Measurement of Laminar Burning Speeds and Investigation of Flame Stability of Acetylene \((C_2H_2)/air\) Mixtures

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Abstract

Laminar burning speeds and flame structures of spherically expanding flames of mixtures of acetylene (C$_2$H$_2$) with air have been measured over a wide range of equivalence ratios, temperatures, and pressures. Experiments have been conducted in a constant volume cylindrical vessel with two large end windows. The vessel was installed in a shadowgraph system equipped with a high speed CMOS camera, capable of taking pictures up to 40,000 frames per second. Shadowgraphy was used to study flame structures and transition from smooth to cellular flames during flame propagation. Pressure measurements have been done using a pressure transducer during the combustion process. Laminar burning speeds were measured using a thermodynamic model employing the dynamic pressure rise during the flame propagation. Burning speeds were measured for temperature range of 300 to 590 K, pressure range of 0.5 to 3.3 atmospheres, and the range of equivalence ratios from 0.6 to 2. The measured values of burning speeds compared well with existing data and extended for a wider range of temperatures. Burning speed measurements have only been reported for smooth and laminar flames.
1 Introduction

Acetylene is used for oxyacetylene gas welding and cutting due to the high temperature of the flame. For constant volume and internal energy using STANJAN Its combustion produces a flame of over 3000 K. In addition, it produces the Higher Heating value (HHV) of about 50 KJ/g [1].

Laminar burning speed is one of the fundamental thermo-physical properties of any fuel/air mixture and is defined as the speed relative to the unburned gas at which a planar, one-dimensional flame front travels along the normal to its surface [2]. Some researchers have studied laminar burning speeds of different C₂H₂/air mixtures. Egolfpolous et al. [3] measured laminar burning speeds of mixtures of C₂-hydrocarbones with oxygen and nitrogen for pressures of 1 and 2 atm at ambient temperature. Jomaas et al. [4] measured laminar burning speeds of C₂–C₃ hydrocarbons at atmospheric and elevated pressures using counter flow method. Levine and Gerstein [5] studied fundamental flame speeds of pure hydrocarbons, using tube method. Milton et al. [6] measured laminar burning speeds in stoichiometric hydrogen and hydrogen-hydrocarbon gas mixtures using constant volume method. Rallis et al. [7] measured laminar burning speeds of acetylene-air mixtures also using constant volume method.

In this work, experiments have been conducted in a constant volume cylindrical vessel. Laminar burning speeds and flame structures of spherically expanding flames of mixtures of C₂H₂ with air have been studied over the range of fuel air equivalence ratios from 0.6 to 2. Burning speeds were measured from ambient temperature up to 590 K and for pressures of 0.5 to 3.3 atm. In order to report only laminar burning speed measurements, cell formation conditions have been identified via a shadowgraph system.
2 Experimental Facilities

In this section the overall experimental setup in the laboratory is described. The individual components are described as well as the experimental procedure that is followed in order to fill the combustion vessels, ignite the mixture, and to collect data.

2.1 Spherical Vessel

The spherical combustion vessel shown in figure 1 is constructed of two 4140 steel hemispheric heads bolted together resulting in a 15.4 cm inner diameter sphere. The chamber was designed to handle pressures up to 425 atm and has been fitted with ports for spark electrodes, various diagnostic probes, and the appropriate plumbing for filling and evacuation of the vessel. To monitor the initial temperature of the mixture, a thermocouple is housed in one of the ports. Another port has been fitted with a Kistler 603B1 piezoelectric pressure transducer connected to a Kistler 5010B charge amplifier for measuring the pressure-time history of the combustion process. Ionization probes have been mounted flush with the inner chamber wall at the top and bottom in order to check the arrival time of the flame and to check for spherical symmetry and buoyant rise. The entire vessel is contained within an oven that is capable of preheating to 500 K.
Figure 1: Spherical combustion chamber.
2.2 Cylindrical Vessel

The laboratory is also equipped with a companion cylindrical vessel that is shown in figure 2. It has an inner diameter of 13.5 cm and a length of 13 cm and has been equipped with diagnostic instruments similar to those of the spherical vessel. In addition, the cylindrical chamber is equipped with two viewing windows of 14 cm diameter size. A Z-type Schlieren/Shadowgraph ensemble shown in figure 3 is set up to visualize the flame propagation and incorporates a high speed CMOS camera with a capture rate of up to 40,000 frames per second. Two band heaters and a rope heater that envelope the vessel can be heated up to 500 K. Both vessels have the extended-electrode automotive spark plugs shown in figure 4 installed for central ignition of the mixture. The spark plugs are constructed by grinding off the ground electrode and welding a stainless steel rod to the central electrode in order to extend it. Both of the vessels are connected to a data acquisition system that is used to coordinate the ignition system with the high-speed camera (when using the cylindrical vessel) and to capture the pressure-time data as well as the ionization probe signals.
Figure 2: Cylindrical combustion chamber.
Figure 3: Z-type Schlieren/Shadowgraph ensemble with a high speed CMOS camera.
Figure 4: Typical automotive spark plugs modified with extended electrode for use in combustion vessels.
2.3 Gas Handling System

Both combustion chambers are connected to the gas handling system shown in figure 5. The system consists of a valve manifold connected to gas cylinders to distribute gas mixtures to the vessels and a vacuum pump that is used to evacuate the manifold and vessels. The system is equipped with two piezoelectric pressure transducers for measuring static pressures and a thermocouple pressure transducer for measuring vacuum pressures. It is from this manifold that each vessel can be filled to a prescribed mixture composition by the method of partial pressures.
Figure 5: Fuel handling system used to fill combustion vessel.
2.4 Ignition

The ignition system consists of a power box, a transformer circuit, and the extended-electrode spark plugs. An AC source that is isolated by a transformer in order to prevent stray voltage from causing damage to laboratory equipment powers the ignition box. This AC source is converted to a DC source and is sent to a voltage divider whose output can be varied via a selector switch. When the output is selected, the DC source is used to charge a capacitor to the set point. Once the trigger is fired, a signal is sent from the data acquisition system (DAS) that connects the capacitor to the output ground and the DC pulse is sent to a transformer circuit. The pulse is converted through mutual inductance with a turn ratio of 1:100 to a voltage on the order of 3000 V at which point breakdown occurs and a spark is generated at the electrodes. Figure 6 shows a schematic of the ignition circuit.

2.5 Schlieren/Shadowgraph System

A Z-type shadowgraph setup has been incorporated with the cylindrical vessel in order to observe flame structure and propagation. A 10-Watt halogen lamp with a 0.3 mm pinhole is used as the light source. The light emanates from the pinhole and strikes a spherical mirror that reflects and collimates the light to a circular beam that passes through the combustion vessel. The light is then reflected by a second spherical mirror whose focal point lies in the plane of the camera. The high speed CMOS camera (HG-LE, Redlake Inc.) with a capture rate of up to 40,000 frames per second (fps) is used to capture the combustion event.
Fig 6: Schematic of ignition circuit.
2.6 Experimental Procedure

A spreadsheet is used in order to determine the appropriate partial pressures of fuel and air for a specified mixture composition. The gas manifold and combustion vessel are evacuated using the vacuum pump (Welch Chemstar™1402N). The vessel is then filled with fuel to the appropriate partial pressure and is then sealed by closing a valve at the vessel inlet. The manifold and fill lines are then evacuated with the pump to remove any fuel left in the filling system. Air is then allowed to build pressure until it is greater than the fuel pressure inside the tank (usually by a factor of two) to prevent fuel from escaping when the vessel is opened. The valve is opened and the air is added to the vessel until the appropriate pressure is reached for the mixture composition. The vessel is closed and the mixture is allowed to rest for several minutes to become quiescent. This prevents turbulence within the vessel and allows the mixture to become homogenous. Based on statistical analysis, three runs at each initial condition are sufficient to achieve a 95 confidence level [8-10]. Measurements of burning speed are limited to flames larger than 4 cm in diameter where the effects of stretch become negligible. Measurements are also bounded in that they are only made until the flame reaches the vessel wall.
3 Flame Structure and Thermodynamic Model

3.1 Flame Structure

Burning speed measurements have been done only for smooth flames. Therefore, it was necessary not to include data from cellular flames into calculations. Flame structures of all conditions have been studied and the critical conditions at which cell formations occurred were identified by using optics. Figures 7 and 8 show the snapshots of \( \text{C}_2\text{H}_2 \)-air flames for two different initial conditions at three equivalence ratios. It can be seen that as flame radii and pressure increase the tendency of flame cellularity increases.

![Snapshots of C\(_2\)H\(_2\)-air flames at three different equivalence ratios, T\(_i\) = 298 K, P\(_i\) = 0.5 atm.](image)

Figure 7: Snapshots of \( \text{C}_2\text{H}_2 \)-air flames at three different equivalence ratios, \( T_i = 298 \text{ K}, P_i = 0.5 \text{ atm} \).
Figure 8: Snapshots of C\textsubscript{2}H\textsubscript{2}-air flames at three different equivalence ratios, T\textsubscript{i} = 298 K, P\textsubscript{i} = 1 atm.

### 3.2 Burning speed model

A thermodynamic model has been used to calculate the laminar burning speed based on the pressure rise during the flame propagation inside the constant volume vessels. This model was developed by Metghalchi and Keck [11] and was modified to account for the energy losses to electrode and vessel wall and radiation from the burned gas to the wall as well as the temperature gradient in the preheat zone. It is assumed that gases in the combustion chamber can be divided into burned and unburned gas regions separated by a reaction layer of negligible thickness. Also, burned and unburned gases are ideal, pressure throughout the chamber is uniform, and compression of both burned and unburned gases is isentropic. Figure 9 shows the schematic of
the model. The burned gas in the center of chamber is divided into a number of shells whose number is proportional to the combustion duration. Burned gases are assumed to be in chemical equilibrium in each shell. Burned gases are surrounded by a preheat zone ($\delta_{ph}$) having variable temperature, which is itself surrounded by unburned gases. A thermal boundary layer ($\delta_{wb}$) separates the unburned gas from the wall. The effect of energy transfer from burned gas to the spark electrodes is considered by a thermal boundary layer ($\delta_{bl}$).

Figure 9: Schematic of different zones and their corresponding temperatures in the thermodynamics model.
A detailed description of the model is demonstrated in previous publications [12-17]. The equation of state, volume and energy equations will be solved simultaneously:

\[ PV = RT \]  

(1)

Where \( P \) is the pressure, \( v \) is the specific volume, \( R \) is the specific gas constant and \( T \) is the temperature. The mass conservation equation for the burned and unburned gas regions is:

\[ m = m_b + m_u = P_i(V_c - V_e)/RT_i \]  

(2)

Where \( m \) is the total mass of the chamber, \( m_b \) is the mass of the burned gas zone; \( m_u \) is the mass of the unburned gas zone. \( V_c \) is the volume of the chamber and \( V_e \) is the volume of the spark electrodes. In this equation, subscript \( i \) denotes the initial conditions, and subscripts \( u \) and \( b \) denote the unburned and burned gas conditions, respectively. The total volume of the gas in the combustion chamber is:

\[ V_i = V_c - V_e = V_b + V_u \]  

(3)

And the energy conservation equation is:
\[ E_i - Q_e - Q_w - Q_r = E_b + E_u \]  \hspace{1cm} (4)

Where \( E_i \) is the initial energy of the gas, \( Q_e \) is the conductive energy loss to the electrodes, \( Q_w \) is the energy loss to the wall, \( Q_r \) is the radiation energy loss. Volume (mass balance) and energy balance equations can be written as:

\[
\int_0^{x_b} (v_b - v_u) \, dx = v_i - v_u + (V_{eb} + V_{wb} + V_{ph})/m
\]
\hspace{1cm} (5)

\[
\int_0^{x_b} (e_b - e_u) \, dx = e_i - e_u + (p V_{ph} / (\gamma_u - 1) + p V_{eb} / (\gamma_b - 1) + p V_{wb} / (\gamma_u - 1) - Q_r) / m
\]
\hspace{1cm} (6)

Where \( v_i = (V_e - V_c) / m \) and \( e_i = E_i / m \) are the initial specific volume and energy of the unburned gas in the chamber, \( v_{hs} \) is the specific volume of isentropically compressed burned gas, \( v_{us} \) is the specific volume of isentropically compressed unburned gas. \( V_{wb}, V_{ph} \) and \( V_{eb} \) are displacement volume of wall boundary layer, displacement volume of preheat zone ahead of the reaction layer and displacement volume of electrode boundary layer respectively. \( e_{hs}, e_{us} \), and \( \gamma_u \), are the specific energy of isentropically compressed burned gas, specific energy of isentropically compressed unburned gas and specific heat ratio of unburned gas respectively. The above equations must be solved for two unknowns: burned gas mass fraction and the burned gas temperature of the last shell. Given pressure as a function of time (measured in the experiments), they can be solved numerically to find the burned mass fraction \( x_b(t) \) and radial temperature distribution \( T(r, t) \).
Ultimately, laminar burning speed may be defined as:

\[ S_u = \frac{\dot{m}_b}{\rho_u A_b} = \frac{m \dot{x}_b}{\rho_u A_b} \]  \hspace{1cm} (7)

Where \( A_b \) is the area of the sphere having a volume equal to that of the burned gas.
4 Results

4.1 Stretch Effects

Stretch can affect the laminar burning speed values. Typically a radius of ~ 4 cm is required for stretch to be considered negligible [2, 17]. Flame stretch is caused by the variation of flame area over time. For spherically expanding flames stretch rate can be defined as:

\[ \kappa = \frac{1}{A} \frac{dA}{dt} = 2 \frac{dr}{r \, dt} \]  

Where \( \kappa \) is the stretch rate, \( A \) is the area of flame, \( t \) is time, and \( r \) is the flame radius.

In order to study the effect of stretch, a set of tests have been arranged to measure the laminar burning speeds of a mixture of \( \text{C}_2\text{H}_2/\text{air} \) for \( \phi = 0.8 \) at three different conditions. Laminar burning speeds were measured at temperatures of 370, 380, and 390 K and pressures of 1.1, 1.2, and 1.3 atm at different stretch rates. For this purpose, different initial conditions have been selected along an isentrope in such a way that all tests produced an unburned gas mixture having temperature and pressure of these three cases during the combustion process as it is shown in figure 10. This allowed us to measure the laminar burning speed with different stretch rates due to different radii. Figure 11 shows variation of laminar burning speed versus stretch rates. As it is seen, variation of laminar burning speeds in this range of stretch rate is negligible. It can also be seen that high stretch rates occur for \( \text{C}_2\text{H}_2 \) mixtures because the flame speeds have larger values.

Figure 12 shows the variation of laminar burning speed and flame temperature for different equivalence ratios. The burning speeds are the experimental data for this work and flame temperatures were calculated using STANJAN. As it is shown in this figure, both data follow the
same trend. Regarding the mixture concentration, both maximum flame temperature and maximum burning speed occur at $\phi=1.4$.

Figure 10: Unburned gas initial conditions along an isentrop for $\varphi=0.8$. 
Figure 11: Laminar burning speed versus stretch rate for C$_2$H$_2$.

Figure 12: Laminar burning speeds and flame temperatures of C$_2$H$_2$-air flames for different equivalence ratios, T$_i$ = 298 K, P$_i$ = 1 atm.
4.2 Burning Speeds Results

Burning speed measurements were conducted for the mixtures with two different initial pressures of 0.5 and 1 and initial temperatures of 298 to 475 K for a range of equivalence ratios from 0.6 to 2.

Correlations have been developed for laminar burning speeds of C₂H₂. A power law correlation has been used to fit to the data over all the equivalence ratios, temperatures and pressures. The values of T₀ and P₀ are 298 K and 1 atm, respectively. S₀ is burning speed of stoichiometric mixture at reference condition:

\[
S_u = S_{u0}(1 + a(\phi - 1) + b(\phi - 1)^2) \left[ \frac{T_u}{T_{u0}} \right]^\alpha \left[ \frac{P}{P_0} \right]^\beta
\]  

(9)

The least square fitted parameters are shown in table 1. These parameters were fitted over the temperature range of 298 to 590 K, pressure range from 0.5 to 3.3 atm, and equivalence ratios from 0.6 to 2. It can be seen that pressure exponent (β) is a very small negative value.
Table 1: Fitted parameters for C2H2 burning speeds correlation.

<table>
<thead>
<tr>
<th>$S_{uo}$ (cm/s)</th>
<th>$a$</th>
<th>$b$</th>
<th>$\alpha$</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>128.757</td>
<td>-0.921</td>
<td>-0.992</td>
<td>1.502</td>
<td>-0.043</td>
</tr>
</tbody>
</table>

Figures 13 to 15 show laminar burning speeds of acetylene-air mixtures with initial pressure of 0.5 atm and initial temperatures of 298, 350 and 475 K for different equivalence ratios along isentropes. Figures 16 and 17 show laminar burning speeds of acetylene-air mixtures with initial pressure of 1 atm and initial temperatures of 298 and 350 K for different equivalence ratios along isentropes. Finally, the laminar burning speeds coverage can be seen in figure 18.

In these figures, the pressure corresponding to each temperature can be estimated from the isentropic compression relation:

$$P = P_i (T/T_i)^{\gamma_a/\gamma_s}$$  \hspace{1cm} (10)
Figure 13: Laminar burning speeds of $\text{C}_2\text{H}_2$-air flames for different equivalence ratios, $T_i = 298$ K, $P_i = 0.5$ atm.

Figure 14: Laminar burning speeds of $\text{C}_2\text{H}_2$-air flames for different equivalence ratios, $T_i = 350$ K, $P_i = 0.5$ atm.
Figure 15: Laminar burning speeds of C$_2$H$_2$-air flames for different equivalence ratios, $T_i = 475$ K, $P_i = 0.5$ atm.

Figure 16: Laminar burning speeds of C$_2$H$_2$-air flames for different equivalence ratios, $T_i = 298$ K, $P_i = 1$ atm.
Figure 17: Laminar burning speeds of C$_2$H$_2$-air flames for different equivalence ratios, T$_i$ = 350 K, P$_i$ = 1 atm.
Figure 18: 3-D plot of present burning speed data coverage.
4.3 Comparison

Figure 19 shows the comparison between present work and available data in the literature. The comparison has been done for atmospheric pressure and room temperature. It shows a good agreement between the present study and previous ones.

Figure 19: Comparison of C₂H₂-air mixtures laminar burning speeds with other literatures for atmospheric condition.
4.4 Transition to cellular flame

One of the important properties of a combustible mixture is recognized as mass burning rate. Mass burning rates of the mixtures of C\textsubscript{2}H\textsubscript{2}/air with initial pressure of 0.5 atm and ambient temperature with different equivalence ratios have been shown in figure 20 for three different runs. It shows that mass burning rate of C\textsubscript{2}H\textsubscript{2} mixtures increases with increasing the temperature. As shown in this figure, for the equivalence ratio of 1.4, cellularity begins at a pressure and a temperature of 1.52 atm and 402 K, respectively. Therefore, mass burning rates increase significantly as flame becomes cellular (due to increase in flame area).

More results of mass burning rate can be seen in figures 33 and 34 in Appendix A.

Figure 20: Comparison of C\textsubscript{2}H\textsubscript{2}-air mixtures mass burning rates for three different equivalence ratios.
4.5 Error Analysis

An uncertainty analysis has been done for laminar burning speed measurement. Based on equation 9, since $S_u = S_u(\phi, T_i, P_i, P(t))$ the effects of uncertainties in the parameters of $\phi$, $T_i$, $P_i$, and $P(t)$ on laminar burning speed have been studied. The total experimental uncertainty in laminar burning speed ($\Delta S_u$) was calculated using the following relation:

$$\Delta S_u = \sqrt{\sum_{i=1}^{n} \left( \frac{\partial S_u}{\partial x_i} y_i \right)^2}$$

(11)

In this equation, $x_i$ parameters are considered as $\phi$, $T_i$, $P_i$, and $P(t)$, therefore $n=4$. The fixed error in each of the measurement variables due to the experimental facilities are represented by $y_i$, which are as follows:

1. Error in equivalence ratio of mixtures: $\Delta \phi = 0.02$ It was calculated by using a gas chromatography system.
2. Error of in the initial temperature (considering type K thermocouples): $\Delta T_i = 2$ K.
3. Error of reading the initial pressure from pressure transducer (Omega type) $\Delta P_i = 0.0025$ atm.
4. Error of reading the dynamic pressures from pressure transducer (Kistler 603B1): $\Delta P(t) = 0.0002$ atm.
Finally, the range of relative experimental uncertainty in the laminar burning speed data was found to be less than 4%.

Some results of this analysis can be shown in figure 21, which has done for two different conditions having different equivalence ratios.

Figure 21: Error analysis data from experimental work for two different conditions.
5 Summary and Conclusion

Laminar burning speeds covered a wide range of temperatures and pressures up to 590 K and 3.3 atm, respectively for the range of equivalence ratios from 0.6 to 2. Measurements have been done using the pressure rise during spherical flame propagations in a constant volume cylindrical vessel. The maximum value of burning speed observed at the equivalence ratio of 1.4 and it is consistent with available data in literature. Structures of spherically expanding flames for all of the test conditions were studied and onset of cell formation has been identified. Increasing the acetylene concentration causes the flame to become cellular at lower pressures. This trend is continuing up to the $\varphi=1.4$, which also has the maximum value for the burning speed and then the trend is increasingly.
References


Appendix A

Data Processing

Acetylene Global Reaction

To determine the global reaction for burning of C\textsubscript{2}H\textsubscript{2}, it was assumed that the only products of combustion would be CO\textsubscript{2}, N\textsubscript{2} and H\textsubscript{2}O. Performing an atom balance results in the following global reaction:

\[ \text{C}_2\text{H}_2 + 2.5(\text{O}_2+3.76\text{N}_2) \rightarrow 2\text{CO}_2 + \text{H}_2\text{O} + 9.4\text{N}_2 \]  \hspace{1cm} (12)

Equilibrium calculations were performed using STANJAN and nearly all possible chemical species that could be present at equilibrium were included in the calculations. A list of the possible species is shown in table 2. The results confirm that the most significant products of combustion present at equilibrium are those assumed above. From this reaction it is seen that the stoichiometric air for burning C\textsubscript{2}H\textsubscript{2} is 11.9 moles. This value is used as an input to facilitate the use of the FORTRAN routine used to calculate burning speed.
**Data Analysis**

The burning speed calculations are restricted to flames greater than approximately 4 cm where the effects of stretch become negligible. A typical pressure file from an experimental run of C\textsubscript{2}H\textsubscript{2} in the cylindrical vessel is shown in figure 22. In order to prevent errors in the burning speed code, the pressure file must be smooth so that it reflects the physics of the combustion event which can be seen in figure 23. That is, the pressure versus time file should represent a monotonically increasing function of time. Note also that flame reaches the vessel wall in the cylinder much earlier than the maximum pressure is seen. In order to determine when the flame hits the vessel wall, the high speed camera images are used to find the flame time of arrival.

The raw burning speed result from the FORTRAN code is shown in figure 24. This plot depicts burning speed along an isentrope for equivalence ratio of 0.8 at the initial condition \(T_i = 298\) K, \(P_i = 0.5\) atm.

The burning velocities from the raw output were then fitted across all equivalence ratios and isentropes to the form equation (9), which are mentioned in the result section. A sample result from fitting the data for the above mentioned condition is shown in figure 25. The results from fitting the data for all tested conditions are shown in figures 26 to 33.
Table 2: List of possible species used in STANJAN calculations to verify global reactions.

<table>
<thead>
<tr>
<th>H2</th>
<th>H</th>
<th>O</th>
<th>O2</th>
<th>OH</th>
<th>H2O</th>
<th>H2O2</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH</td>
<td>CH2</td>
<td>CH2(S)</td>
<td>CH3</td>
<td>CH4</td>
<td>CO</td>
<td>CO2</td>
<td>HCO</td>
</tr>
<tr>
<td>CH2O</td>
<td>CH2OH</td>
<td>CH3O</td>
<td>CH3OH</td>
<td>C2H</td>
<td>C2H2</td>
<td>C2H3</td>
<td>C2H4</td>
</tr>
<tr>
<td>C2H5</td>
<td>C2H6</td>
<td>HCCO</td>
<td>CH2CO</td>
<td>HCCOH</td>
<td>CH3CHO</td>
<td>N2</td>
<td>HO2</td>
</tr>
</tbody>
</table>
Figure 22: Typical pressure output file from experimental run, $T_i = 298 \text{ K}$, $P_i = 0.5 \text{ atm}$, $\phi = 0.6$. 
Figure 23: Laminar burning speed along isentropes of C$_2$H$_2$: raw measure values,

\[ T_i = 298 \text{ K}, P_i = 0.5 \text{ atm}, \phi = 0.6. \]
Figure 24: Laminar burning speed along isentropes of C$_2$H$_2$: raw measure values superimposed by fitted values, $T_i = 298$ K, $P_i = 0.5$ atm, $\varphi = 0.6$. 
Figure 25: Laminar burning speeds of C$_2$H$_2$-air flames for different equivalence ratios, T$_i$ = 298 K, P$_i$ = 0.5 atm.
Figure 26: Laminar burning speeds of C$_2$H$_2$-air flames for different equivalence ratios, T$_i$ = 350 K, P$_i$ = 0.5 atm.
Figure 27: Laminar burning speeds of C$_2$H$_2$-air flames for different equivalence ratios, T$_i$ = 400 K, P$_i$ =0.5 atm.
Figure 28: Laminar burning speeds of C$_2$H$_2$-air flames for different equivalence ratios, $T_i = 475$ K, $P_i = 0.5$ atm.
Figure 29: Laminar burning speeds of C₂H₂-air flames for different equivalence ratios, T₁ = 298 K, P₁ = 1 atm.
Figure 30: Laminar burning speeds of C$_2$H$_2$-air flames for different equivalence ratios, T$_i$ = 350 K, P$_i$ = 1 atm.
Figure 31: Laminar burning speeds of C\textsubscript{2}H\textsubscript{2}-air flames for different equivalence ratios, T\textsubscript{i} = 400 K, P\textsubscript{i} = 1 atm.
Figure 32: Laminar burning speeds of C₂H₂-air flames for different equivalence ratios, Tᵢ = 475 K, Pᵢ = 1 atm.
Figure 33: Mass burning rates of C$_2$H$_2$-air flames for different equivalence ratios, $T_i = 298$ K, $P_i = 0.5$ atm.
Figure 34: Mass burning rates of C₂H₂-air flames for different equivalence ratios, Tᵢ = 298 K, Pᵢ = 1 atm.