Experiments on the Effect of Exhaust Gas Recirculation Diluent on the Laminar Burning Speed and Stability of Syngas/Air flames

A Thesis Presented

by

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to

The Department of Mechanical and Industrial Engineering

in partial fulfillment of the requirements
for the degree of

Master of Science

in

Mechanical Engineering

in the field of

Thermo-fluids

Northeastern University
Boston, Massachusetts

May 2016
Abstract

The laminar burning speed is one of the most important intrinsic properties of a combustible mixture that adequately characterizes a fuel. It is important to understand the laminar burning speed’s dependence on various parameters such as the fuel, pressure and temperature, fuel/oxidizer equivalence ratio and diluent. The laminar burning speed of synthetic gas (syngas), which is a gaseous mixture of H\textsubscript{2} and CO, that is diluted with inert exhaust gas recirculation (EGR) is presented in this thesis as well as a study of flame stability. Experiments were performed in a spherical chamber and a cylindrical chamber. The cylindrical chamber is installed in a Schlieren/shadowgraph setup that captures the density variations of a propagating flame using a high-speed CMOS camera, which are used to track any deviations from a smooth, spherical, and laminar flame, such as cellularity or buoyancy. The combustible mixture is centrally ignited in the vessel using extended spark plugs and the pressure rise resulting from combustion is recorded by a pressure transducer fitted to the wall of the chamber, which is the primary input to the thermodynamic model used to calculate the laminar burning speed. The conditions presented in this work are for 5:95, 10:90, and 25:75 H\textsubscript{2} to CO fuel ratios, over equivalence ratios that ranged from 0.6 to 3.0, pressures of 0.5-3 atm, and temperatures of 298-400K, which were diluted by 5% and 10% EGR that has a composition of 14% CO\textsubscript{2} and 86% N\textsubscript{2}. A power law correlation is presented for the laminar burning speeds of H\textsubscript{2}/CO/air/EDG.
Acknowledgements

I would like to give my sincere thanks to my professor and advisor Hameed Metghalchi for the all of the guidance, patience, and motivation throughout my years at Northeastern University and I also would like to express my gratitude for the unique and memorable opportunity of a lifetime to present at a conference in India. Without your help, I would not have been able to learn and experience as much as I did. I also must thank Omid Askari for answering all of my questions, all of the assistance around the laboratory, and the assurance, without which I would not have been able to get very far.

I would like to thank my friends and colleagues Ziyu Wang, Xiayuan Wang, Mohammed Alswat, Matt Ferrari, Mimmo Elia, Matteo Sirio, and Guangying Yu for all of the help with research, the technical discussions, and above all, the company. I also would like to thank Ali Moghaddas, Alden Alholm, and Emad Rokni for the correspondence and help with the code.

I also extend my thanks to Joyce Crain and Japhet Noah with the assistance of the logistical issues, and to Tom Olson, Kevin McCue, and Jon Doughty for being both friendly and helpful with technical issues.

Finally, I must express my gratitude to my family for all of the support, encouragement, and cooked food for all of those late and exhausted nights. None of this would be possible without their hard work to afford such an opportunity, and for that I am grateful and indebted.
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1 Introduction

1.1 Background

The laminar burning speed of a combustible mixture is defined as the one-dimensional speed of a planar adiabatic flame front relative to an unburned gas mixture. The laminar burning speed and its dependence on equivalence ratio, pressure and temperature, and mixture composition is one of the most important intrinsic properties of any combustible mixture. Additionally, the laminar burning speed is suggested to be an important parameter in the calculation of correlations of other properties of a combustible mixture such as flashback, minimum ignition energy, and turbulent flame velocities [1]. The laminar burning speed adequately characterizes a fuel and provides a good indicator of how a fuel performs. It is widely used and contains information about a mixture’s exothermicity, diffusivity, and reactivity.

Synthetic gas, also known as syngas, is primarily a mixture of hydrogen and carbon monoxide gas and is considered to be an alternative fuel because it can be created through waste products such as biomass gasification and recycling of flue exhaust. Syngas has seen increased popularity as a fuel because of the rise of integrated gasification combined cycle (IGCC) technology, resulting in cleaner fuels from coal with lower emissions. Thus, the development and research pertaining to syngas fuel are becoming more relevant amid growing concerns about pollutants and carbon emissions.

Syngas is considered as a strong candidate to replace many fuels currently in use, therefore it is imperative to fully understand and characterize how syngas behaves in various conditions. It is also important to study the laminar burning speed in a high pressure environment as well as with different diluents, since those are normally gas turbine-
relevant conditions. One typical form of diluent is the inert gas found in exhaust gas recirculation (EGR) technique that is commonly used in automobile engines, which is primarily a mixture of carbon dioxide, nitrogen, and water.

There is a wide assortment of literature on the laminar burning speed of syngas fuels with and without different kinds of diluent. Hassan et al. [2] used the constant pressure method in a spherical combustion chamber with viewing windows to measure the laminar burning speeds of various hydrogen to carbon monoxide ratios, pressures (0.5-4 atm), equivalence ratios (0.6-5.0) at ambient temperature. Sun et al. [3] used a dual-cylindrical chamber to extract laminar burning speed data at atmospheric temperature from many different hydrogen percentages, elevated pressures (less than 40 atm), and equivalence ratios (0.5-5.0). Sun et al. also replaced nitrogen with helium as the diluent in order to increase flame stability, allowing them to obtain data at extreme pressures. Vu et al. [4] compared the effects of CO₂, N₂, and He as diluents on the stability of 50% hydrogen percent syngas flames at elevated pressures, and reported that helium is the most effective at suppressing instability and the least effective in decreasing laminar burning speed. Burbano et al. [5] studied the effects of CO₂ and N₂ diluent on the laminar burning speed and stability of syngas/air flames over a wide equivalence ratio (0.6-4.3) using the burner method. Han et al. [6] used the dual-cylindrical constant pressure method to obtain laminar burning speeds of syngas/air flames for equivalence ratios of $\phi = 0.8$ and $\phi = 1.0$ at elevated pressures and temperatures for various CO₂ diluent percentages (up to 40%).

There is a wide range of scientific literature that is currently available on the laminar burning speed of syngas flames diluted with CO₂ or N₂, but there is a scarcity of literature on syngas flames diluted with CO₂ as well as N₂ with the same heat capacity as EGR (14%
CO₂ and 86% N₂). In these experiments, syngas is considered as a mixture of H₂ & CO gas
\((\alpha H₂ + (1 - \alpha)CO\) where \(0 < \alpha < 1\) and the extra diluent gas (EDG) percentage \(\beta\) \((0 < \beta < 1)\) is with respect to the final mixture composition (e.g.: 10% EDG has 90% Syngas/Air).

1.2 Experimental Methods used to calculate Laminar Burning Speed

Accurate and reliable determination of laminar burning speeds is paramount and there have been many experimental methods used with varying degrees of accuracy and reliability. The following section is meant to be a general overview of the methods used to measure the laminar burning speed of various fuels as well as a brief summary of the benefits and challenges associated with each method. Interested readers are directed to the excellent literature reviews by Andrews and Bradley [7] as well as Rallis and Garforth [1] for more detail.

Experimental measurements of laminar burning speeds can be divided into two main methods: stationary flames and propagating flames.

Stationary flames encompass nozzle burners and flat flame burners. Nozzle burners are the most commonly used types of burners since they are inexpensive and simple to use and operate in a similar fashion as Bunsen burners, such as those employed by Burbano et al. [5]. Laminar flow of premixed combustible mixture is consumed by a stationary flame located at the top of a nozzle burner, where unburned gas mixture is heated and then transformed into combustion products. Since the flame is stationary for a steady flow, the laminar burning speed is simply equal to the normal velocity component of the unburned mixture entering the flame. The simplicity of this experimental method is offset by the fact
that the exact surface area can be difficult to determine and energy losses significantly reduce the laminar burning speed. For example, conical flames turn out to be not exactly conical, velocity at the rim of the burner as well as the tip of the cone are not uniform and are unequal, the temperature profile of the unburned gas entering the flame is not uniform, and there is some arbitrariness as to what is considered the flame. The most visible part of the flame is not the beginning of the combustion process, but rather the end of it, and flame front thicknesses are on the order of the burner diameters. Schlieren and shadowgraph or particle velocimetry techniques are recommended to circumvent these challenges. Flat flame burners utilize glass beads, fine diffusion screens, and layers of plain and corrugated metal tape, resulting in a laminar flow and a disk-like flat flame with rounded edges. The flat flame burner is most nearly one-dimensional and therefore stretch is not a large concern. However, the flat flame burner is limited to slow moving flames and tends to under-predict because of the nonadiabatic energy loss to the tubular matrix that created the laminar flow.

Propagating flames include the cylindrical tube, the soap bubble method, and the spherically propagating flames, which can be further subdivided into constant pressure and constant volume methods. The cylindrical tube method involves igniting a premixed combustible mixture on the open end of a cylindrical tube and photographing the propagation of the flame as it travels towards the closed end. However, several serious complications arise due to gravitational and wall quenching effects. Laminar burning speed results provide different values whether the tube is oriented horizontally or vertically, and wall quenching effects may deform the surface area of the flame thereby creating error in the calculation of the laminar burning speed. The soap bubble method involves filling a
soap bubble with combustible mixture whereupon it is centrally ignited and recorded via a camera. The flame propagates centrally outward until it reaches the soap bubble film, finally bursting. The soap bubble method allows for simple calculation but is limited to low speed flames, and also introduces error by altering the composition of the combustible mixture.

Constant pressure freely propagating spherical flames in rigid constant volume containers are used by McLean et al. [8] and Hassan et al. [2] and many other authors. A premixed combustible mixture is centrally ignited in a rigid spherical vessel that has viewing windows, through which a camera records the initial portion of the combustion process. This initial portion of the combustion event is assumed to have a negligible pressure rise, i.e. “constant pressure”, and data beyond a critical pressure rise is discarded. An analysis of the flame pictures yields the rate of radius change \((dr/dt)\) and therefore the laminar flame speed. However, the constant pressure method suffers from stretch and other ignition effects because of the relatively small flame radii and therefore require some form of extrapolation to the unstretched laminar burning speed. The dual-cylindrical chamber developed by Qin and Ju [9] and used by subsequent authors [3, 4, 6] extends the region of constant pressure and allows for larger radius measurement by housing a cylindrical chamber within another cylindrical chamber. The outside chamber is filled with an inert gas, while the inner cylindrical chamber has a magnetic locking system that opens when the pressure of the inner chamber reaches a critical value. The constant pressure method results in one data point for one experiment and there is some arbitrariness in choosing the location of the flame when flame thickness is large.
The constant volume method was developed first by Lewis and von Elbe [10] and later by Metghalchi and Keck [11, 12]. Takizawa et al. [13] also used the constant volume technique to measure the laminar burning speed of fluorinated compounds. The constant volume method measures the dynamic pressure rise that results from the combustion process, which is then used to obtain the mass fraction of burnt gas. This information is used to calculate the laminar burning speed over a range of temperatures and pressures from a single experiment. Additionally, since the constant volume method is not restricted to the regime of constant pressure, the effects of ignition energy and stretch are minimized meaning that little to no extrapolation is required to obtain the unstretched laminar burning speed. It is this method that is presented in this thesis.
2 Experimental Facilities and Procedure

2.1 Cylindrical Combustion Chamber

The cylindrical combustion chamber is 13.5cm in diameter and 13cm in length and is capped on both ends by 5.08cm thick fused quartz windows, which are used to record the combustion event with a high-speed camera, as shown in Figure 1. The windows are seated on the body of the cylindrical chamber by using elastomer O-rings that also create a vacuum seal. The cylindrical chamber is equipped with a piezoelectric pressure transducer, two thermocouples, and two extended spark plugs for central ignition with a gap of about 1mm. The spark energy is tuned to minimize the effect of spark discharge on the propagation of the flame. The cylindrical chamber is installed in a ‘Z-shaped’ Schlieren system where flame propagation is captured by a high-speed CMOS camera. Ignition, pressure-time data, and flame images are controlled, synchronized, and recorded using a LabVIEW program and camera software. The cylindrical chamber is limited to a maximum of 50 atmospheres due to the windows and a maximum of 500K due to the elastomer O-rings. More information regarding the cylindrical chamber can be found in [14, 15]

2.2 ‘Z-shaped’ Schlieren Photography System

The ‘Z-shaped’ Schlieren photography system is used in conjunction with the cylindrical chamber and is shown schematically in Figure 2. Light is produced from a lamp that enters a pin hole and is captured by the first concave spherical mirror. The beams reflect from the first spherical mirror, pass through the cylindrical chamber’s windows and the medium of interest within (a gas), and then reflect off of the second spherical mirror into the high-speed CMOS camera with a razor edge. Tracing the rays from the light source
to the camera creates the so called ‘Z-shaped’ setup. The shadowgraph/Schlieren setup is such that the beams travelling through the cylindrical chamber are initially parallel to each other and but become deflected when passing through media with differing densities, which result in a change in refractive index. Beams that are greatly deflected after passing through the entire medium do not pass the razor edge and result in dark spots in the captured images. The razor edge is the difference between a Schlieren setup and a shadowgraph setup. A more detailed description of the Schlieren photography method can be found in [16-18].

2.3 Gas Supply System

The cylindrical vessel is attached to a gas delivery system that is comprised of valves, high accuracy pressure transducers, a vacuum pump, constituent gases, and a manifold, as shown in Figure 3. There are four pressure gauges, one of which is connected to a thermocouple vacuum transducer and three of which are piezoelectric pressure transducers, each suited for different pressure ranges. The thermocouple vacuum gauge is firstly used to determine vacuum pressure within the manifold and combustion chamber (~100-120 milliTorr is considered to be sufficiently close to vacuum pressure) and is secondly used to calibrate the piezoelectric pressure transducers, since piezoelectric pressure transducers only measure dynamic pressure. Once a vacuum pressure reading is chosen, the corresponding readings of the other three pressure gauges are considered as offsets for subsequent pressure readings. The volume percentage of the compressed air tank is 21% O\textsubscript{2} and 79% N\textsubscript{2}. The volume percentage of the O\textsubscript{2}/He tank is 20.95%/79.05%. The volume percentage of the exhaust gas recirculation (EGR) tank is 14.07% CO\textsubscript{2} and 85.93% N\textsubscript{2}. 
2.4 Experimental Procedure

Generally, the procedure for filling the chamber with different gases follows the method of partial pressures and will be explained in detail in the following section. First, the chamber and manifold are opened to the vacuum pump and evacuated to a pressure of \(~100\) milliTorr, which is a process that can take up to half an hour, depending mainly on the quality of the vacuum seal of the chamber and of course the power of the vacuum pump. Vacuuming the system is the rate-limiting step of the experimental procedure. Once a vacuum pressure is selected, the corresponding readings of the piezoelectric pressure transducers are recorded as offsets in an Excel spreadsheet that is used to calculate the partial pressures of each constituent gas. Gases are filled one at a time in order of the smallest partial pressure to the largest, and sufficient care is taken during the filling process to ensure that there is no backflow when opening the chamber. Once the prescribed partial pressure is achieved, the chamber is closed and the manifold is evacuated to vacuum pressure, and the process is repeated until all constituent gases have been filled. After completing the filling procedure, one minute is given to allow the gases to reach quiescence (further time was not needed because experiments were performed at ambient temperature). Then the ignition box is turned on, the camera is primed, and the ignition is triggered via a LabVIEW program. Normally, the LabVIEW program has a time delay added for the cylindrical chamber to allow persons in the area to evacuate the room for safety reasons. After the combustion event, the ignition box is turned off, the chamber is evacuated, and the camera images and pressure data is collected and filed away.
Of the entire combustion process, pressure data is only considered for flame radii greater than 4 cm, since laminar burning speed is affected by spark ignition and stretch at small radii [19-21]. Pressure data collected after the flame touches the wall is also neglected, which is determined by using the camera images that are synchronized with pressure data collection using the data acquisition system (DAQ). More information regarding the DAQ can be found in [22]. The camera images are also used to determine whether the flame is stable or cellular and the time at which the flame becomes cellular or unstable. Pressure data used for laminar burning speed calculation is only considered while the flame is smooth, laminar, and spherical. Experiments were performed at least twice until the relevant pressure rise history is identical, as shown in Figure 4.

2.5 Gas Chromatography

A Varian CP-3800 Gas Chromatograph (GC) is used to verify the accuracy of the mixture composition of the gases filled using the partial pressure method. Currently, the GC is equipped with a Thermal Conductivity Detector (TCD) that is used in conjunction with a MolSieve 13x packed column that can be used to identify some permanent gases (O₂, N₂, CH₄, CO, but not CO₂), as well as a HayeSep DB porous polymer column and a CP-Sil 5B capillary column. Currently the GC is configured to sample from gaseous flow and is calibrated using several calibration gases of differing mixture compositions.
3 Theoretical Model

3.1 Burning Model and Laminar Burning Speed

The thermodynamic developed by Metghalchi and Keck [11] is used in this work in order to calculate the laminar burning speed given the pressure rise history of the propagating flame of a fuel and oxidizer mixture that is contained within a constant volume chamber. The main assumptions of the thermodynamic burning model are as follows:

1. The unburned gas mixture is initially at a uniform temperature and composition and is quiescent
2. The chamber is divided into a burned gas zone and an unburned gas zone at local thermodynamic equilibrium, with the unburned gas composition frozen
3. The thickness of the reaction zone is negligible
4. The pressure is constant and uniform throughout the chamber at any particular instant of time
5. The reaction flame front is uniformly smooth and spherical
6. The unburned and burned gases behave ideally and are compressed isentropically

Figure 5 shows the burning model as well as the temperature variation with increasing radius. A burned gas core with variable temperature is surrounded by the unburned gas shell, separated by a reaction layer of negligible thickness. Immediately outside the burned gas core is the preheat zone, which is a layer of unburned gas that is $\delta_{ph}$ thick and has variable temperature due to conductive energy transfer. Following the preheat zone is the unburned gas layer that has a uniform temperature which is in turn followed by a wall boundary layer that is $\delta_{bl}$ thick and has variable temperature that is in contact with the chamber wall.
The equation used to calculate the laminar burning speed is given by:

\[
S_u = \frac{m \dot{x}_b}{\rho_u A_f}
\]

(3.1)

where \( m \) is the total mass of the mixture, \( \dot{x}_b \) is the burned gas mass fraction burning rate, \( \rho_u \) is the density of the unburned gas, and \( A_f \) is the area of the flame. Once the pressure rise history \( p(t) \) is given from experiments, the burned gas mass fraction burning rate \( \dot{x}_b \) can be obtained through simultaneously solving the conservation of mass and conservation of energy equations, as outlined in Casey Bennett’s Thesis [15].

3.2 Conservation Equations

The two conservation equations used for the constant volume combustion process are:

Conservation of Mass

\[
\frac{V}{m} = \int_0^{x_b} v_b \, dx' + (1 - x_b) v_u - \frac{V_{wb} + V_{eb} + V_{ph}}{m}
\]

(3.2)

Conservation of Energy

\[
\frac{E}{m} = \int_0^{x_b} e_b \, dx' + (1 - x_b) e_u + \frac{Q_{wb} + Q_{eb} + Q_{rad}}{m}
\]

(3.3)

where \( V \) is volume, \( E \) is energy, \( Q \) is energy transfer due to heat interaction, \( m \) is the total mass, \( v \) is the specific volume of the gas, \( e \) is the specific volume of the gas, \( x \) is the mass fraction of burned gas, \( p \) is the pressure, \( T \) is the temperature, subscript \( b \) and \( u \) refer to burned and unburned gas, respectively, subscript \( wb \) is the wall boundary layer, subscript \( eb \) is the electrode boundary layer, subscript \( ph \) is the preheat zone, subscript \( rad \) is
radiation. Readers that are interested in the derivation of equations (3.2) and (3.3) are directed to Eisazadeh-Far et al. [14].

3.3 Unburned Gas Properties

The temperature of the unburned gas is calculated from the pressure rise history using the assumption of isentropic compression. The temperature of the unburned gas \(T_u(t)\) is iteratively solved for until the change in entropy is close enough to zero:

\[
\Delta s = s(T_u(t), p(t)) - s(T_{u,0}, p_o) = \int_{T_{u,0}}^{T_u(t)} c_p(T) \frac{dT}{T} - R \ln \frac{p(t)}{p_o}
\]

where \(s\) is the specific entropy of the unburned gas, \(T_{u,0}\) is the initial temperature of the unburned gas, \(T_u(t)\) is the temperature of the unburned gas at time \(t\), \(R\) is the specific gas constant of the unburned gas mixture, \(p_o\) is the initial pressure of the mixture, \(p(t)\) is the pressure of the chamber at time \(t\), and \(c_p(T)\) is the constant pressure specific heat of the mixture. \(c_p(T)\) is given by the NASA polynomial fit [23]:

\[
\frac{c_p(T)}{\bar{R}} = a_1 + a_2 T + a_3 T^2 + a_4 T^3 + a_5 T^4
\]

where \(c_p(T)\) is the molar specific heat at constant pressure, \(\bar{R}\) is the universal gas constant, and the constants \(a_1, a_2, \ldots\) are given in [23]. The iterative method used to find the root of equation (3.4) is the Newton-Raphson method:

\[
x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)}
\]

where \(f\) is any function that is dependent on the independent variable \(x\), \(f'\) is the derivative of the function, and \(n\) and \(n + 1\) denote the current and the next iteration, respectively. In this case, the function \(f\) is equation (3.4) and \(T_u\) is the independent variable.
Once the temperature of the unburned gas is found, the specific volume \( v_u \) of the unburned gas can be calculated using the ideal gas law:

\[
v = \frac{RT}{p}
\]

Then the specific energy of the unburned gas \( e_u \) is found using the definition of specific enthalpy:

\[
e = h - RT
\]

where \( h \) is defined as:

\[
h = h(T_u) = \int_{T_{ref}}^{T_u} c_p(T) \, dT
\]

for a semi-perfect gas and \( c_p(T) \) is found using equation (3.5).

### 3.4 Burned Gas Properties

Given the pressure rise history as a function of time \( p(t) \), the burned gas properties \( v_b(T_b, p) \) and \( e_b(T_b, p) \) as well as the burned gas mass fraction \( x_b \) and the temperature of the burned gas \( T_b \) are found using the thermodynamic equilibrium code STANJAN [24].

An initial guess for \( x_{b,i} \) and \( T_{b,i} \) as well as the measured pressure \( p \) is used to calculate \( v_b \) and \( e_b \), which are then used to check if equations (3.2) and (3.3) are satisfied. If the equations are not satisfied, then a new guess \( x_{b,i+1} \) and \( T_{b,i+1} \), where \( i + 1 \) is used to denote the new guess, is calculated using the Newton-Raphson Method that has been extended for a system of two equations, but basically has the same form as equation (3.6) (see Appendix 1 of Mimmo Elia’s Thesis [25] for the exact formulation of the system of equations). This process is repeated iteratively until the difference between the new and the previous guess
$i + 1$ and $i$ is lower than some tolerance. The initial guess for $x_b$ and $T_b$ is based on experience and should be chosen to be in the neighborhood of the exact answer.

### 3.5 Laminar Burning Speed Calculation

Once equations (3.2) and (3.3) have been satisfied for each time step, the mass fraction burning rate $\dot{x}_b(t)$ can be obtained by numerically differentiating $x_b(t)$ with respect to time. With the assumption of a spherical flame, the volume, radius, and area of the burned gas are calculated as:

\[
V_b = m x_b v_b
\]  
(3.10)

\[
r_f = \left( \frac{3 V_b}{4 \pi} \right)^{\frac{1}{3}}
\]  
(3.11)

\[
A_f = 4 \pi r_f^2
\]  
(3.12)

where $V_b$ is the volume of the burned gas, $r_f$ is the radius of the burned gas volume, and $A_f$ is the surface area of the burned gas volume. Finally, the laminar burning speed can be calculated using equation (3.1).
4 Results & Discussions

4.1 Summary of Test Conditions

The experimental initial conditions that are covered in this thesis are summarized in the following section. Syngas/Air pressure-time data is collected for hydrogen percentages in the fuel of 5, 10, and 25%, initial pressures of \( p = 0.5 \) atm, 1.0 atm, and 2.0 atm, equivalence ratios of \( \phi = 0.6, 1.0, 2.0, \) and 3.0, and for two diluents 5% EGR, and 10% EGR, all at ambient temperature 298K. Experimental data reported in this thesis for syngas/air that is not diluted with EGR (i.e. 0% EGR) is borrowed from previous researchers (Askari et al. [26]) and is presented in this paper for the purpose of comparison with the present diluted experiments.

4.2 Stretch Tests

Stretched laminar burning speeds obtained from spherically propagating flames are a function of the geometry of the experiment and are therefore not a fundamental thermo-physical property of a combustible mixture. Unstretched laminar burning speeds are normally obtained from a linear or nonlinear extrapolation to zero stretch. Stretch is defined as:

\[
\kappa = \frac{1}{A_f} \frac{dA_f}{dt} = \frac{2}{r_f} \frac{dr_f}{dt} \tag{4.1}
\]

for spherical flames. From equation (4.1), it is easy to see that it is advantageous to calculate laminar burning speeds when the flame radius is large, as stretch will be minimized and closer to the unstretched laminar burning speed. In order to investigate the effect of stretch for syngas/air/EDG mixtures, different tests were selected from the
isentrope obtained from an experiment, such that the only difference in the initial conditions between the first experiment and the subsequent stretch test experiments are the initial pressure and temperature. The initial pressures and temperatures selected must be a point that lies on the isentrope of the first experiment. Finally, a point is chosen that is shared by all of the experiments and the laminar burning speed as well as the corresponding stretch is calculated for that point. More detail on the procedure can be found in [21, 27]. Figure 6 shows the results of the stretch tests for a chosen point when $EDG = 10\%$. As it can be seen, the laminar burning speed does not vary widely when stretch is less than $100s^{-1}$.

4.3 Flame Stability Study

Over the experimental conditions tested, both smooth flames as well as cellular flames were observed. Cellular flames are the result of intrinsic instabilities of the fuel/air mixture, i.e. hydrodynamic instabilities and thermal-diffusive instabilities [28], whereas smooth flames are the result of the suppression of intrinsic instabilities [26]. The results of EDG addition to syngas/air flames are shown in Figure 7. The flame images show that flame instability is affected by equivalence ratio as well as the percent of EDG addition. Increasing EDG percentage results in a smoother and less cellular flame for equivalence ratios $\phi = 0.6, 2$, and $3$, but not for $\phi = 1$. Also note that with increasing EDG percentage, the time required for the flame to reach the same radius as the $EDG = 0\%$ case is increased, suggesting that the laminar burning speed has decreased as a result of a decrease in the adiabatic flame temperature.
4.4 Laminar Burning Speed

The laminar burning speed results as well as the power law fit and its dependence on various properties such as equivalence ratio, pressure, hydrogen percentage, and extra diluent percentage were investigated. Figure 8 shows that the laminar burning speed non-monotonically increases and decreases with increasing equivalence ratio, peaking at an equivalence ratio of about 2. Figure 9 shows the negative pressure dependence of laminar burning speed. Figure 10 shows that the laminar burning speed increases with increasing hydrogen content, whereas Figure 11 shows that the laminar burning speed decreases with increasing EDG percentage. The addition of inert diluents to the premixed mixture appears to act as a sink of energy that decreases the adiabatic flame temperature, and ultimately the laminar burning speed.

All of these trends are encapsulated within the power law fit equation, which is a function of equivalence ratio, pressure, temperature, and EDG percentage and is shown below:

\[ S_u = S_{u0} (1 + a(\phi - 1) + b(\phi - 1)^2) \left( \frac{T}{T_o} \right)^\alpha \left( \frac{p}{p_o} \right)^\theta (1 - \beta)^\gamma \] (4.2)

where \( S_{u0} \) is the laminar burning speed at a reference point defined at \( \phi = 1, T_o = 298 \, K, p_o = 1 \, atm \), \( \phi \) is the equivalence ratio, \( T \) is the temperature, \( p \) is the pressure, and \( \beta \) is the EDG percentage. The exponents \( \alpha, \theta, \) and \( \gamma \) are linear functions of the equivalence ratio specified by:

\[ \alpha = \alpha_1 + \alpha_2(\phi - 1) \] (4.3)
\[ \theta = \theta_1 + \theta_2(\phi - 1) \] (4.4)
\[ \gamma = \gamma_1 + \gamma_2(\phi - 1) \] (4.5)
The values of the coefficients are summarized in Table 1 and are given for hydrogen percentages of 5, 10, and 25%. The correlation is only valid for smooth laminar flames for equivalence ratios $0.6 < \phi < 3$.

4.5 Comparison of Laminar Burning Speeds with Data in the Literature

Since there is no data available in the literature for syngas/air/EDG dilution at the specific EDG composition of 14% CO$_2$ and 86% N$_2$, comparisons were made to available data for stoichiometric syngas/air at atmospheric pressure and ambient temperature with no dilution and is presented in Figure 12. The results given by the power law fit agree well within experimental uncertainty. Laminar burning speeds within the fuel-lean and near stoichiometric range agree well with other researchers whereas our results tend to over-predict in the fuel-rich range.
5 Conclusions & Future Work

Laminar burning speeds for diluted syngas with 5% and 10% EDG, which has the same specific heat as EGR (14% CO₂ and 86% N₂), over an equivalence ratio range of 0.6 to 3, a pressure range of 0.5 to 3 atm, a temperature range of 298 to 400 K, for syngas fuel ratios of 5, 10, and 25% is presented. Stretch tests have indicated that the laminar burning speeds measured and reported were in the regime of low stretch. Increasing EDG concentration delays the onset of cellularity and acts as an energy sink, decreasing the adiabatic flame temperature and consequently the laminar burning speed. A power law fit correlation of the form (4.2) has been developed for hydrogen concentrations of 5, 10 and 25% over equivalence ratios of 0.6 to 3.0 for smooth flames only. Laminar burning speed results agree with the available data in the literature.

The speed of experiments can be increased if the quality of the vacuum seal is assured using an O-ring that does not begin to fail at high pressures and temperatures. The need to replace O-rings every time the cylindrical chamber system is brought from high to low temperature is a costly process. The gas chromatograph (GC), if properly calibrated using the correct calibration gases, can be used to ascertain the uncertainty associated with the partial pressure filling process. The current gas chromatograph setup is not ideal for calibration gases that contain CO₂, which may result in skewed results. Either an implementation of a bypass mechanism for the GC should be investigated or calibration gases that do not contain CO₂ should be purchased. A piece of plexiglass found in the lab can be used to create a barrier for the cylindrical chamber. An older version of the burning speed code should be updated to meet contemporary standards, as there was some difficulty in reaching convergence for some cases.
6 References


*Exp. Fluids*, 43, 887-894.


Figure 1: Picture of cylindrical chamber.
Figure 2: ‘Z-shaped’ Schlieren/shadowgraph setup and the cylindrical chamber.
Figure 3: Main components of the gas supply system.
Figure 4: Two experiments that are considered identical.
Figure 5: Burned and unburned gas separated by a reaction sheet of zero thickness. A plot of temperature variation along the radius is also shown including the preheat zone and wall boundary layer.
Figure 6: Stretch test results for EDG=10% experiments.
Figure 7: Snapshots of syngas/air/EDG flames for various EDG percentages and equivalence ratios when the hydrogen percentage is 25%, initial temperature is 298 K, and initial pressure is 1 atm.
Figure 8: Laminar burning speed of syngas/air/EDG mixture along isentropes at different equivalence ratios for initial pressure of 0.5 atm, initial temperature of 298 K, hydrogen concentration of 25% and EDG concentration of 10%
Figure 9: Laminar burning speed of stoichiometric syngas/air/EDG mixture along isentropes at different initial pressures for initial temperature of 298 K, hydrogen concentration of 5% and EDG concentration of 10%
Figure 10: Laminar burning speed of syngas/air/EDG mixture along isentropes at different hydrogen concentrations for initial pressure of 1 atm, initial temperature of 298 K, equivalence ratio of 3.0 and EDG concentration of 5%
Figure 11: Laminar burning speed of syngas/air/EDG mixture along isentropes at different EDG concentrations for initial pressure of 0.5 atm, initial temperature of 298 K, equivalence ratio of 0.6 and hydrogen percentage of 10%
Figure 12: Laminar burning speed comparison with experimental data from other researchers using the power law fit for stoichiometric syngas/air with hydrogen percentage of 5% at atmospheric pressure and ambient temperature with no dilution.
Power Law Fit Coefficients

<table>
<thead>
<tr>
<th>$S_{u0}$</th>
<th>$a$</th>
<th>$b$</th>
<th>$\alpha_1$</th>
<th>$\alpha_2$</th>
<th>$\theta_1$</th>
<th>$\theta_2$</th>
<th>$\gamma_1$</th>
<th>$\gamma_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha = 5%$</td>
<td>33.351</td>
<td>1.313</td>
<td>-0.410</td>
<td>1.884</td>
<td>-0.008</td>
<td>-0.136</td>
<td>-0.003</td>
<td>3.130</td>
</tr>
<tr>
<td>$\alpha = 10%$</td>
<td>47.433</td>
<td>1.337</td>
<td>-0.444</td>
<td>1.843</td>
<td>0.004</td>
<td>-0.173</td>
<td>0.019</td>
<td>3.579</td>
</tr>
<tr>
<td>$\alpha = 25%$</td>
<td>76.209</td>
<td>1.351</td>
<td>-0.510</td>
<td>1.842</td>
<td>0.008</td>
<td>-0.175</td>
<td>0.035</td>
<td>3.631</td>
</tr>
</tbody>
</table>

Table 1: Correlation coefficients are valid only when the flames are smooth, spherical, and laminar and for equivalence ratios $0.6 < \phi < 3$. 