Optimizing Mixture Properties for Accurate Laminar Flame Speed Measurement from Spherically Expanding Flame: Application to H$_2$/O$_2$/N$_2$/He Mixtures

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ABSTRACT

The uncertainty on the laminar flame speed extracted from spherically expanding flames can be minimized by using large flame radius data for the extrapolation to zero stretch-rate. However, at large radii, the hydrodynamic and thermo-diffusive instabilities induce the formation of a complex cellular flame front and limit the range of usable data. In the present study, we have employed the flame stability theory of Matalon to optimize the properties of the initial mixture so that transition to cellularity may occur at a pre-determined, large radius. This approach was employed to measure the laminar flame speeds of H$_2$/O$_2$/N$_2$/He mixtures with equivalence ratios from 0.6 to 2.0, at pressures of 50/80/100 kPa and a temperature of 300 K. For all the performed experiments, the uncertainty related to the extrapolation to zero stretch-rate (performed with the linear curvature model) was below 2% as shown by the position of the data points in the ($L_b/R_f,U$, $L_b/R_f,L$) plan, where $L_b$ is the burned Markstein length; and $R_f,L$ and $R_f,U$ are the flame radii at the lower and upper bounds of the extrapolation range. Comparison of the predictions of four chemical mechanisms with the present unstretched laminar flame speed data indicated an error below 10% for most conditions. In addition, unsteady 1-D simulations performed with A-SURF demonstrated that the flame dynamical response to stretch rate could not be captured by the mechanisms. The present work indicates that although the stability theory of Matalon provides a well defined framework to optimize the mixture properties for improved flame speed measurement, the uncertainty of some of the required parameters can result in largely over-estimated critical radius for cellularity onset which compromise the accuracy of the optimization procedure.
1. INTRODUCTION

One of the most important fundamental quantity in combustion science is the unstretched laminar flame speed, \( S_0 \), [1–3]. It is defined as the normal propagation velocity of fresh gas relative to a fixed, planar flame front and represents a measure of the mixture reactivity and diffusivity [1]. Because the turbulent combustion properties scale with the laminar ones [4, 5], accurate experimental data obtained under laminar conditions are needed to predict and model turbulent combustion which is relevant to the conditions found in real applications, such as internal combustion engine or gas turbines [4], or accidental explosion [5, 6]. Laminar flame speed is also widely used to develop and validate detailed reaction models [7, 8] which can then be directly employed within engineering correlations [9] or be reduced/tabulated and included in multi-dimensional numerical simulations [4, 10] with the goal of predicting the risk of accidental combustion events [10, 11], evaluating existing facility [12, 13] or developing and optimizing new combustion devices [14, 15].

Whereas several approaches can be employed to measure the flame speed, including counter flow burners [16], heat flux burners [17, 18], Bunsen burners [19], the spherically expanding flame (SEF) technique is the most widely employed and enables accessing high pressure relevant to real applications [2]. Using the SEF method along with a high-speed visualization system, the laminar flame speed can be extrapolated to zero-stretch rate from the temporal evolution of the radius of a centrally spark-ignited flame. Despite its apparent simplicity, the measurement of the flame speed using the SEF technique is complicated by a number of considerations as reviewed by Lipatnikov et al. [3]. These include: (i) spark ignition energy effects; (ii) confinement effects; (iii) heat losses through radiation; (iv) product density non-uniformity; (v) compression effects; (vi) flame instabilities; and (vii) stretch effects.

Many of these perturbations can be eliminated or mitigated in a simple manner [1, 3]. Perturbations (i) and (iv) only affect flames of small radii and consequently these can be excluded from the analysis of the \( R_f(t) \) curve. Perturbations (ii) and (v) are relevant to large flame radii with respect to the combustion vessel’s characteristic length scale and the part of the \( R_f(t) \) curve affected by these two perturbations can be readily removed from the analysis [20]. Perturbation (iii) is only relevant to slow flames at very large radius, so that many conditions can be studied without considering this limitation. For near flammability limit or decomposition flames [21], which demonstrate low propagation velocity, empirical correlations [22] are available to estimate the increased uncertainty on the flame speed. Perturbations (vi) and (vii) are by far the most challenging especially when targeting a wide range of pressure for the measurements.

The effect of stretch rate on the flame propagation can be accounted for by using various linear or non-linear extrapolation equations [23] which enable to extract the unstretched laminar flame speed from the experimental data obtained with stretched flame. Nevertheless, Wu et al. [23] have demonstrated that, for conditions where the Lewis number (\( Le \)) is away from unity, these equations cannot reproduce the flame dynamics which may lead to significant error in the measured unstretched flame speed. Recent studies by Nativel et al. [24] and Huo et al. [25] have shown that, when using large flame radius data, the uncertainty due to the extrapolation method used can be minimized. In particular, Huo et al. have established an error diagram which depends on the Markstein length (\( L_b \)) normalized by the initial (\( R_{f,I} \)) and final (\( R_{f,U} \)) flame radius data points used for the extrapolation to zero-stretch rate. However, the use of flame with large radii for measuring the flame speed increases the detrimental impact of perturbation (vi). The flame instability, which results in the formation of a cellular flame, is induced, on the one hand, by the gas expansion across the flame front (hydrodynamic or Darrieus-Landau instability), and on the other hand, by the non-equidiffusion of mass and heat of the deficient reactant (thermo-diffusive instability).

The strategy to mitigate the development of cellular instabilities and the extrapolation-induced error
consists in adding helium to the reactive mixture to limit the expansion through the flame front, limiting hydrodynamic instability, and to increase the effective Lewis number of the mixture, decreasing thermo-diffusive instability and stretch impact on flame propagation. Whereas this approach has been implemented by several groups [2, 26–30], it is noteworthy that it has not been generalized and that no well defined scientific procedure has been proposed to optimize the mixture properties to minimize the uncertainty related to perturbations (vi) and (vii).

The goal of the present study is to develop a well defined scientific procedure to optimize the mixture properties so that flame instability is delayed up to a predefined large flame radius, thus allowing to perform the flame speed measurement over a range of radii for which the uncertainty associated with the extrapolation method is minimized. We have developed such a procedure which relies on Matalon’s stability theory and applied it to hydrogen-air mixtures over a range of pressure from 50 to 100 kPa.

2. MATERIALS AND METHODS

2.1. Experimental facility

The experimental facility employed has been previously described in [24, 31]. It is a constant volume spherical bomb with inner diameter of 476 mm. Optical access is allowed by two opposite windows with a diameter of 200 mm. The combustion vessel can sustain a maximum pressure of 20 MPa and can be heated up to 573 K using a thermal heating fluid. The visualization of the flame was obtained using a Z-type schlieren arrangement. The process of flame propagation was recorded using a high-speed camera (PHANTOM V1610), with an acquisition rate of up to 25,000 frames per second. Two tungsten electrodes connected to a high voltage power supply enable to centrally spark-ignite the mixture. The spark energy was on the order of 2 mJ as determined from high voltage and current probes measurement. The spherical vessel is equipped with a Kistler piezo-electric pressure transducer (model 601A) synchronized with the imaging system to ensure that the pressure remains constant during the propagation period employed to extract the flame speed. Prior to an experiment, the combustion chamber was evacuated to a pressure on the order of 1 Pa. The reactive mixtures were prepared using the partial pressure method. After all the gas components of the mixture were introduced, eight fans were turned on for 3 minutes to ensure mixture homogeneity. The gas was then let to settle for 3 minutes before ignition.

We studied H$_2$/O$_2$/N$_2$/(He) mixtures for which the ratio of the diluent mole fraction to the oxygen mole fraction was maintained constant at 3.76. The amount of helium introduced in the diluent fraction was optimized to ensure the stability of the flame as described in the following subsection. The hydrogen mole fraction to oxygen mole fraction ratio was defined by the equivalence ratio which ranged between 0.6 and 2.0. All gases were of high-purity grades and supplied by Air Liquide. The initial temperature was between 293 and 300 K, and the pressures were 50/80/100 kPa.

2.2. Procedure to optimize mixture properties

According to the theory of spherical flame stability of Matalon [32–34], the critical flame radius for the onset of cellular instability ($R_c$) is given by

$$R_c = P_e \delta = \frac{\delta \Omega}{\omega} = \frac{\delta}{\omega} \left( Q_1 + \frac{\beta (L_eff - 1)}{\sigma - 1} Q_2 + Pr Q_3 \right),$$

(1)
where $Pe_c$ is the critical Peclet number; $\delta$ is the flame thickness; $\omega$ corresponds to the contribution of the hydrodynamic effects to the flame instability; $\Omega$ corresponds to the contribution of thermo-diffusive effect to the flame instability; $\beta$ is the Zeldovich number; $Le_{eff}$ is the effective Lewis number; $\sigma$ is the expansion ratio; $Pr$ is the Prandtl number; $Q_1$, $Q_2$, and $Q_3$ are complex terms which depend on the expansion ratio, the spherical harmonic wavenumber ($n$), and the thermal conductivity ($\lambda$), see [33].

The flame thickness was calculated using the temperature gradient definition

$$\delta = \frac{T_{ad} - T_u}{(dT/dx)_{\max}},$$  \hspace{1cm} (2)$$

where $T_{ad}$ is the adiabatic flame temperature; $T_u$ is the unburnt gas temperature; and $(dT/dx)_{\max}$ is the maximum temperature gradient in a 1-D planar flame. The Zeldovich number $\beta$ was defined as

$$\beta = \frac{E_a T_{ad} - T_u}{RT_{ad}^2},$$  \hspace{1cm} (3)$$

where $E_a$ is the activation energy and $R$ is the perfect gas constant.

The effective Lewis number $Le_{eff}$ was obtained from

$$Le_{eff} = 1 + \left(\frac{Le_E - 1}{1 + e} + \frac{Le_D - 1}{1 - e}\right),$$  \hspace{1cm} (4)$$

where $e = 1 + \beta (\Xi - 1)$ with $\Xi = \Phi$ for rich mixtures and $\Xi = 1/\Phi$ for lean mixtures. $\Phi$ is the equivalence ratio.

All the required parameters were calculated using the thermo-chemical and transport utilities available in the Cantera package [35].

The optimization procedure consisted of the following steps

1. Step 1: Define a target critical radius. We have used $R_c^t = 10$ cm, which corresponds to the optical windows radius.
2. Step 2: Calculate the theoretical critical radius $R_c^{th}$ for the mixture of interest.
3. Step 3: Compare $R_c^{th}$ to $R_c^t$.
4. Step 4: If $R_c^{th} > R_c^t$, stop the procedure.
5. Step 5: Calculate the theoretical critical radius $R_c^{th}(He)$ for a mixture with same equivalence diluted only with He.
6. Step 6: If $R_c^{th}(He) > R_c^t$, go to step 7.
7. Step 6': If $R_c^{th}(He) < R_c^t$, go to step 11.
8. Step 7: Replace part of the nitrogen by helium (considering the initial mixture composition).
9. Step 8: Calculate the theoretical $R_c^{th}(mod)$ for the modified mixture.
10. Step 9: Compare $R_c^{th}(mod)$ and $R_c^t$.
11. Step 10: If $R_c^{th}(mod) = R_c^t$, stop the procedure.
12. Step 10': If $R_c^{th}(mod) \neq R_c^t$, repeat step 7 to 9.
• Step 11: Maintaining the hydrogen to oxygen ratio, increase the dilution. The only diluent is helium.

• Step 12: Calculate the theoretical $R_{th}^H(He/\text{mod})$ for the mixture whose dilution level has been modified.

• Step 13: Compare $R_{th}^H(He/\text{mod})$ and $R_e^c$.

• Step 14: If $R_{th}^H(He/\text{mod}) = R_e^c$, stop the procedure.

• Step 14': If $R_{th}^H(He/\text{mod}) \neq R_e^c$, repeat step 11 to 13.

A Matlab routine was developed to apply this procedure. The required Cantera calculations were directly launched from Matlab. The built-in Matlab optimization function “fminsearch”, which relies on the Nelder-Mead simplex algorithm, was employed to control the modification of the mixture composition. We finally obtain a mixture of a given equivalence ratio whose $R_{th}^c$ is at least 10 cm, so that the flame speed measurement can be performed for large flame radii. It is noted that for the conditions we used in the present study, the dilution was the same as for hydrogen-air mixtures for all cases, i.e. no additional dilution was required to stabilize the flame. The compositions of the mixtures we studied experimentally are given in Table 1.

### Table 1: Composition of the H$_2$/O$_2$/N$_2$/He mixtures. The initial conditions, the measured parameters, and some calculated parameters are also given.

<table>
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<th>$\Phi$</th>
<th>$X_{H_2}$</th>
<th>$X_{O_2}$</th>
<th>$X_{N_2}$</th>
<th>$X_{He}$</th>
<th>$P_1$ (kPa)</th>
<th>$T_1$ (K)</th>
<th>$R_e^c$ (cm)</th>
<th>$R_{th}^c$ (cm)</th>
<th>$S_0^u$ (cm/s)</th>
<th>$L_b$ (mm)</th>
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<td>0.168</td>
<td>0.146</td>
<td>0.485</td>
<td>100</td>
<td>297</td>
<td>7.1</td>
<td>10.00</td>
<td>205</td>
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<td>0.148</td>
<td>0.379</td>
<td>0.177</td>
<td>100</td>
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<td>0.412</td>
<td>0.114</td>
<td>100</td>
<td>294</td>
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<td>297</td>
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<td>0.129</td>
<td>0.404</td>
<td>0.080</td>
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#### 2.3. Data reduction procedure

Figure 1 shows an example of spherical flame propagation that we observed experimentally. The evolution of the flame radius as a function of time is obtained using an in-house Matlab program which detects the flame edge and fits a circle to it, thus allowing to deduce the flame radius. Further details about this laminar flame analysis program can be found in [24, 36]. Figure 2 shows a typical $R_f = f(1/R_f)$ curve we obtained, where $R_f$ is the flame radius. The flame speed was obtained by performing a third order differentiation of $(R_f, t)$ data points. Part of the curve is not linear due to the influence of the initiation
Figure 1: Schlieren images of a spherical flame propagating in a rich hydrogen-air mixture. Conditions: $\Phi=2$; $P=82.4$ kPa; $T=296$ K.

energy at low $R_f$, and of the cellularity onset at high $R_f$. To select the most appropriate range of data to extract the flame speed, we have employed the two following rules:

- The minimum flame radius ($R_{f,l}$) is simply fixed at 3 cm. This value was selected based on the study of Huo et al. [25].
- The maximum flame radius ($R_{f,u}$) is selected to maximize the linearity of the $S_b=f(1/R_f)$ in the range $[(1/R_f)_{max}, (1/R_f)_{min}]$, where $(1/R_f)_{max}$ is obtained using $R_{f,l}$.

This procedure ensured that the data employed for extracting the flame speed, shown as blue crosses in Figure 2, correspond to the phase during which the flame propagates according to the quasi-steady
regime [37].

The unstretched laminar flame speed is extracted using the LC equation [38] which considers a linear relationship between the flame speed and curvature

\[ S_b = S^0_b - 2S^0_b L_b / R_f \]

where \( S_b \) is the stretched flame speed with respect to the burnt gas; \( S^0_b \) is the unstretched flame speed with respect to the burnt gas; and \( L_b \) is the Markstein length. The choice of the LC equation was motivated by the results of Chen [39] which showed that for mixtures with positive Markstein length, this equation is the most accurate to extract the flame speed. Figure 2 also shows the evolution of the flame speed as a function of stretched rate calculated with Equation 5 and the parameters \( S^0_b \) and \( L_b \) obtained by fitting the experimental data. The laminar flame speed with respect to the unburnt gas, \( S^0_u \), was obtained by dividing \( S^0_b \) by the expansion ratio at chemical equilibrium.

![Figure 2: Evolution of the stretched flame speed as a function of \( 1/R_f \). Conditions: H_2/air mixture; \( \Phi=1.5; X_{He}=0; P=80 \text{ kPa}; T=300 \text{ K.} \)](image)

2.4. Numerical simulations

The steady 1-D freely propagating flame code of the Cantera package [35] was employed to calculate the unstretched laminar flame speed. The multi-component transport model was adopted and the Soret effect was taken into account. As previously mentioned, the Cantera package was also employed to calculate the thermodynamic and transport properties required for the optimization of the mixture’s composition. In addition, unsteady expanding spherical flames were simulated using A-SURF, which detailed description can be found in [40, 41]. The initial conditions of velocity and wall temperature at each grip point before ignition were 0 cm/s and 300 K. To avoid perturbation due to confinement effects [42], the radius of the spherical numerical domain was set at \( r=120 \text{ cm} \). The flame radius used for determining the laminar flame speed and the Markstein length was less than 10 cm, to be consistent with the experiments. The radiation effect was neglected. Multi-component transport and Soret effects were also included in the A-SURF simulations.

For the optimization procedure, the only detailed reaction model used was that of Wang et al. [43] which consists of 14 species and 38 reactions. We have also verified the performances of three other reaction models: Konnov’s model [44] (15 species and 75 reactions); Burke’s model [45] (13 species and 27 reactions); and Curran’s model [46] (11 species and 21 reactions).
3. RESULTS AND DISCUSSION

3.1. Critical flame radius for cellularity onset

As seen in Figure 1, the flame surface remains essentially smooth up to a flame radius of several cm. The initial perturbation induced at the ignition stage by the presence of the electrodes [47] does not grow for several ms. Eventually, because of the decrease of the stabilization by the thermo-diffusive effects at large radii, a cellular structure develops from the initial perturbation and progressively covers the flame surface. The development of the cellular structure is accompanied by oscillations of the apparent flame speed as the cells undergo successive phases of growth and breaking. Because determining the critical radius for cellularity onset through a visual inspection can lead to a subjective interpretation, we have chosen to define it as the last flame radius that we employed in our flame speed analysis. As a consequence, the \( R_c \) values that we are reporting correspond to the maximum flame radius for which the flame propagation is not affected by the development of the cellular flame front. These values are reported in Table 1.

![Figure 3: Deviation of \( R_c \) from \( R_{th}^c \) predicted by Matalon’s theory for \( \text{H}_2/\text{O}_2/\text{N}_2/\text{He} \) mixtures at \( T=300 \) K.](image)

Figure 3 shows the evolution of the ratio \( R_{exc}/R_{th}^c \) with equivalence ratio for the three pressures we investigated. This ratio ranges between 0.3 and 0.7, which indicates that the theory of Matalon significantly over-estimate the critical radius for cellularity onset. It is also noted that the deviation is lower at 80/100 kPa as compared to the one observed at 50 kPa. Although under certain conditions, the theory of Matalon predicts with good accuracy the critical radius (or Peclet number) for cellularity onset, discrepancies of up to factor of 4 between the predicted and measured critical radius were previously reported by Law et al. [48]. It should be noted that some of the parameters, such as the Zeldovich number, that need to be calculated to determine \( R_{th}^c \) may exhibit large uncertainty. Grosseuvres et al. [49] have recently demonstrated the inability of several detailed reaction models to reproduce the experimentally measured activation energy which directly impact the value of the Zeldovich number and thus the predicted impact of the thermo-diffusive effect, see Equation 1 and Equation 3.

3.2. Flame speed measurements

Figure 4 shows the position of the experimental data points in the diagram of extrapolation-induced uncertainty established by Huo et al. [25]. The uncertainty related to the extrapolation to zero stretch-
rate is below 2% for all the experimental cases performed in this study which reveals the relevance of the mixture properties optimization and data reduction procedures we applied. The overall uncertainty on the flame speed measured ($\Delta S^0_u$) can be estimated using the formula employed by Nativel et al. [24]

$$\Delta S^0_u = \sqrt{\left(\Delta S_{u,ext}\right)^2 + \left(\Delta S_{u,T}\right)^2 + \left(\Delta S_{u,r}\right)^2 + \left(\Delta S_{u,rad}\right)^2}$$

where $\Delta S_{u,ext}$ is the uncertainty due to the extrapolation to zero stretch rate, taken equal to 2%; $\Delta S_{u,T}$ is the uncertainty due to the uncertainty on the temperature, taken equal to 0.4%; $\Delta S_{u,r}$ is the uncertainty due to the uncertainty on the flame radii, taken equal to 0.9%; and $\Delta S_{u,rad}$ is the uncertainty due to radiation, taken equal to 0.7%. This analysis leads to a maximum uncertainty of 2.3%.

Figure 4: Experimental data points in the map of extrapolation uncertainty. Conditions: H$_2$/O$_2$/N$_2$/He mixtures; $\Phi = 0.6$–2; $P = 50$–100 kPa; $T = 293$–300 K.

Figure 5 shows the evolution of the flame speed as a function of equivalence ratio for the three pressures investigated. For all pressures, the flame speed increases in the range $\Phi = 0.6$ to $\Phi = 1.5$. In the range $\Phi = 1.5$ to $\Phi = 2.0$, the flame speed plateaus at $P = 50$ and 80 kPa and decreases at $P = 100$ kPa. Similar trends were observed in previous studies [26, 50, 51] and are explained by the respective changes of the mixture diffusivity and of the chemical energy release rate with equivalence ratio. Under the conditions we have studied, the flame speed is increasing with pressure for all equivalence ratio. Although the interpretation of the results is complicated by the simultaneous change of the flame temperature and the pressure, it might be concluded that under the conditions we employed, both the chain terminating reaction H+O$_2$+M=HO$_2$+M and the chain branching reaction H+O$_2$=OH+O promote flame propagation. It was shown by Yang et al. [52] using sensitivity analysis, that the competition between these two chemical paths is a complex function of temperature, pressure and mixture’s initial composition.

3.3. Chemical model predictions

Figure 5 compares the experimental laminar flame speed with the prediction of the four reaction models we have selected. The performances of the mechanisms were quantified and the deviation between the
Figure 5: Comparison between the experimental and calculated unstretched laminar flame speed for H$_2$/O$_2$/N$_2$/He mixtures at different pressures and T=293-300 K.

Experimental and calculated values are also shown in Figure 5. The relative error on $S^0_u$ ($E_r(S^0_u)$) was calculated using

$$E_r(S^0_u) = \frac{\Delta S^0_u}{S^0_u(Exp)} = \frac{S^0_u(Cal) - S^0_u(Exp)}{S^0_u(Exp)}$$  (7)

where $S^0_u(Exp)$ and $S^0_u(Cal)$ are the experimental and calculated unstretched laminar speed, respectively. For these calculations, the freely propagating flame code in Cantera was employed. All four models reproduce qualitatively the trends observed experimentally. Quantitatively, the deviation between the
experiments and the different models is below 10% except for Konnov’s model in the case for which \( \Phi=0.6 \) and \( P=50 \) kPa. It is noted that the model of Konnov tends to over-estimate the flame speed in general whereas the model of Wang tends to under-estimate it. The results obtained with Burke’s and Curran’s models are close and agree better with the experimental data than the results obtained with Konnov’s and Wang’s models. The Curran’s model performs better at 50 kPa, whereas the Burke’s model performs better at 80 kPa and 100 kPa. The mean absolute error for the models of Burke, Curran, Konnov, and Wang are, 2.6%, 2.7%, 4.9%, 3.6%, respectively.

We have also evaluated the ability of the reaction models to reproduce the dynamical response of the flame to stretch rate using unsteady simulation performed with A-SURF. An example of such a calculation is shown in Figure 6. For the case presented, the behavior observed experimentally is qualitatively and quantitatively captured by the reaction model.

![Figure 6: Experimental and simulated non-dimensional stretched flame speeds as a function of \( 1/R_f \). Conditions: \( \Phi=2; X_{He}=0; P=100 \) kPa; \( T=300 \) K. The simulation was performed with Wang’s model.](image)

As the dynamical response of the flame to stretch rate is quantified by the Markstein length, we have compared the experimental and calculated values obtained for this parameter, as shown in Figure 7. Qualitatively, the models tend to better reproduce the evolution of the Markstein length with equivalence ratio at \( P=50 \) kPa. At higher pressures, the models essentially fail at reproducing the U-shaped curves observed experimentally with a maximum at \( \Phi=1.2 \). It is also noted that Curran’s and Burke’s models predict a negative Markstein length in the case for which \( \Phi=0.6 \) and \( P=50 \) kPa, whereas a positive Markstein length was measured. This indicates that these two models predict an increase of the flame speed with the increase of stretch rate whereas a decrease is observed experimentally. Quantitatively, the mean absolute error on the Markstein length, calculated in the same way as the error on the flame speed, see Equation 7, for the models of Burke, Curran, Konnov, and Wang are, 31.4%, 44.6%, 26.8%, 27.3%, respectively.

### 4. CONCLUSION

In the present study, a numerical implementation of the stability theory of Matalon has been employed to optimize the mixture properties so that the development of the cellular flame front is delayed up to a predefined flame radius. Using the large flame radius data, the unstretched laminar flame speed was measured in the quasi-steady regime, in which the uncertainty associated with the extrapolation method...
Figure 7: Comparison between the experimental and calculated Markstein length for $\text{H}_2/\text{O}_2/\text{N}_2/\text{He}$ mixtures at $T=293-300$ K and $P=50/80/100$ kPa.

is minimum. Although the experimental critical radius was found to be significantly lower than the theoretical one, the flame speeds measured exhibit an uncertainty below 2.3%. The performances of four models from the literature were evaluated with respect to the unstretched laminar flame speed and the Markstein length using steady and unsteady numerical simulation performed with the multi-component transport model and the Soret diffusion. While the flame speed was reproduced within 5% on average by the four models, large discrepancies, above 25% on average, were observed for the Markstein length.

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