. The Markstein length is approximately 3 times higher for helium-diluted mixtures compared to N₂-diluted mixtures. Flames studied over equivalence ratios of 1.0 to 1.6 for n-decane/O₂/He are stable over the entire range whereas the n-decane/O₂/N₂ flames become unstable at phi=1.2. Such a large difference in the response to stretch is attributed to the largely different diffusivities of He and N₂.

![Figure 7. Measured Markstein length as a function of fuel equivalence ratio for n-decane/air and MCH/air flames, both at an initial temperature of 400 K and a pressure of 1 atm.](image)

![Figure 8. Measured Markstein lengths of n-Decane/O₂/He and n-Decane/O₂/N₂ flames as a function of equivalence ratio at 400 K and 1 atm.](image)

Conclusions

Laminar flame speeds and Markstein lengths of n-decane/air and MCH/air flames were measured over fuel equivalence ratios of 0.7-1.6, at an initial temperature of 400 K and a pressure of 1 atm using spherically expanding flames. n-Decane/O₂/He flames were also considered by replacing nitrogen in air with helium. The experiments used a preheated spherical combustion chamber resided inside a customized oven which can be heated to temperatures up to 600 K. Two fuel vaporization methods were used to ensure accuracy in determination of fuel-air equivalence ratios. Both linear and nonlinear extrapolation methods were considered for data extraction and the results were compared. Corresponding numerical simulations were performed using the 1-D planar freely-propagating flame code PREMIX with detailed reaction mechanisms. For n-decane flames, three reaction mechanisms were considered. They are the mechanisms of Zhao et al., Honnet et al., and the JetSurF 1.1. For MCH, the mechanism of Ranzi et al. and the JetSurF 1.1 were used. The major conclusions are discussed below:

1. For the two methods used for fuel vaporization and injection, the ways to determine fuel-air equivalence ratios were based on the partial pressure of the fuel vapor and the volume of the liquid fuel, respectively. The two methods, however, produced essentially the same flame speed data for a given condition, indicating accuracy in determination of fuel equivalence ratios.

2. The difference in flame speed using linear and nonlinear extrapolation is within 1 cm/s for n-decane/air flames, with the maximum difference occur at fuel-lean conditions. This difference is smaller than those observed in other experiments.
may be partly due to the fact that a relatively larger combustion chamber was used which can reduce the nonlinear nature of flame response to stretch.

(3) The present measured flame speeds of n-decane/air flames and MCH/air flames are in general lower than the measurements made in counterflow flames at most equivalence ratios. For n-decane/air flames, the present measurements have better agreement with the data of Ji et al. \textsuperscript{31}. For both fuels, JetSurf 1.1 predicted data closest to the experiments. Large discrepancies exist among the simulation results using different mechanisms of n-decane.

(4) For both fuels, as the fuel equivalence ratio increases, the Markstein length decreases and the transition from stable flames to unstable flames occurs at a fuel equivalence ratio of 1.2 for n-decane and approximately 1.3 for MCH. This trend is consistent with other large hydrocarbon fuels and is opposite to that of light fuels such as hydrogen or methane.

(5) For n-decane flames, replacing nitrogen with helium results in a 3-4 times increase in flame speed due to the much lower heat capacity of Helium. Helium addition promotes preferential diffusion stability, which is also reflected by the increased Markstein length, and therefore extends the measurement range of fuel equivalence ratio.

REFERENCES


