Extinction Limits of Laminar Diffusion Counterflow Flames of Various Gaseous Fuels including Syngas and Biogas

by

Timothy Kwan

A thesis submitted in conformity with the requirements for the degree of Master of Applied Science
Graduate Department of Aerospace Science and Engineering
University of Toronto

Copyright © 2013 by Timothy Kwan
Abstract

Extinction Limits of Laminar Diffusion Counterflow Flames of Various Gaseous Fuels including Syngas and Biogas

Timothy Kwan
Master of Applied Science
Graduate Department of Aerospace Science and Engineering
University of Toronto
2013

This work investigates the extinction limits of laminar diffusion counterflow flames for various gaseous (methane, syngas, biogas) fuels using a high flow rate counterflow burner designed and built for this work. Equal momenta of the fuel and oxidizer streams were not maintained to provide data to check the fidelity of the numerical schemes and their chemical mechanisms at ”non-standard” conditions. Strain rate values at extinction were obtained as a function of fuel mole fraction. Preliminary work with the new burner found that the methane extinction limit results were consistent with results from literature. The results provide insight into the extinction limit conditions of the aforementioned fuels. The strain rate was found to increase with increasing fuel mole fraction. Extinction limit results indicated that fuels with the highest concentration of hydrogen have the greatest extinction limit, which is believed to be attributed to the high diffusivity and reactivity of hydrogen.
Acknowledgements

First, I would like to thank Prof. Ömer L. Guilder for giving me this wonderful opportunity to collaborate with him on this challenging project and for giving me the opportunity to learn from him. He has patiently supported me and has graciously provided me with the resources I needed to complete my project. I am truly grateful for all of his support and this thesis would not have been successful without him.

I would like to acknowledge the help, support, and advice from my friends and colleagues at the University of Toronto Institute for Aerospace Studies (UTIAS) combustion and propulsion research group. They were always there when I needed a helping hand, and made the lab environment much more interesting and fun: Gorngrit Intasopa, Dr. Mario Commodo, Owen Wong, Francisco Hernandez-Perez, Arup Barua, Ivo Fabris, and Daniel Cormier. Those with whom I had the pleasure to work alongside with: Sanaz Ghasemi, Ali Nasseri, Nasim Shahbazian, Parsa Tamadonfar, Sina Kheirkhah, Dr. Frank Yuen, Dr. Peter Joo, and Emre Karataş, Jason Liang, and John (Zhao) Liu. Of the above, I would especially like to thank Emre Karataş who taught me most of what I know about my work, assisted with the experimental apparatus and methodology, and even sat in the dark with me as we did experiments.

I would like to thank my various friends outside of UTIAS. You know who you are. This paragraph is for all of you. Thank you for being there and making my life so much more wonderful during my master’s.

I would also like to thank my dearly beloved Sheila for being there with me as I worked on the corrections to my thesis in the final few months of my master’s. Your love and support was of tremendous assistance during this difficult time.

Last but not least I would like to thank my mom, who was always there supporting me during the entire stretch of my educational journey - from my first day in kindergarten, to the end of my master’s.
# Contents

Abstract
Acknowledgments
Table of Contents
List of Figures
List of Tables

1 Introduction
   1.1 Biofuels
   1.2 Syngas and the Gasification Process
   1.3 Types of Flames
   1.4 Counterflow Diffusion Flames
   1.5 Strain Rate of Counterflow Diffusion Flames
   1.6 Extinction of Counterflow Diffusion Flames
      1.6.1 Brief History of Flame Extinction in Literature
      1.6.2 H₂ Flame Extinction in Literature
   1.7 Soot Formation in Combustion
      1.7.1 Soot Formation
      1.7.2 Soot Extinction Limit
      1.7.3 Soot Formation in Counterflow Flames
   1.8 Motivation
   1.9 Objectives

2 Experimental Apparatus
   2.1 Counterflow Burner
   2.2 Gas Delivery System

3 Experimental Methodology
   3.1 Burner Outlet Matrix Type
   3.2 Calibration
   3.3 Experimental Procedure
   3.4 Ignition Methodology
   3.5 Flow Calculations
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5.1</td>
<td>Case 1: Fuel Mole Fraction Constant</td>
<td>34</td>
</tr>
<tr>
<td>3.5.2</td>
<td>Case 2: Strain Constant</td>
<td>36</td>
</tr>
<tr>
<td>3.5.3</td>
<td>Viscosity of Fuel Gas Mixtures and Reynold’s Number</td>
<td>36</td>
</tr>
<tr>
<td>4</td>
<td>Preliminary Experiments with CH₄</td>
<td>38</td>
</tr>
<tr>
<td>4.1</td>
<td>Methane Extinction Results</td>
<td>38</td>
</tr>
<tr>
<td>4.2</td>
<td>Effect of Burner Outlet Conditions on Extinction</td>
<td>42</td>
</tr>
<tr>
<td>5</td>
<td>Results and Discussion</td>
<td>45</td>
</tr>
<tr>
<td>5.1</td>
<td>Flame Appearance and Soot Presence</td>
<td>46</td>
</tr>
<tr>
<td>5.2</td>
<td>Extinction Limit</td>
<td>48</td>
</tr>
<tr>
<td>5.3</td>
<td>Sources of Uncertainty and Error Analysis</td>
<td>53</td>
</tr>
<tr>
<td>5.3.1</td>
<td>CH₄ Preliminary Results and Literature</td>
<td>53</td>
</tr>
<tr>
<td>5.3.2</td>
<td>Turbulent Conditions in Nozzle</td>
<td>56</td>
</tr>
<tr>
<td>5.3.3</td>
<td>Extinction Limit Results - Laminar Regime</td>
<td>58</td>
</tr>
<tr>
<td>6</td>
<td>Conclusions and Recommendations</td>
<td>65</td>
</tr>
<tr>
<td>A</td>
<td>Burner Technical Drawings</td>
<td>68</td>
</tr>
<tr>
<td>B</td>
<td>Experimental Flow Rates</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>Bibliography</td>
<td>81</td>
</tr>
</tbody>
</table>
List of Figures

1.1 Four types of counterflow flames .............................................. 7
1.2 Illustration of the oxidizer and flame side velocity gradient .......... 10
1.3 Soot formation in SF and SF/O flames ....................................... 21

2.1 Old counterflow burner ......................................................... 25
2.2 New counterflow burner ......................................................... 26
2.3 New counterflow burner tip .................................................... 27
2.4 Gas delivery system for the gaseous fuel experiments .................. 29

4.1 CH\textsubscript{4} extinction results from present work and literature .. 39
4.2 Extinction of CH\textsubscript{4} with different burner exit conditions .... 43

5.1 Development of a S5M50 flame ................................................. 47
5.2 The presence of soot in a methane flame ................................... 48
5.3 Extinction limits of gaseous fuel flames .................................... 49
5.4 Extinction of gaseous fuel results with an extended range ............ 50
5.5 Extinction of pure syngas with respect to percent volume CH\textsubscript{4} 52
5.6 Extinction of pure syngas with respect to percent volume CO ........ 52
5.7 Extinction of pure syngas with respect to percent volume H\textsubscript{2} ... 52
5.8 Error analysis on preliminary CH\textsubscript{4} results from present work for \(x_F < 0.5\) 55
5.9 Error analysis on CH\textsubscript{4} results from Maruta et al. [39] .... 55
5.10 Error analysis on CH\textsubscript{4} results from Tsuji et al. [25] ....... 56
5.11 Fuel stream pipe Reynolds number ........................................ 57
5.12 Oxidizer stream pipe Reynolds number .................................... 58
5.13 Error analysis on S2 results from the present work ................... 60
5.14 Error analysis on S5 results from the present work ................... 60
5.15 Error analysis on S1 results from the present work ................... 61
5.16 Error analysis on S5M25 results from the present work ............. 61
5.17 Error analysis on S5M50 results from the present work ............. 62
5.18 Error analysis on B1 results from the present work ................... 62
5.19 Error analysis on the preliminary CH\textsubscript{4} results from the present work for all values of \(x_F\) ....................................................... 63

A.1 Assembly: burner final ....................................................... 68
A.2 Assembly: burner subassembly ............................................. 69
A.3 Assembly: burner upper ...................................................... 69
A.4 Assembly: burner lower ........................................... 70
A.5 Assembly: mounting ............................................... 70
A.6 Part: burner upper plate ......................................... 71
A.7 Part: burner bottom plate ....................................... 71
A.8 Part: inner nozzle - sintered metal ......................... 72
A.9 Part: inner nozzle - smooth bore ......................... 72
A.10 Part: outer nozzle ............................................. 73
A.11 Part: base plate mounting ..................................... 73
A.12 Part: porous matrix, inner downstream ............... 74
A.13 Part: porous matrix, inner upstream ..................... 74
A.14 Part: porous matrix, outer .................................... 75
A.15 Part: sleeve, inner downstream ............................. 75
A.16 Part: sleeve, inner upstream, press fit ................. 76
A.17 Part: sleeve, inner upstream, slip fit .................... 76
A.18 Part: sleeve, outer ............................................ 77
## List of Tables

3.1 Compositions (in %volume) of the gaseous fuels .................................. 33
3.2 Properties of the gaseous fuels and their individual species at 300K and 1 atm ................................................................. 37
4.1 Comparison of pure CH$_4$ extinction results from literature ............... 41
B.1 Flow rates for CH$_4$ experimental results ........................................... 78
B.2 Flow rates for S2 experimental results ................................................ 79
B.3 Flow rates for S5 experimental results ................................................ 79
B.4 Flow rates for S1 experimental results ................................................ 80
B.5 Flow rates for S5M25 experimental results ........................................... 80
B.6 Flow rates for S5M50 experimental results ........................................... 81
B.7 Flow rates for B1 experimental results ................................................ 81
Chapter 1

Introduction

Ever since the first flame was lit, humans have relied on combustion as a source of energy. Whether it be for heating, transportation, power generation, or industrial processes, combustion has been pivotal for the development of modern society. Current demand for combustible fuels is at an all time high and is expected to continue growing. It was estimated that about 85% of the world's energy was supplied by fossil fuels in 2001 [1]. Approximately 88% of the total energy consumption for transportation in the US was supplied by petroleum products in 2008 [2]. The world’s future energy demand is expected to increase by 50% from 2005 to 2030 [3]. To help fill this demand for fuel, first generation biofuel technology has allowed the production of fuel from the sugars and vegetable oils found in arable crops. But there is much criticism over the use of these first generation biofuels as they compete with current food demand [4]. In a world where over a billion people do not have enough to eat, is it ethical to produce fuel from food sources [5]? This rising controversy has led to the development of second generation biofuels, which are derived from non-food lignocellulosic biomass and agricultural residues.
1.1 Biofuels

Biofuel is a renewable fuel source that is derived from organic matter. One of the main benefits of biofuels is that it is a carbon neutral resource, where the carbon released through burning of the biofuel is offset by the amount of carbon reabsorbed by the crops used in the production of biofuels. The first generation biofuels were produced from food resources, such as starch, sugar, vegetable oil, and animal fats, creating a competing demand for food resources [4]. There is an ethical concern with producing fuels from food resources which go towards feeding others. The second generation of biofuels on the other hand is produced from non-food resources, which can include agricultural by-products and organic waste such as wood waste from the forestry industry. In addition, second generation biofuels may make use of crops that can grow in conditions where normal food crops cannot grow [6]; however there is concern of degradation of soil fertility and quality if biowaste is used as a feedstock, as it could remove many of the nutrients that come from biomass decomposition [6].

Second generation biofuels can be obtained through two different processes: biochemical, or thermo-chemical [7]. The bio-chemical approach involves the breakdown of cellulose components of the biomass using enzymes or acids to sugars, followed by the fermentation of the sugars to alcohol using micro-organisms. The thermo-chemical approach involves converting the feedstock biomass to an intermediate gas called syngas through gasification, which is then converted to liquid biofuels. Both methods offer their own set of advantages and disadvantages, but the net yield and economic and environmental issues of both are similar, and there currently exists no preference between the two methods for the production of biofuels [8–10].

Second generation biofuels may have great potential for the aviation industry, and is of great interest to the US army. The transportation sector currently accounts for 26% of global CO$_2$ emissions [11], of which 2.6% comes from the aviation sector [12]. Road transport accounts for 81% of the total energy use from the oil dependent transportation
sector [11]. Emerging technologies such as hybrid, plug-in electric, and hydrogen fuel cells can provide alternatives for road transport. But for air transport, there appears to be very few energy alternatives that can meet the same performance, safety and economic requirements as combustible fuel. So unlike other transportation industries which can slowly wean their dependence from combustible fuel, the aviation industry will be dependent on it for quite some time. Concerns surrounding the environmental impact and future security of fuel supply have the aviation industry looking for alternative fuel sources such as biofuels. The US army in particular is interested in biofuels as a secure source of fuel to reduce their dependency on foreign oil [13].

1.2 Syngas and the Gasification Process

Syngas, the intermediate gas that is used in the thermo-chemical process of biofuel production, can be obtained from various biomass waste feedstock, such as wood, rice husks, coconut shells [14], and other non-edible parts (lignocellulosic) of biomass [15]. The biomass feedstock is broken down through thermal cracking to produce the components of syngas: CO, H\textsubscript{2}, CO\textsubscript{2}, minor amounts of CH\textsubscript{4}, and trace amounts of other gases [7]. Syngas is one of the most flexible and inexpensive substrates for the production of renewable fuels and chemicals, as it can be produced from a wide range of materials.

Gasification of biomass has existed as early as 1812 where combustible gas was made from coal or biomass, and was in widespread use for industrial heat and power applications up until the 1920s when oil powered combustion devices becomes more popular [14]. Between 1920 and 1940, it was predicted that there would be an unreliable oil supply caused by the two world wars. As a result Europe ended up switching back to the use of gasifiers to produce gaseous fuels. After this period, the popularity of gasification declined, until the energy crisis of the 1970s, which once again renewed interest in gasification of biomass to produce gaseous fuels for small scale power generation, which
was popular in developing countries that could not afford the high oil prices at the time. There hasn’t been much interest in the gasification technology in the developed world since the 1970s until recently. This is as a result of the growing demand for biofuels, which requires syngas if produced through the gasification process.

Gasification of solids is a thermo-chemical conversion process which causes a change in the chemical structure of solid biomass by partial oxidation in the presence of a gasifying agent at 500-900 °C. Examples of gasifying agents includes air, oxygen, water vapour, or a mixture of these [16]. There are two types of gasification processes: 1) direct gasification in which the gasification agent oxidizes the feedstock and provides the heat for the process, and 2) indirect gasification which still relies on a gasifying agent which oxidizes the feedstock, but the heat is provided by an external source.

The most promising biomass gasification process so far is the Dual Fluidised-Bed Gasifier, or DFBG process [16], which is an indirect gasification process. This process has two reactors; the first reactor relies on steam to oxidize the biomass feedstock into syngas at 700-900 °C. The second reactor is a combustor which uses air as the oxidizing agent with residual char material from the first reactor, and provides the heat source necessary for the first reactor. Syngas and flue gases are the by-products from the first and second reactors respectively.

For the thermal-chemical method of production of biofuels, where solid biomass is converted to syngas, the final step involves converting the syngas into useful biochemicals and biofuels [7]. There are multiple methods of syngas conversion to biofuels, but most are done through microbial processes, such as syngas fermentation, where anaerobic microorganisms are used for the bio-catalytic conversion of syngas to biofuels [17]. A large variety of anaerobic microorganisms are known to metabolize syngas into various by-products through fermentation [18], such as hydrogen, ethanol, butane, acetic acid, butric acid, methane, biopolymers, and single cell proteins.

Unlike first generation biofuels which was produced from food resources, second gen-
eration biofuels produced from syngas allows fuels to be produced from waste, or inedible feedstock that does not compete or rely on food resources. In addition, there also appears to be interest in industry and scientific literature on using syngas as a drop-in fuel for gas turbines for power generation that normally run with methane [19, 20]. Because coal represents one of the largest remaining reserves of fossil fuels, there is great interest in developing clean coal based power generation plants [20]. The integrated gasification combined cycle (IGCC) process involves using a gasifier which converts coal to syngas through the gasification process, then the syngas is burned in an existing commercial gas turbine for power generation that normally burns methane.

1.3 Types of Flames

In literature flames are classified into three categories: premixed, partially premixed and non-premixed (diffusion flames). In a premixed flame, the fuel and oxidizer are mixed prior to chemical reaction. In a diffusion flame, the fuel and oxidizer are initially separated and the chemical reaction occurs at the interface between the two reactants, where the fuel and oxidizer diffuse into the reaction zone. A partially premixed flame is an intermediate of a premixed, and diffusion flame, where some of the oxidizer and fuel are premixed prior to entering the reaction zone, while the remaining oxidizer and fuel reactants diffuse separately into the reaction zone.

Each of these flames can be further categorized as laminar or turbulent flames. Laminar flames are smooth and predictable. Whereas turbulent flames are chaotic, unpredictable, and are usually characterized using statistical methods. Turbulent combustion introduces further mixing process between the fuel and oxidizer due to small turbulent eddies, and involves interacting effects between turbulent and chemical times scales.

Most practical combustors operate under turbulent combustion, but because laminar and turbulent combustion both have similar underlying fundamental characteristics [21],
research on laminar combustion is still an important part of combustion scientific literature. Laminar flames are easier to study because of their predictable nature, and ease of isolating certain parameters during experiments. In addition, using the flamelet concept one can gain further insight into turbulent combustion by studying laminar flames under elevated strain rates [22].

Diffusion flames are complicated by the sharp temperature and concentration gradients that occur within these flames [23]; however many practical combustion systems (examples include rocket and jet propulsion, reciprocating engines, and furnaces) rely on diffusion combustion, making the study of these flames necessary [24].

1.4 Counterflow Diffusion Flames

Tsuji wrote a comprehensive review of counterflow diffusion flames [25] where he classified four types of counterflow configurations (see Figure 1.1): 1) quasi-flat flame at the impingement of two opposed jets supplied by port burners, 2) the quasi-flat flame at the impingement of two opposed jets supplied by matrix burners, 3) the flame at the forward stagnation region of a spherical porous burner, and 4) the flame at the forward stagnation region of a cylindrical porous burner. A type I counterflow flame is used for the experiments in the present work.

Type I and II counterflow flames which are unidirectional and quasi-one dimensional, are very convenient for studying diagnostic techniques, soot formation, and the effects of electric fields [25]. These types of counterflow flames are flat, and the flow velocity from the fuel and oxidizer nozzle are similar. Generally it is best to maintain equal momenta between the oxidizer and fuel streams to ensure a symmetrical flow field with the stagnation plane located equal distance from the two burner nozzles. Type I and II counterflow burners often employ a co-flowing nitrogen flow for the purposes of [26]: 1) preventing the mixing of ambient and experiment gases, 2) reducing the curvature in the
stagnation surface, and 3) minimizing radial temperature gradients. There is often an inner and outer flame present with this flame type, with the inner flame being the one of interest. The co-flow nitrogen can be used to extinguish the outer flame, leaving only the inner flame, which is useful if optical diagnostic measurement are to be used. Type I and II flames are highly dependent on the aerodynamics and flow field of the reactants. Separation and flow rates need to be carefully controlled to get a stable flame.

Type III and IV flames are known to be very stable due to the stable flow field in the forward stagnation region. This stability makes them suitable for detailed studies of flame structure and flame extinction with good reproducibility. The flame is easily stabilized over a wide range of fuel and oxidizer flow velocities, but generally the flow velocity of the fuel is much slower than that of the oxidizer. Type III flames are completely two dimensional, with the stagnation plane resting between the cylinder surface and the flame [25].

Counterflow burners are research tools which are commonly used in scientific literature for numerous reasons [25]:

1) Counterflow burners produce purely diffusion flames unlike co-flow diffusion burners which tend to have a small premixing region near the base of the flame. This is caused by a dead space near the rim of the burner, where the flame is not present due to loss
Chapter 1. Introduction

of heat and active radicals to the wall. Fuel and oxygen interdiffuse into this dead space producing small regions of premixed gases at the base of the flame.

2) Counterflow burners can be used to quantify and control the strain rate of the flame sheet by varying the exit velocities, and in the case of type I and II flames, the burner separation. This makes counterflow burners popular in literature for studying the effects of elevated strain rate on flame characteristics such as the flame extinction limit.

3) Type I and type II flames are quasi one dimensional which makes them convenient for optical diagnostics, most of which require taking optical line measurements. For a typical co-flow diffusion burner which produces a 2D flame, taking measurements is time consuming as measurements have to be taken in both the radial and axial direction, whereas for a counterflow burner, which produces a flame which can be approximated as quasi-1D along the centerline, measurements only have to be taken in the axial direction which greatly reduces experimentation duration. In addition, fewer computational resources are needed for the numerical simulation of 1D flames, which are used for gaining further insight into the experimental conditions. Since type III and IV flames are 2D, they do not share the same advantage.

1.5 Strain Rate of Counterflow Diffusion Flames

Aerodynamic strain rate is defined as the spatial velocity gradient $\partial V/\partial x$, where $V$ is velocity, and $x$ is the spatial coordinate, and is expressed in units of inverse time (s$^{-1}$).

Combustion is a rate process, in which the rate of diffusion of reactants (for diffusion combustion), aerodynamic effects, and reaction rates all play a role on the characteristics of a flame [21], each of which can be expressed as a characteristic timescale: aerodynamic time scale $\tau_a$, chemical timescale $\tau_c$ and diffusion timescale $\tau_d$.

Of the three characteristics rates, diffusion is the slowest, and thus the rate limiting process for diffusion combustion. Aerodynamic and diffusion times scales are usually on
the same order of magnitude, but the chemical time scale is much smaller [27]. Because the diffusion time scale is the rate limiting step for diffusion combustion, but not premixed combustion, diffusion flames are more susceptible to the effects of elevated strain rate. High strain rate conditions in diffusion combustion can result in the reactants being swept away before they can diffuse into the reaction zone.

The strain rate can be determined by measuring the velocity gradient on the oxidizer side or fuel side of the flame. If the velocity gradient is measured on the oxidizer side right before the flame, it is denoted as $K_{\text{ext}}$. If the velocity gradient is measured on the fuel side right after the flame, it is denoted as $M_{\text{ext}}$ [28]. Both $K_{\text{ext}}$ and $M_{\text{ext}}$ are illustrated in Figure 1.2. Often in literature, $K_{\text{ext}}$, the oxidizer side velocity gradient is used to quantify the strain rate.

One method for obtaining the strain rate experimentally is to measure the maximum local velocity gradient along the centerline at the oxidizer side just before the flame ($K_{\text{ext}}$). This can be done with optical flow visualization techniques that allow instantaneous velocity field measurements of fluid flow, such as Laser Doppler Velocimetry (LDV) or Particle Image Velocimetry (PIV). Alternatively, the strain rate can be approximated with a global strain rate formulation, which is a function of the nozzle exit velocities, burner separation, and densities of the two reacting streams.

In literature, the global strain rate expression was first derived by Seshadri and Williams [29], but was first explicitly used by Puri et al. [30] to approximate the extinction strain rate of methane. In the derivation, Seshadri and Williams treated the mixing layer as a thin sheet at the stagnation plane, the inviscid flow as rotational, and assumed a large Reynolds number. Potential flow analysis applied to an isothermal flow in a counterflow geometry dictates a linear deceleration in the axial and radial velocities as it hits a stagnation region, from which a global approximation of the strain was derived:

$$K = -\frac{2V_O}{L} \left[ 1 + \frac{V_F}{V_O} \left( \frac{\rho_F}{\rho_O} \right)^{1/2} \right]$$ (1.1)
where $L$, $V$, and $\rho$ are the distance between the burners, burner exit velocity, and densities respectively. The subscripts F and O refer to the fuel and oxidizer streams respectively. Unfortunately the global strain approximation tends to deviate from the local strain for small burner separations. Small burner separations leads to a collapse in the potential flow approximation [31–34] causing a variation in radial pressure at the nozzle exit, resulting in reactant leakage from the centerline to the edges and causing the axial velocity to vary in the radial direction. This causes the global strain rate, which approximates a bulk velocity, to overestimate the local strain rate at the centerline.

1.6 Extinction of Counterflow Diffusion Flames

There are numerous factors which affect the flame extinction limit: 1) residence time effects, 2) diluents effects, 3) chemical effects, and 4) burner effects.

1) Residence time effects: combustion is a rate process where chemical, aerodynamic, and diffusion processes are occurring. Generally the chemical time scale is much smaller than both the aerodynamic and diffusive time scale, with the aerodynamic and diffusive
Chapter 1. Introduction

time scales usually on the same order of magnitude [27]. Strain rate is a representation of the residence time of reactants in the reaction zone, where high strain rates correspond to a low aerodynamic time scale.

Premixed flames are dependent on the chemical and aerodynamic time scales only, and thus the extinction of premixed flames are not dependent on diffusion time scale effects.

Diffusion flames on the other hand are dependent on chemical, aerodynamic, and diffusion time scales. As the diffusion and aerodynamic time scale are generally on the same order of magnitude, diffusion flames are much more susceptible to extinction from aerodynamic time scale effects. At high enough strain rates, the aerodynamic time scale can easily fall below the diffusive time scale, in which case the reactants get swept away before they can diffuse into the reaction zone. This makes the extinction of diffusion flames much more susceptible to the effects of aerodynamic time scale effects than premixed flames. For diffusion combustion, fuels with low diffusivity will extinguish at a lower strain than fuels with high diffusivity [35].

2) Diluent effects: diluents in the fuel leads to a reduction in the reactant concentration, causing a decrease in the overall reaction rate, and making the flame more susceptible to residence time effects and flame extinction [36]. In addition, the presence of diluent leads to a decrease in flame temperature slowing down the chain branching reactions, making the flame more susceptible to extinction [37].

3) Chemical effects: certain chemicals, when added to the fuel, can inhibit some elementary combustion reactions and cause the flame to extinguish [36].

4) Burner effects: for type I and type II counterflow burners, the effect of the burner apparatus on the flame extinction strain rate has been studied in literature. The exit velocity profile, nozzle diameter, burner separation, and heat loss effects from the flame to the nozzle all have an effect on the measured strain rate at extinction [24].

In literature, burner separation is often quantified by the normalized burner separation
ratio. This is the ratio of the burner separation distance to the nozzle inner diameter, $L/D$. The effects of the burner separation and burner exit velocity profile on the flame extinction are interrelated. Type I counterflow burners usually have a parabolic exit velocity profile as a result of the straight tube geometry, whereas type II counterflow burners tend to have a top hat, or uniform exit velocity profile due to the matrix material at the burner exit.

A burner with a uniform velocity profile (type II burner) is more susceptible to burner separation effects, although parabolic velocity profile burners (type I) are still susceptible to burner separation effects [38]. The uniform velocity profile in type II burners will eventually become parabolic as it travels downstream from the burner exit due to drag from the surrounding air. After a certain $L/D$, when the flow distribution becomes fully developed, any further increase in burner separation will not have an effect on flame extinction. This $L/D$ in which the extinction strain rate is invariant to burner separation is called the free float burner separation ($L_{FF}$), and corresponds to a value of $L/D > 2$ [35]. In addition, the global strain rate formulation tends to overestimate the local strain rate value, but as the burner separation increases to approach the free float burner separation, the global extinction strain rate approaches the local extinction strain rate [38].

Aside from burner separation and exit velocity effects, heat loss effects also exist. Heat loss from a type I and II counterflow flame to the upper and lower burners can occur, although it is mostly prevalent in the upper burner due to buoyancy effects. This can lead to preheating of the fuel and oxidizer gases upstream of the burner exits, affecting the strain rate extinction results [39].

### 1.6.1 Brief History of Flame Extinction in Literature

Flame extinction has been studied extensively in literature both numerically and experimentally for both gaseous and liquid fuels. Covered here is most of the early pioneering
Spalding [40, 41] investigated the extinction of a counterflow diffusion flame with a flame stabilized in the forward stagnation region of a spherical porous burner (type III flame) burning a liquid fuel. Following that, experimental work was done by Simmons and Wolfhard [42] using a hemispherical porous burner (type III flame) to study the limiting oxygen concentrations for diffusion flames in air diluted with nitrogen. Potter and Butler [43], studied the experimental extinction of various gaseous fuels using a novel experimental set up where a counterflow diffusion flame was stabilized between two vertically opposed jets (type I flame) of oxidizer and fuel. The authors increased both the fuel and oxidizer flow rates, and found that the flame extinguished abruptly at a reproducible flow rate. During this time, there was no conventional means of quantifying flame extinction in literature, so the authors used the mass flow rate per unit area when the flame extinguished to quantify the flame extinction limit and referred to it as “flame strength.” The authors used converging nozzles which gave a uniform flow profile, but it was discovered that extinction results were dependent on burner separation. They realized that the flow velocity profile from the converging nozzle burner changed depending on the distance from the burner exit. When a straight tube burner was used, which gave a parabolic velocity profile that is invariant with distance from the burner exit, the flame extinction results became independent of jet spacing over a wide range.

Between 1967 and 1982 Tsuji et al. [25, 44–47] performed a number of experiments on counterflow diffusion flames with methane, propane, and hydrogen. These studies made use of a diffusion flame stabilized in the forward stagnation region of a porous cylinder (type IV flame). Dixon-Lewis et al. [48] performed a 1D numerical study of a methane-air diffusion flame stabilized in the forward stagnation region of a porous cylinder (type IV flame), and found that there was fair agreement with the aforementioned work by Tsuji et al. with regards to temperature and species mole fraction profiles, but with some discrepancy. The error was attributed to the 2D pressure effects caused by the
apparatus, or the flame itself.

Puri et al. [30] investigated the theoretical and experimental extinction limits of a flame stabilized between two opposed jets of fuel and air from port burners (type I flame). Methane and propane were used, and both the fuel and oxidizer jets were diluted with nitrogen. The goal was to study the fluid dynamics, transport processes, and chemistry in laminar flames for the use of modeling turbulent diffusion flames. The theoretical predictions were compared to the experimental results and the overall chemical kinetic rate parameters for the gas phase oxidation of a methane and propane diffusion flame, were investigated. This is the first work recorded in literature in which the global strain rate formulation was explicitly used.

Chelliah et al. [28] investigated the experimental and numerical extinction conditions for methane-air diffusion flames in an opposed jet nozzle burner system, for pressures ranging from 0.25 to 2.5 atm, and for a oxidizer stream oxygen mass fraction from 0.233 to 0.190. Two flow conditions were studied: plug flow, where the exit velocity of the burner had no radial velocity; and potential flow, where the exit velocity of the burner included a radial velocity component. It was revealed that changing the burner exit conditions from plug to potential flow can cause the extinction strain rate (as defined by the oxidizer side axial velocity gradient $K_{\text{ext}}$) to vary as much as a factor of two depending on the design of the burner. The results indicate that the strain rate as defined by the axial velocity gradient on the oxidizer side of the flame ($K_{\text{ext}}$) is dependent on the flow field. While the strain rate as defined by the axial velocity gradient on the fuel side of the flame ($M_{\text{ext}}$) is nearly independent of the flow field. It was suggested that $M_{\text{ext}}$ was a good single parameter to characterize the extinction condition when the flow field could not be simulated exactly in numerical studies. For the pressure range considered, it was found that the extinction strain rate increases with increasing pressure, but less strongly at higher pressures.

Du et al. [37] investigated the effects of flame location (as defined by the stoichiometric
mixture fraction $Z_{st}$) on flame extinction using numerical and experimental methods. The authors found that increasing $Z_{st}$ (i.e. moving the flame closer to the fuel nozzle by decreasing the fuel stream’s fuel mass fraction and increasing the oxidizer stream’s oxygen mass fraction) caused the extinction strain rate to increase. This resistance to extinction with increasing stoichiometric mixture fraction results from a rise in the $O_2$ profile into regions of higher temperature, resulting in greater OH and O production rates and concentration in this region, resulting in a stronger flame.

1.6.2 $H_2$ Flame Extinction in Literature

The high diffusivity of hydrogen leads to hydrogen flames having much greater extinction limits than other hydrocarbon fuels, making extinction limit studies of hydrogen flames very challenging [35]. In literature, specialized burners have been constructed solely for the extinction study of pure hydrogen fuel. The high strain and flow rates that are required to reach the hydrogen flame extinction limit often leads to turbulent flow in conventional counterflow burner designs. To keep the flow laminar at high flow rates, Pellett et al. [35] employed a burner with smaller nozzle diameters. To prevent burner pre-heating effects, the burner separation had to be relatively large with respect to the burner nozzle’s inner diameter, resulting in a large $L/D$. This contrasts with typical counterflow burner designs in literature which make use of larger burner diameters and smaller burner separations. Hydrogen flames in counterflow burners also exhibit an outer flame even with the presence of co-flow nitrogen, which is mostly likely a result of the high diffusivity of hydrogen. Because of this, there is often no point in employing co-flowing nitrogen for hydrogen flames.

Pellett et al. [35] was the first to study the extinction of hydrogen counterflow flames past a fuel mole fraction of 21%, which was made possible with the small diameter burner design. Various parameters were studied: a) plug-flow and parabolic input velocity profiles, b) jet burners (converging nozzles) with exit diameters ranging from 2.7 – 7.2
mm, and tube burners (straight nozzles) with exit diameters ranging from 1.8 to 10.0 mm, c) various burner separations, and d) H\textsubscript{2} fuel mole fractions ranging from 14\% to 100\%. Extinction limits were normalized by jet and tube burner diameters. Jet and tube burners were used because they allowed for plug and parabolic exit velocity profiles respectively. The authors found that pure hydrogen extinction is around 30 times higher than that of CH\textsubscript{4}, and that the extinction results were three times greater for the jet (converging nozzle with plug exit velocity profile) than with the tube (straight tube with parabolic exit velocity profile), mostly likely due to the additional radial strain component introduced by parabolic velocity profile at the exit of the tube burner. The authors also observed that the extinction strain rate is invariant with the burner separation within a certain range as long as the burners are set far apart enough to prevent heat loss (flame anchoring) effects, and close enough to prevent entrainment of the surrounding gases. The results agreed closely with numerical 1D results based on potential flow input boundary conditions between fuel mole fractions of 14 – 50\%, but started to diverge beyond that range [35].

1.7 Soot Formation in Combustion

Soot particulates are carbon particles produced as a byproduct of incomplete combustion in diffusion flames and are responsible for both the orange glow and smoke emitted from a candle flame. It is believed that after carbon dioxide, soot is the second largest contributor to global warming [49]. Unlike other greenhouse gases, which remain in the atmosphere for many years, soot particles remain for only a few weeks. Thus removing soot from our atmosphere would be an effective means of immediately combating climate change [50]. In addition, it is believed that fine soot has a negative impact on the respiratory system and that Polycyclic Aromatic Hydrocarbons (PAHs), a precursor of soot, may be carcinogenic [51]. Moreover, soot particles deposit on the chamber walls
of combustion systems, leading to inefficiency and premature wear of these combustion system. Because of these issues there is great interest among researchers to find means of limiting soot formation in combustion.

### 1.7.1 Soot Formation

The amount of soot released from a flame is equal to the soot formed, minus the soot oxidized. Soot formation is a complex process, involving many reactions occurring in parallel, and over a time period of milliseconds. The exact mechanism is still unresolved in the combustion research community, but there exists quite a bit of agreement on certain aspects of the formation process. Soot formation can be grouped into the following major steps: 1) the formation of molecular soot precursors; 2) soot particle nucleation; 3) soot particle growth; and finally 4) soot particle coagulation and agglomeration. There are many proposed pathways leading to particle nucleation, but it is commonly accepted that soot particle inception is a result of the Polycyclic Aromatic Hydrocarbon (PAH) mechanism, where PAHs grow to form soot particles [52].

The formation of molecular soot precursors is important because it is believed to be the rate limiting step for soot formation. In this first step, fuel undergoes pyrolysis, where larger fuel molecules break down to smaller products. The decomposition products undergo reactions to form aromatic rings, of which benzene is believed to be the most important. Many pathways for the formation of the first benzene ring have been proposed. One of the pathways involves the addition of acetylene (C$_2$H$_2$) to n-C$_4$H$_3$ and n-C$_4$H$_5$ to form benzene, also known as the “even-carbon pathway” [52]. A different pathway proposed by Miller and Melius [53] suggests that benzene is formed from the combination of propargyl radicals (n-C$_3$H$_3$), which is often referred to as the “odd-carbon pathway.”

Following the formation of the first aromatic ring is the growth of these rings into PAHs. It is commonly accepted in the combustion community that the Hydrogen Abstraction and Carbon Addition (HACA) mechanism advocated by Frenklach and Wang...
is responsible for this growth. In the HACA mechanism, a hydrogen atom is removed (H abstraction) from the reacting fuel by a gaseous hydrogen radical to produce H₂ and a hydrocarbon radical. A gaseous acetylene (C₂H₂) molecule then attaches to the radical site of the hydrocarbon radical (carbon addition). The resulting gaseous PAHs molecules cluster together and grow, accumulating more and more mass until nucleation of a solid soot particle occurs [52].

The early soot particles grow in size and mass by surface reactions. The most accepted mechanism for surface growth is absorption of acetylene, similar to the molecular HACA mechanism for PAH growth. Most of the soot particle’s mass is gained during this step [52].

Soot particles can further increase in size through inter-particle agglomeration and coagulation, where early soot particles collide and stick together [52].

### 1.7.2 Soot Extinction Limit

In a flame, the strain rate is a representation of residence time. Since soot formation is a rate process, its formation is affected by the residence time in the high temperature region of a flame. Higher flame strain rates results in lower soot residence time in the flame, and can potentially lead to reduced soot emissions [55].

At high enough strain rates, the flame reaches a point where sooting stops, called the soot extinction limit. Tsuji and Yamaoka [44] found that increasing the strain rate in a counterflow diffusion flame, a point can be reached where the yellow luminosity disappears indicating the absence of soot. Du et al. [56] further studied the soot extinction limit by assessing the effects of flame temperature and fuel concentration on the soot extinction limit in a counterflow flame. Flame temperature was controlled by substituting equal moles of nitrogen with argon in the nitrogen stream of the oxidizer burner, and fuel concentration was controlled by diluting the fuel stream with nitrogen. It was found that increasing either the flame temperature or the fuel mole fraction, while holding the other
variable constant, causes the soot extinction limit to increase. Du et al. [57] studied the effects of pressure and fuel nozzle molar fraction on soot extinction limits using ethylene in a counterflow configuration. Following the same experimental approach, Sung et al. [22] extended the work done by Du et al. to include methane and propane. It was shown by Du et al. and Sung et al. that the density weighted soot extinction limit ($\rho_{ox}K_p$) varies linearly with $x_F^{0.5}P$ for ethylene, methane and propane, where $\rho_{ox}$ is the density of the oxidizer stream, $K_p$ is the soot extinction global strain rate, $x_F$ is the fuel molar fraction, and $P$ is the pressure. Bohm and Lacas [58] also studied the effect of fuel concentration and pressure on soot extinction limit using methane in a counterflow configuration. They showed that the soot extinction limit increases with increasing mass fraction of fuel ($Y_{CH_4}$). It was also shown that the soot extinction limit increases with increasing pressure until reaching a maximum and then decreases.

Work has also been reported in literature to assess the effects of increasing strain rates on the spatial soot profiles in a flame. Beltrame et al. [55] studied the effects of increasing strain rates on both soot and NO formation using experimental and numerical methods. The authors showed that higher strain rates significantly reduce the amount of soot formed in a counterflow laminar diffusion flame. Karatas [59] also discovered that increasing strain rate resulted in a significant drop in the amount of soot in a flame while studying the effects of fuel mixtures and synergistic effects on soot formation.

### 1.7.3 Soot Formation in Counterflow Flames

A “soot formation (SF) flame” occurs on the fuel side of the stagnation plane, and a “soot oxidization (SF/O) flame” occurs on the oxidizer side of the stagnation plane [60]. In most studies, the momenta of the oxidizer and fuel stream are usually equal. As a result of this, the actual fuel to air mass ratio is much greater than the stoichiometric ratio, which leads to the formation of a SF flame. Unless there is a significant amount of fuel dilution, counterflow flames are usually SF type flames.
In a SF flame, the flame and soot formation occurs on the oxidizer side of the stagnation plane. Soot particles are generated on the fuel side of the flame near the flame, and get transported toward to the stagnation plane (swept away from the flame). The soot size and concentration increases as it approaches the stagnation plane (which is lower in temperature). In a SF type flame, soot never enters the air side of the flame and thus is emitted without getting oxidized [60]. This process is illustrated in Figure 1.3a.

In a SF/O flame, the flame and soot formation occurs on the fuel side of the stagnation plane. As fuel molecules from the fuel nozzle approach the higher temperature regions of the flame, they undergo pyrolysis followed by the formation of PAHs and soot particles leading to an increase in soot volume fraction. The volume fraction keeps increasing until it reaches a maximum and then decreases as the soot particles enter regions towards the stagnation plane with high OH radical concentration, where they break up and oxidize [60]. This process is illustrated in Figure 1.3b.

1.8 Motivation

This work looks into the extinction limit condition of various fuels, including syngas and biofuels and is motivated by the following:

1) Increasing interest in second generation biofuels produced from syngas: as discussed earlier in Section 1.1, demand for biofuels has been increasing due to environmental concerns over conventional fossil fuels, a desire for renewable and sustainable energy sources, and a desire for domestic and more secure fuel supply [61]. Second generation biofuels will satisfy all these demands without competing with food supply, which caused much controversy over the first generation of biofuels.

2) Increasing interest in syngas: as discussed in Section 1.2, second generation biofuels can be produced using syngas as an intermediate gas using the thermo-chemical process. In addition, syngas produced from coal can be used to power existing commercial gas
Chapter 1. Introduction

21

(a) SF flame

(b) SF/O flame

Figure 1.3: Soot formation in SF and SF/O flames [59].

3) Limited syngas extinction studies in literature: there are numerous works in literature studying the extinction of individual syngas components, such as methane and hydrogen, but very few for syngas itself. All of the current syngas extinction studies appear to be numerical investigations. Park et al. [62] numerically studied the effects of adding CO$_2$ to the extinction characteristics of H$_2$/CO syngas diffusion flames. The authors diluted syngas with CO$_2$, and an artificial species with the same thermo-chemical, transport, and radiation properties of CO$_2$ to isolate the chemical effects of CO$_2$ on the extinction of syngas. The authors concluded that the chemical effects of adding CO$_2$ reduces the CO$_2$ mole fraction at which the flame extinguishes as it suppresses the reaction rate of the principle chain branching reaction.
Shih et al. [63] numerically studied the effect of composition, dilution gases (using \(\text{CO}_2\), \(\text{H}_2\text{O}\), and \(\text{N}_2\)), and pressure on the flame structure and extinction limits of \(\text{H}_2/\text{CO}\) syngas diffusion flames. The minimum \(\text{H}_2\) fraction until extinction for the syngas mixture was obtained for a given strain rate. Higher \(\text{H}_2\) fractions and pressures were observed to extend the extinction limits of the syngas fuels studied. In addition, the radiation and chemical effects of the different dilution gases at various strain rates were investigated.

Chun et al. [64] numerically studied the effects of increasing \(\text{H}_2\) fraction, fuel dilution, higher initial temperature, and pressure on the flame structure, extinction limits, and \(\text{NO}_x\) emissions of syngas/air diffusion flames. The extinction limits were found to increase with increasing \(\text{H}_2\) fraction, lower fuel dilution, and higher initial temperature. Extinction limits were also found to increase with pressure, but only for the case of highly diluted fuel.

Ding et al. [65] numerically studied the extinction limit of dry syngas (without \(\text{H}_2\text{O}\)) and moist syngas (with \(\text{H}_2\text{O}\)), at various dilutions (using \(\text{N}_2\), \(\text{CO}_2\), and \(\text{H}_2\text{O}\)) and pressures. It was found that: 1) \(\text{CO}_2\) diluted flames have the same extinction limit for both moist syngas and dry syngas. 2) The presence of \(\text{H}_2\text{O}\) in the fuel mixture deceases the extinction limit of \(\text{N}_2\) diluted flames. 3) Impure syngas with \(\text{CH}_4\) increases the extinction limit, but has no effect on temperature in \(\text{CO}_2\) diluted flames. 4) For diluted moist syngas, the extinction limit increases with higher pressure.

4) Strain rate applications: In many practical applications, combustion occurs in the turbulent regime. For example, gas turbine engines used for aerospace propulsion and power generation rely on turbulent diffusion combustion. The complex and chaotic nature of turbulent combustion makes it difficult to study. Laminar flames on the other hand are much easier to study because of their steady nature. There exists a regime of turbulent combustion where the turbulent flame can be approximated as being locally laminar but subjected to high aerodynamic strain rate. This is often referred to as the flamelet concept. Thus one may gain potential insight into some of the mechanisms of
turbulent combustion by studying laminar flames under elevated strain rates.

1.9 Objectives

The aim of this work is to investigate the flame extinction limit conditions of various gaseous fuels in a laminar diffusion counterflow burner. Equal momenta of the fuel and oxidizer streams were not maintained to provide data to check the fidelity of the numerical schemes and their chemical mechanisms at “non-standard” conditions. The extinction was characterized by the global strain rate approximation, and was obtained for different values of fuel mole fraction diluted with nitrogen. The gaseous fuels considered were: methane, biogas, and different syngas mixtures with varying compositions of H\textsubscript{2}, CO, CH\textsubscript{4}, and CO\textsubscript{2}. For this work, it was necessary to design and build a high flow rate counterflow burner capable of achieving high strain rates.
Chapter 2

Experimental Apparatus

2.1 Counterflow Burner

A new counterflow burner was developed that eliminated some of the shortcomings of the original counterflow burner at UTIAS Combustion Labs [59]. The original counterflow burner shown in Figure 2.1a was designed for soot studies at low flow rates, and as a result, develops a flame with a wave-like structure at higher flow rates. It is believed that this flame structure is caused by inlets ports which are aligned perpendicular with respect to the outlet flow direction. This causes the incoming flow to make an abrupt change in direction before exiting the burner. As shown schematically in Figure 2.1b, this abrupt change in flow direction at high flow rates can cause a nonuniform flow distribution inside the burner and create the observed wave-like flame structure.

The new burner shown schematically Figure 2.2 was designed with inlets that are parallel to the flow, and increased channel length to encourage the development of uniform flow distribution inside the burner and minimize the formation of vortices regardless of flow rate.

The new burner consists of an upper burner assembly and a lower burner assembly. Both the upper and lower burner assemblies are similar, except that they have different
base plates. Both burner assemblies have an outer nozzle, and an inner nozzle. The inner nozzle supplies fuel and oxidizer for the lower and upper burners respectively. The outer nozzles supply co-flowing nitrogen for both burner assemblies.

The new burner was designed using the 3D CAD software SolidWorks, from which 2D technical drawings were produced and submitted for fabrication by the University of Toronto Mechanical and Industrial Engineering machine shop, MC-78. The burner assembly and part technical drawings are presented in Appendix A.

The burner was designed such that the matrix at the outlets of the outer and inner nozzles are interchangeable. Different matrix types produce different flow distributions. For example, a sintered metal matrix produces a top hat velocity profile, whereas the absence of any matrix material produces a parabolic flow distribution. Various counterflow outlet matrix types were used in literature for flame extinction studies: honeycomb \([23, 66]\), mesh \([67–70]\), a combination of both honeycomb and mesh \([26]\), or the absence of any matrix material \([24, 39, 71]\). Because of the wide range of matrix materials used in literature, and the current author’s inexperience with flame extinction studies, the burner

![Figure 2.1: Old counterflow burner designed for soot studies at low flow rates.](image)
Chapter 2. Experimental Apparatus

(a) New burner cutaway

(b) New burner assembly

Figure 2.2: New counterflow burner designed for high flow rates.

was designed such that the matrix at the outlet can be switched between various types: sintered metal, honeycomb, mesh, or the absence of any matrix material. Some examples of the various matrix types at the exit of the inner nozzle of the new counterflow burner are shown in Figure 2.3.

The sintered metal matrix for both the inner and outer nozzle was tolerated with a slip fit such that it can easily be removed by hand. As shown in Figure 2.3a, a sleeve was designed to secure all matrix parts in place as they may slip off due to pressure drops experienced across the matrices during experiments. The sleeve is secured via a threaded interface between the nozzle’s inner surface and the sleeve’s outer surface. Previous
burners in the research group were designed with a press fit sleeve, in which friction held
the sleeve securely in place. The problem with this design is that removing the sleeve
became extremely difficult. The MC-78 machine shop advised that the threaded sleeve
interface would be most suitable for our application. To ease the installation of parts that
required assembly via insertion, slip fit tolerances were specified on the mating surfaces
to reduce the force required for insertion. In addition, all sharp edges were given 0.254
mm (0.010 ′′) chamfers at 45° degrees to help guide the inserted part during assembly,
and to prevent the premature wear of edges during disassembly and reassembly.

![Image](image1.png)

(a) Cutaway (b) Sintered metal (c) Smooth bore

Figure 2.3: New counterflow burner tip with sintered metal in the outer nozzle, and
various matrix types in the inner nozzle.

The use of a soot formation (SF) type counterflow flame with its high fuel to air
ratio, coupled with the high flow rates required to study the flame extinction limit,
resulted in a lot of unburnt fuel leaving the flame environment. This unburnt fuel poses
a safety hazard if not exhausted properly. As a result, the new counterflow burner was
designed with an exhaust enclosure and chimney system to remove the unburnt fuel
from the laboratory. The exhaust enclosure consists of aluminum rails for the frame,
with transparent material acting as the enclosure walls. The transparent walls allow for
visual observation of the flame, and if necessary, to allow the use of laser light extinction
optical diagnostic measurements to measure flame soot volume fraction. Originally the
transparent walls were made of polycarbonate sheets, but with a relatively low melting
Chapter 2. Experimental Apparatus

temperature of around 150 °C, they started to deform from the heat of the flame after a few experiments. The polycarbonate sheets were replaced with ceramic glass with a rated maximum temperature of 680 °C on three of the chamber walls. The fourth wall was made of titanium with a drilled hole for ignition access that was plugged during experiments.

To reduce manufacturing costs and ease assembly, the use of off-the-shelf components was incorporated into the design as much as possible. Swagelok fittings are used for the inlet port connectors, Thorlab optic posts are used as the separation posts between the upper and lower burners, and Thorlab aluminum rails are utilized for the exhaust enclosure frame.

Burner separation is easily adjusted using the Thorlab optical posts; each of the four separation posts contains a mechanism for both fine and course height adjustment. The length of each of the four separation posts can be adjusted individually to ensure the burners are aligned parallel to each other. Large tolerances in the mounting holes on the top burner base plate allows for horizontal adjustment to ensure concentric alignment between the upper and lower burners.

2.2 Gas Delivery System

For gaseous fuel experiments, a gas delivery system shown schematically in Figure 2.4 was designed to deliver co-flow nitrogen, carrier gas nitrogen, air, and fuel to the burner system. The co-flow nitrogen, carrier gas nitrogen, and fuel are supplied from high pressure compressed cylinders. The air is supplied from compressed shop air that is filtered and dried. For each of the gases, a pressure regulator is placed directly upstream of the flow controllers, followed by a ball valve to close the lines in the event emergency shut off is required. High pressure Swagelok 1/4 inch tubing and fittings are used throughout the gas delivery system.
Two types of flow controllers are used: A) SLA5850 Brooks Smart II Thermal Mass flow controllers, each of which is connected to a central controller, and B) Swagelok M-series metering valves (model number SS-4MG-MH). The Brooks flow controllers are factory calibrated to a maximum flow rate of 10 SLPM ($1.667 \times 10^{-4}$ m$^3$/s) for specific gases, and thus are only used for experiments that do not exceed this maximum flow rate. The Swagelok flow controllers are used for experiments that require higher flow rates.

The Brooks flow controllers allow operation within 1% accuracy and it monitors the flow meters in percentage of their calibrated span. The Brooks electronic flow controllers have a closed loop feedback system, and the flow rate is constantly monitored and maintained at the specified flow rate by the central controller. Because of this control system,
precise monitoring of inlet pressure is not critical as long as the pressure is reduced enough to prevent damage to the flow controller.

The Swagelok metering valve flow controller is a manually controlled needle type valve with no closed loop feedback system. The position of the needle stem tip, along with the inlet pressure determines the flow rate. Because of this, the inlet pressure going into the Swagelok manual flow controller must be carefully controlled. A vernier handle is present on the Swagelok flow controller to indicate the position of the stem tip. For a given vernier reading (stem position) and inlet pressure, the Swagelok flow controller will return a repeatable flow rate. One can calibrate the vernier readings to a given flow rate for any given pressure, and plot this for a range of flow rates.
Chapter 3

Experimental Methodology

It is common in literature to have the burner separation ($L$) approximately equal to the inner nozzle inner diameter ($D$) such that $L/D \approx 1$ [38, 39, 72, 73]. For this work $D = 11.18$ mm (0.44 ″) for the straight tube inner nozzle, and $D = 10.16$ mm (0.4 ″) for the sintered metal tip inner nozzle. Burner separation was set at $L = 10.16$ mm (0.4 ″) such that $L/D$ was 0.91 and 1.00 for the straight tube and matrix tip inner nozzles respectively. Sarnacki et al. [38] showed that extinction strain rate is $L/D$ dependant, so it was desirable to keep $L/D$ constant for all experiments.

For all experiments the co-flow $N_2$ was maintained at approximately 2 SLPM ($3.333 \times 10^{-5}$ m$^3$/s). It was observed that moderate changes in the co-flow $N_2$ had minimal impact on the extinction limits.

3.1 Burner Outlet Matrix Type

Results from literature [35, 38], and the preliminary results from the present work with methane discussed in Section 4, showed that the burner outlet velocity profile had a significant effect on extinction results. It was decided that the straight tube inner nozzle, without the presence of any matrix material, should be used as preliminary results with $CH_4$ in Section 4 showed that the repeatability of the straight tube inner nozzle with no
matrix at the tip was better than the inner nozzle with the porous sintered metal at the burner exit.

### 3.2 Calibration

The flow controllers were calibrated before any set of experiments. A Gilian Gilibrator-2 Flow Calibrator, or an American Meter Company (AMC) DTM-325 diaphragm meter was used to externally confirm the flow rate for any given controller setting. The Gilibrator flow calibrator has three interchangeable flow cells for the flow ranges of 1 - 250 cc/min \((1.667 \times 10^{-8} - 4.167 \times 10^{-6} \text{ m}^3/\text{s})\), 20 cc/min - 6 SLPM \((3.333 \times 10^{-7} - 1.000 \times 10^{-4} \text{ m}^3/\text{s})\), and 2 - 30 SLPM \((3.333 \times 10^{-5} - 5.000 \times 10^{-4} \text{ m}^3/\text{s})\). Any flow rate higher than 30 SLPM \((5.000 \times 10^{-4} \text{ m}^3/\text{s})\) required calibration with the AMC diaphragm meter. Numerous flow readings were taken at different controller settings and a relationship was obtained such that any flow rate could be calculated for any given controller setting.

### 3.3 Experimental Procedure

Flame extinction studies in literature often employ either one of the following methods to achieve flame extinction: 1) increasing the strain rate while maintaining constant fuel mole fraction of the fuel stream, or 2) decreasing the fuel mole fraction of the fuel stream while maintaining constant strain. For this work, both methods were used to investigate if extinction strain results are independent of extinction method. From the global strain rate formulation expressed by Equation 1.1 in Section 1.5, the strain rate can be controlled by adjusting the flow rate of the oxidizer and fuel streams, and the burner separation. The fuel mole fraction of the fuel stream can be varied through dilution of the fuel stream with nitrogen. The onset of flame extinction can be visually observed when the inner flame disappears abruptly.

For both cases, a rapid increase in strain rates was found to cause early extinction, so
it was necessary to increase the strain rate slowly near extinction. However, it was found acceptable to rapidly increase the strain rate far from the extinction point, then slow the increase of the strain rate as the extinction limit was approached to save time and fuel. For case 1), extinction was reached by slowly increasing the strain rate through small sequential increases in the fuel flow, followed by an increase in carrier gas $N_2$ flow, then an increase in air flow. Similarly for case 2), the fuel mole fraction was slowly decreased through small percentage sequential decreasing of the fuel flow, followed by an increase in carrier gas $N_2$ flow, followed by an increase in air flow, until the flame extinction limit was reached. A small delay was introduced in-between each increment to allow the flow to stabilize between flow rate changes. The rate of change was approximately $\sim 0.5\text{-}1\%$ of the extinction strain rate increment per second.

Pure methane, biogas, and various syngas compositions which contain various amounts of CO, $H_2$, $CH_4$, and $CO_2$ were used for this work. A summary of all the gases and their compositions are presented in Table 3.1.

Table 3.1: Compositions (in %volume) of the gaseous fuels

<table>
<thead>
<tr>
<th>Fuel</th>
<th>CO (%vol)</th>
<th>$H_2$ (%vol)</th>
<th>$CH_4$ (%vol)</th>
<th>$CO_2$ (%vol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>0</td>
<td>0</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>S1</td>
<td>50</td>
<td>25</td>
<td>0</td>
<td>25</td>
</tr>
<tr>
<td>S2</td>
<td>37.5</td>
<td>37.5</td>
<td>0</td>
<td>25</td>
</tr>
<tr>
<td>S5</td>
<td>37.5</td>
<td>37.5</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>S5M25</td>
<td>18.75</td>
<td>18.75</td>
<td>52.5</td>
<td>10</td>
</tr>
<tr>
<td>S5M50</td>
<td>28.125</td>
<td>28.125</td>
<td>28.75</td>
<td>15</td>
</tr>
</tbody>
</table>
3.4 Ignition Methodology

The flame was ignited with the fuel and oxidizer fuel streams running at flow rates well below the extinction limit conditions, with the co-flow nitrogen stream closed. An extended barbecue lighter was inserted through the hole in the titanium wall of the exhaust chamber and was used to ignite the flame. Occasionally after ignition, only the outer flame appeared without the inner flame, which is the flame of interest. If only the outer flame was present, compressed air from an air gun was used to blow air towards the side of the outer flame, deflecting parts of it into the inner flame region, igniting the inner flame. Depending on the fuel, strain rate, and fuel mole fraction, turning on the co-flow nitrogen following this procedure may extinguish the outer flame, leaving only the inner flame present.

3.5 Flow Calculations

As the flow rates were constantly changing during experiments, various fuel calculators were written using a spreadsheet to aid in experimental operation. The flow calculators would calculate the required fuel, carrier gas $N_2$, and air flow rates at any given strain rate and fuel mole fraction. Equal momenta of the fuel and oxidizer streams were not maintained to provide data to check the fidelity of the numerical schemes and their chemical mechanisms at “non-standard” conditions.

3.5.1 Case 1: Fuel Mole Fraction Constant

As discussed earlier, two cases were considered for the experiments. In the first case, fuel mole fraction was held constant, while the strain rate was increased until extinction was reached. In the second case, the strain rate was held constant, while fuel mole fraction was decreased until extinction was reached. For the first case with fuel mole fraction held constant, a flow calculator was written so that for any given fuel mole fraction, values for
the flow rates for fuel, carrier gas $N_2$, and air could be generated for any desired strain rate. This calculator aided in the experimental operation as it allowed the operator to quickly determine the appropriate flow rates for any desired strain rate and fuel mole fraction condition. The necessary equations used for the flow calculator are presented below:

1) Applying conservation of mass at the exit of the fuel stream (carrier gas $N_2$ and gaseous fuel):

$$\rho_{N2}V_{N2}A + \rho_FV_FA = \rho_{FS}V_{FS}A \quad (3.1)$$

where $V$ is the burner exit velocity, $\rho$ is the density, and $A$ is exit area of the inner nozzle, which is the same for both the fuel and oxidizer streams. Subscripts F, N2 and FS denotes the fuel, carrier gas $N_2$, and fuel stream (which contains both the fuel and carrier gas $N_2$) flows respectively.

2) The density of the fuel stream at the nozzle exit can be expressed as:

$$\rho_{FS} = x_F\rho_F + (1 - x_F)\rho_{N2} \quad (3.2)$$

Where $x_F$ is the fuel mole fraction, which because of Avogadro’s law is equal to the fuel volume fraction.

3) Using Equations 3.1, and 3.2 and $\dot{Q}_i = V_iA$ at the exit, where $V_i$ is the exit velocity of gas stream $i$ in question ($i = F$, or N2), the flow rate of the fuel, and carrier gas $N_2$ ($\dot{Q}_F$, $\dot{Q}_{N2}$) can be calculated for any given value of fuel mole fraction ($x_F$). For any given fuel mole fraction, the strain rate was slowly increased by sequentially increasing the flow rate of fuel, carrier gas $N_2$, and then air with the assistance of the calculator, until the extinction limit was reached.

4) The global strain rate expression can be written as [29]:

$$K = -\frac{2V_A}{L} \left[ 1 + \frac{V_{FS}}{V_A} \left( \frac{\rho_{FS}}{\rho_A} \right)^{1/2} \right] \quad (3.3)$$

where $L$ is the distance between the upper and lower burners. Knowing $V_{FS}$ calculated
from above, and using a predefined air flow rate (see Appendix B), the strain rate can be obtained.

The properties for the gaseous fuels and their individual components are summarized in Table 3.2. It is assumed that these gases at the burner exit are at room temperature and atmospheric pressure.

3.5.2 Case 2: Strain Constant

The second case involved holding the strain rate constant, and decreasing fuel mole fraction until extinction. The derivations for the flow calculator for the second case is similar to the first case of constant fuel mole fraction and increasing strain. Exceptions are that the above relationships (Equations 3.1, 3.2, and 3.3) are reformulated so that with predefined air flow rates (see Appendix B), the flow rate of the fuel, carrier gas $N_2$ ($\dot{Q}_F$, $\dot{Q}_{N2}$), and fuel mole fraction ($x_F$) can be calculated for any given value of strain rate ($K$). Recall that for case 2, the fuel mole fraction was slowly decreased by sequentially decreasing the flow rates of the fuel, followed by increasing the flow rate of the carrier gas $N_2$, followed by air, until the flame extinction limit was reached.

3.5.3 Viscosity of Fuel Gas Mixtures and Reynold’s Number

To use experimental counterflow flame results to gain insight into turbulent diffusion flames using the flamelet concept, it is ideal to keep the flame in the laminar flow regime. The pipe Reynolds number at the exit of the inner nozzles, which has been used previously in literature [35] to quantify the turbulent condition of a counterflow flame, was used for this work. For future work one could gain further insight into the turbulent status of the flame with the use of a PIV system to quantify the velocity flow field as the pipe Reynolds number is not entirely representative of the turbulent conditions in the flame. The pipe Reynolds number is given as [74]: $Re_{D,k} = \rho_k V_k D/\mu_k$, where $\rho_k$, $V_k$ and $\mu_k$ is the density, exit velocity, and dynamic viscosity respectively of the stream $k$ in question.
(\(k = \) fuel stream or oxidizer stream). \(D\) is the inner diameter of the nozzles.

Table 3.2: Properties of the gaseous fuels and their individual species at 300K and 1 atm

<table>
<thead>
<tr>
<th>Species</th>
<th>Density (kg/m(^3))</th>
<th>Species</th>
<th>Density (kg/m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>1.123 [75]</td>
<td>B1 biogas</td>
<td>1.096</td>
</tr>
<tr>
<td>H(_2)</td>
<td>0.081 [75]</td>
<td>S1 syngas</td>
<td>1.025</td>
</tr>
<tr>
<td>CH(_4)</td>
<td>0.644 [75]</td>
<td>S2 syngas</td>
<td>0.895</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>1.773 [75]</td>
<td>S5 syngas</td>
<td>0.838</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S5M25 syngas</td>
<td>0.790</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S5M50 syngas</td>
<td>0.741</td>
</tr>
</tbody>
</table>

The fuel stream was a complex mixture of different gases, in which the gaseous fuel was diluted with N\(_2\) gas. In addition, the gaseous fuel was often syngas, which is a further mixture of multiple gaseous species. It is necessary to calculate the dynamic viscosity of the fuel stream to calculate the pipe Reynolds number at the inner nozzle exit. The dynamic viscosity of the gaseous fuel is calculated using the Herning-Zipperer mixing rule [76]: 

\[
\mu_F = \frac{\sum_i (x_i \mu_i M_i^{1/2})}{\sum_i (x_i M_i^{1/2})},
\]

where \(i\) is the individual components of the fuel (\(i = \) CO, \(H_2\), \(CH_4\), or \(CO_2\)). The dynamic viscosity of the fuel stream, which is composed of the gaseous fuel diluted with N\(_2\), is calculated using the Herning-Zipperer mixing rule once again.
Chapter 4

Preliminary Experiments with CH$_4$

4.1 Methane Extinction Results

To verify the experimental apparatus that was developed for this work, the extinction limit of methane was investigated and compared to experimental results published in literature. Maruta et al. [39] studied the extinction strain rate of CH$_4$ as a function of the fuel mole fraction, and presented their CH$_4$ extinction results in contrast with the work by Tsuji et al. [25]. The CH$_4$ extinction results from the present work, Tsuji et al. and Maruta et al. are presented in Figure 4.1. The flow rates for the fuel, carrier gas N$_2$, fuel stream, and oxidizer stream at the extinction limits of the present work can be found in Table B.1 in Appendix B.

For this preliminary work with CH$_4$, fuel mole fraction was held constant and strain rate increased until extinction. Fuel mole fractions from 0.1 to 1.0 was investigated at 0.1 intervals. Nitrogen was used to dilute the methane fuel. The smooth bore straight tube inner nozzle (type I burner) was selected over the sintered metal inner nozzle. The reason for this selection is discussed below in Section 4.2. The inner nozzle inner diameter (11.176 mm, 0.44") was approximately equal to the burner separation (10.16mm, 0.40") such that $L/D = 0.91$. 
Tsuji et al. [25] used a counterflow flame stabilized in the forward stagnation region of a porous cylinder (type IV) for their extinction work. Maruta et al. [39] made use of a type I counterflow flame formed in the impingement region of two opposed jets from port burners. The strain rate was held constant while the fuel mole fraction was decreased until the flame extinction limit was reached. The burner separation was approximately equal to the nozzle inner diameter.

Present experimental extinction results with nitrogen-diluted methane show good agreement with the results from Maruta et al. [39] and Tsuji et al. [25], Figure 4.1. The agreement is better with the work of Maruta et al. than that of Tsuji et al. possibly because both the present work and Maruta et al. used a type I counterflow flame stabilized

Figure 4.1: CH$_4$ extinction results from literature compared to present measurements.
in the impingement region of two opposed jets from port burners, whereas Tsuji et al. made use of a type IV counterflow flame stabilized in the forward stagnation region of a porous cylinder.

Both Maruta et al. [39] and Tsuji et al. [25] studied the extinction limit of methane up to a fuel mole fraction of 0.5, whereas the present work investigates a fuel mole fraction beyond 0.5. To the author’s knowledge, there is currently no CH$_4$ experimental data in literature studying the methane extinction limit for the fuel mole fraction range between 0.5 and 1.0.

There is a wealth of experimental data in literature for the extinction strain rate of pure methane flames ($x_F = 1.0$) stabilized between two opposed jets [28, 30, 37, 38, 72, 77]. The experimental methodology and experimental extinction limit results of these works are summarized in Table 4.1. The results obtained using the global strain rate approximation have a fair amount of scatter, whereas results obtained through local strain rate measurements appear to have less scatter. It has been reported in literature that the global strain rate formulation does have a tendency of overestimating the local strain rate [31–34], which appears to be the case with the presented pure methane extinction results from literature in Table 4.1.

Overall it appears that the preliminary methane extinction results from the present work show good agreement with results from literature and validates the new high flow counterflow burner for experimental use.

It is desirable that the flame remain laminar for the experiments. As an approximation, researchers in the past have used the Reynolds number based on burner pipe exit diameter to estimate if the flame was laminar [35]. It can be difficult to determine if a flame is turbulent, as a laminar flame can sometimes flicker, giving the appearance of a turbulent flame. To the human observer, a turbulent flame may appear axisymmetrical because of the low frame rate of the human eye capturing the average image of the turbulent flame. If an instantaneous shot of a turbulent flame was taken, one would find
that a turbulent flame is very chaotic and far from symmetrical. Visual observation of the flame, combined with the pipe Reynolds number in some cases was used to discern if the flame was laminar. The maximum flow rate scenario, with pure methane near the extinction limit, gave a Reynolds number of 1184 for the fuel nozzle and 620 for the oxidizer nozzle, which is well below the transition Reynolds number of 1700 [74], implying laminar conditions for the entire range of CH$_4$ experimental conditions.

Table 4.1: Comparison of pure CH$_4$ extinction results from literature

<table>
<thead>
<tr>
<th>Source</th>
<th>Method $^1$</th>
<th>$K_{ext}$ $^2$</th>
<th>$L/D$ $^3$</th>
<th>Burner Type</th>
<th>Momentum Bal $^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present Work</td>
<td>Global</td>
<td>333 ± 7</td>
<td>Y</td>
<td>Type 1</td>
<td>Y</td>
</tr>
<tr>
<td>Sarnacki et al. [38]</td>
<td>Global</td>
<td>520</td>
<td>Y</td>
<td>Type 1</td>
<td>Y</td>
</tr>
<tr>
<td>Sarnacki et al. [38]</td>
<td>Local</td>
<td>354 ± 36</td>
<td>Y</td>
<td>Type 1</td>
<td>Y</td>
</tr>
<tr>
<td>Chelliah et al. (2003) [77]</td>
<td>Global</td>
<td>460</td>
<td>Not Given</td>
<td>Type 1</td>
<td>Y</td>
</tr>
<tr>
<td>Chelliah et al. (2003) [77]</td>
<td>Local</td>
<td>390</td>
<td>Not Given</td>
<td>Type 1</td>
<td>Y</td>
</tr>
<tr>
<td>Papas et al. [72]</td>
<td>Local</td>
<td>400 ± 25</td>
<td>Y</td>
<td>Type 1</td>
<td>N</td>
</tr>
<tr>
<td>Du et al. [37]</td>
<td>Local</td>
<td>375</td>
<td>N</td>
<td>Type 2</td>
<td>N</td>
</tr>
<tr>
<td>Chelliah et al. (1990) [28]</td>
<td>Local</td>
<td>380</td>
<td>Not Given</td>
<td>Type 1</td>
<td>N</td>
</tr>
<tr>
<td>Puri et al. [30]</td>
<td>Global</td>
<td>271</td>
<td>N</td>
<td>Type 2</td>
<td>N</td>
</tr>
</tbody>
</table>

$^1$ Refers to the method for obtaining the strain rate of the flame: global or localized measurements

$^2$ Extinction strain rate (s$^{-1}$)

$^3$ Was momentum balanced between the upper and lower burners?

Riechelmann et al. [78] studied the effect of extinction strain rate variation with
oxidizer inlet temperature and found that extinction strain rate increases exponentially with temperature. The upper burner from the present work which provides the oxidizer stream may be susceptible to burner preheating. Buoyancy effects from the flame results in the upper burner heating up much more than the lower burner. After experiments the temperature of the upper burner was usually much higher than the lower burner. During the preliminary experiments with methane, it was observed that as the experiments were carried out the extinction strain would increase slightly as the upper oxidizer burner increased in temperature. But this increase was minimal, with an approximate 5% drift in extinction strain rate measurements over an hour. To minimize experimental error, the burner was given sufficient time to cool down between each set of experiments and any drift in the extinction strain results was monitored.

4.2 Effect of Burner Outlet Conditions on Extinction

The preliminary work also investigated the effects of different burner outlet conditions and burner separations on the extinction conditions of pure methane ($x_F = 1.0$) using the new counterflow burner. The results are summarized in Figure 4.2, where the extinction strain rate at various $L/D$ for the two inner nozzles are plotted. Both the porous sintered metal and straight tube inner nozzles were used. The sintered metal inner nozzle was studied at burner separations of 5.08 mm (0.200 ″) and 7.62 mm (0.300 ″). The smooth bore inner nozzle was studied at burner separations of 5.08 mm (0.200 ″), 7.62 mm (0.300 ″), and 10.2 mm (0.400 ″). The porous sintered metal inner nozzle with an inner diameter of 10.2 mm (0.400 ″) is expected to produce top hat velocity profile. The straight tube inner nozzle with no matrix at the outlet, and an inner diameter of 11.2 mm (0.440 ″) is expected to produce a parabolic velocity profile at the burner exit. As discussed earlier, it was reported in literature that both the velocity profile at the exit, and the $L/D$ ratio have an effect on the extinction limit [24, 35, 38].
Figure 4.2: Extinction of CH$_4$ with different burner exit conditions.

From Figure 4.2 it appears that the top hat profile results show a weak dependence on burner separation, while the parabolic profile results show a strong dependence. This is interesting, as it was suggested in literature [24] that burners that have a top hat exit velocity profiles are more susceptible to burner separation effects than burner with parabolic exit velocity profiles. In addition, there appears to be a large amount of scatter for the porous sintered metal (top hat velocity profile) case compared to the straight tube (parabolic velocity profile) case.

It was observed that for top hat velocity profile scenario near extinction, the inner flame would gradually shrink until a very small flame remained near the centerline, and would remain for a while as the strain rate was increased, usually well above the extinction
strain rate recorded by the straight tube, parabolic profile case. Eventually the small flame would disappear and the inner flame would be extinguished completely. The strain rate at which the entire inner flame was completely extinguished was recorded as the extinction condition. The persistence of this small flame is believed to be caused by a small recirculation zone created at the impingement of the two jets that acts as a flame holder preventing the reactants from being swept out of the reaction zone, allowing a flame to be stabilized at higher strain rates. Because of these inconsistencies with the porous sintered metal, the decision was made to use the straight tube inner nozzles for the extinction experiments. Perhaps this small recirculation zone could be the reason for the inconsistencies as well as the weak dependence that is shown between extinction limit results and burner separation for the sintered metal inner nozzle that produces a top hat exit velocity profile.
Chapter 5

Results and Discussion

Biogas and various syngas compositions of CO, H₂, CH₄, and CO₂ were studied. A summary of all the gases and their compositions was presented earlier in Table 3.1. The properties and experimental conditions for all the gaseous fuels were discussed earlier in Section 3.

The syngas fuel contains large concentrations of hydrogen, and as a result, the extinction strain rate of these gases were much higher than other gaseous fuels which did not contain hydrogen. The high strain rates, which required achieving large flow velocities, may have resulted in turbulent flow in the burner nozzles near the extinction point. Since one of the objectives of this work was to study laminar flames under elevated strain, it was desirable to keep the flames in the laminar regime, which was done through visual observation of the flame, and by using the pipe Reynolds number. The increase in extinction strain rate at higher fuel mole fractions, and the desire to maintain the laminar flow condition made obtaining the extinction at higher fuel mole fractions difficult, as the flow became turbulent before the extinction strain rate was reached. As a result, the majority of the extinction measurements were made at the lower fuel mole fractions.

Pellett et al. [35] investigated the extinction of pure hydrogen and reported that the extinction strain rate of pure H₂ was up to 30 times greater than pure CH₄. In
order to maintain laminar flow and keep the pipe Reynolds number low at such high flow rates, the experiments required the use of very small nozzle inner diameters. At the same time, large $L/D$ ratios were needed to minimize the effect of burner preheating. In literature it is common to have $L/D \approx 1$, but the low burner separations required to maintain this criteria would result in the flame residing very close to the burner exit, and would lead to a substantial amount of heat transfer to the burner and promote burner preheating effects. One can see that trying to maintain laminar flow while working with fuels containing hydrogen is not a trivial matter.

5.1 Flame Appearance and Soot Presence

The appearance of the flame varied depending on the strain rate and fuel used, but there were some general observations. Generally there was both an outer and inner flame present as shown in Figure 5.1, which illustrates the evolution of a S5M50 flame as it neared extinction, with the strain rate held constant as the fuel mole fraction was reduced. After the ignition procedure, before the co-flow $N_2$ was turned on, both the inner and outer flames were present. However, depending on the fuel used and fuel concentration, the outer flame sometimes extinguished when the co-flow $N_2$ was activated, leaving only the inner flame.

Usually the outer flame was always present with fuels that contained hydrogen regardless of the co-flow $N_2$ flow. It is speculated that in the outer flame region, the co-flow $N_2$ normally sweeps the reactants out of the outer flame reaction zone before the reactants can diffuse into the reaction zone (aerodynamic time scale becomes smaller than the diffusive time scale), and the combustion process does not occur causing the outer flame to extinguish. When hydrogen is present in the fuel, the high diffusivity of hydrogen allows the reactive species to diffuse into the reaction zone before they are swept away (the diffusivity time scale becomes smaller than the aerodynamic time scale), allowing
the combustion reaction to occur and the outer flame to remain lit.

At low and moderate strain rates, the inner flame was axisymmetric and steady. But at higher strain rates required by some fuels with higher hydrogen content, the inner flame shape would sometimes deviate from the ideal shape, and would sometimes flicker (no longer steady), or take on a slight wave like structure (no longer axisymmetric). Using a porous matrix at the tip of the burner may have solved these flame instabilities at higher flow rates, but there were issues with the porous sintered metal as discussed earlier in Section 3.1 and 4.2. As a result, the straight tube inner nozzles with the no matrix at the burner tip was selected. Despite these challenges, the results with the straight tube inner nozzle were very repeatable, even at high strain rates when the flames tended to deviate from the ideal axisymmetric steady flame structure.

Figure 5.1: Development of a S5M50 gaseous fuel flame at a constant strain rate ($K = 500 \text{ s}^{-1}$) as fuel mole fraction was reduced.

The inner flame, which is the flame of interest, extinguished abruptly once the extinction strain rate was reached. If there was an outer flame present during the experiment, it sometimes remained after the inner flame extinguished as shown in the last frame of Figure 5.1

A flame that contains a luminous orange glow indicates that soot is present in the flame. Pure methane flames ($x_F = 1$) at low strain rates were blue in color with a luminous orange glow on the fuel side of the flame as seen in Figure 5.2a, indicating the presence of soot. As strain rate was increased, the luminous orange region slowly faded out and disappeared, with only the blue color remaining as shown in Figure 5.2b. This indicated that at higher strain rates, the soot volume fraction decreased until the soot
extinction limit was reached. This is consistent with results reported by Du et al. [56].

The orange glow disappeared rapidly as the fuel mole fraction was decreased. Flames with moderate amounts of CH$_4$, such as B1 and pure CH$_4$, had a slight orange glow indicating the presence of soot. However, attempts to measure soot volume fraction using the laser light extinction system indicated that soot concentrations were below the detectable range. The other syngas flames had no soot as they were blue in color, with no orange luminosity.

![Figure 5.2: The presence of soot in a methane flame as indicated by the orange luminosity.](image)

**5.2 Extinction Limit**

Figure 5.3 presents the gaseous fuel extinction limit results with the strain rate plotted against fuel mole fraction for all the gaseous fuels considered. The results presented are truncated at a strain rate of 1400 s$^{-1}$ which corresponds approximately to a Reynolds number of 2300 for both the oxidizer and fuel streams. Below this point is when the flow is laminar. The flow rates for the fuel, carrier gas N$_2$, fuel stream, and oxidizer stream at the extinction limit for all fuels can be found in Tables B.2 to B.7 in Appendix B. As mentioned earlier, two experimental methods were used to obtain results. In the first case the fuel mole fraction (dilution) was held constant while the strain rate was
slowly increased, and in the second case the strain rate was held constant as the fuel mole fraction was slowly lowered (dilution increased) until the inner flame extinguished. Both cases are illustrated in Figure 5.3. The extinction limit of all the gaseous fuels appear to increase with both strain rate and fuel mole fraction, which is expected.

Figure 5.4 presented below is the same as Figure 5.3, except that the extinction strain rate (y-axis) range is extended to show the pure syngas ($x_F = 1$) extinction results that occurred at very high flow rates, some of which were most likely at turbulent conditions. It should be noted that while the two cases are present in Figure 5.4 (dilution or strain rate constant), the two individual cases are not distinguished.

![Figure 5.3: Extinction limits of gaseous fuel flames, displaying case 1: fuel mole fraction constant, and case 2: strain rate constant.](image)

In Figure 5.3, the extinction results appear to be almost independent of the exper-
Figure 5.4: Extinction of gaseous fuel results with an extended range to include the pure syngas data points which could potentially be at turbulent conditions.

Experimental method used. The two cases covered different ranges of fuel mole fraction and strain rates with little overlap in data, but for any given fuel, the data from either of the two cases appear to deviate very little from the trend. Works in literature have made similar observations. One such work by Won et al. [66] studied two cases of extinction of toluene blended with \( n \)-decane. The first case was with fuel mole fraction held constant with strain rate slowly increased. The second case was with strain rate constant with fuel mole fraction slowly decreased, which was done by decreasing fuel flow rate. The author concluded that the two methods showed good agreement with small error (5%).

In Figure 5.4, the scatter in the data and the error seems to increase with increasing strain rate and fuel mole fraction. The fuels with lower resistance to extinction (lower
extinction strain rate for any given fuel mole fraction) appear to have less spread in data points as the fuel mole fraction approaches unity ($x_F \to 1$) than those with higher resistance to extinction (greater extinction strain rate for any given fuel mole fraction). This increase in error is attributed to the flow transition to turbulence at higher strain and flow rates, which is discussed further in Section 5.3.2

From Figure 5.3, it appears that the fuels with the largest H$_2$ concentration have the greatest extinction strain rate limits for any given fuel mole fraction. Both S2 and S5 with H$_2$ mole fractions of 37.5%, have the greatest flame extinction limit. Both S1 and S5M25 have a lower H$_2$ mole fraction (25% and 28.125% respectively) and flame extinction limit than S2 and S5. Of all the syngas mixtures, S5M50 has the smallest H$_2$ mole fraction (18.75%) and flame extinction limit compared to S2, S5, S1, and S5M25. Finally CH$_4$ and B1, both of which do not contain H$_2$, appear to have the lowest resistance to extinction of all the gaseous fuels. Because B1 is 60% CH$_4$, and 40% CO$_2$, it is essentially diluted CH$_4$, and thus is more prone to extinction than pure CH$_4$. These results strongly suggest that fuels with the largest H$_2$ concentration have the greatest flame extinction limit.

In addition, it appears that H$_2$ has a dominant effect on the flame extinction condition. Fuels with the same H$_2$ mole fraction have very similar extinction properties, even though they have varying amounts of other combustible species such as CO and CH$_4$. For example both S1 and S5M25 have similar H$_2$ mole fractions, but their CO mole fractions are 50% and 18.75% respectively, and their CH$_4$ mole fractions are 0% and 52.5% respectively. Yet they have very similar extinction profiles. Figures 5.5, 5.6, and 5.7 shows the extinction limit of the various syngas fuels at $x_F = 1$ in relation to the concentration of combustible fuel species (CH$_4$, CO, and H$_2$ respectively). These figures show that there is an increasing correlation between H$_2$ fraction and the extinction strain rate (Figure 5.7), but not so much for CO and CH$_4$ (Figures 5.5 and 5.6). In Figure 5.5, there is a downward trend between the CH$_4$ fraction and the extinction limit, which is highly contradictory to known trends in literature [25, 28, 30, 39, 77]. In Figure 5.6, there
is somewhat of a correlation between the CO fraction and extinction limit condition, but it is not as strong as the correlation with $\text{H}_2$. This suggests that $\text{H}_2$ is dominant in determining the extinction characteristics of the flame, regardless of the concentration of the other combustible fuel species. The contradictory downward trend of $\text{CH}_4$ in Figure 5.5 is probably a result of the dominant effect that $\text{H}_2$ has on the flame extinction limit.

Figure 5.5: Extinction of pure syngas with respect to percent volume $\text{CH}_4$.

Figure 5.6: Extinction of pure syngas with respect to percent volume $\text{CO}$.

Figure 5.7: Extinction of pure syngas with respect to percent volume $\text{H}_2$. 
Of all the combustible species of syngas (H\textsubscript{2}, CO, and CH\textsubscript{4}), H\textsubscript{2} has the highest diffusivity. The diffusivities of H\textsubscript{2}, CO, and CH\textsubscript{4} in air at 293.15 K are 0.756 m\textsuperscript{2}/s, 0.210 m\textsuperscript{2}/s, and 0.208 m\textsuperscript{2}/s respectively [79]. These diffusivity values may differ from those in the experimental flame environment, as the flame temperatures are much greater than 293.15K, and the fuel species may not be diffusing through pure air, but these values give a relative indication of the diffusivity of each of these species. It is clear that the diffusivity of H\textsubscript{2} is greater than the other two combustible species of syngas. This could imply that for any flame burning a gas mixture, the combustible gas with the highest diffusivity in the mixture is the species that controls the extinction properties of that flame. The species with the greatest diffusivity will be able to diffuse into the reaction zone of a diffusion flame at strain rates that would otherwise prevent other species from doing so. The species with the greatest diffusivity would be able to sustain the flame where other species with lower diffusivities would fail.

5.3 Sources of Uncertainty and Error Analysis

5.3.1 CH\textsubscript{4} Preliminary Results and Literature

In Figures 5.8, 5.9, and 5.10, the linear curve fit, the 95% confidence interval, and the 95% prediction interval are shown for the CH\textsubscript{4} extinction limit results of the present work and from literature [25, 39] that was presented in Section 4.1. The linear curve fit can be used to quantify the systematic error of the CH\textsubscript{4} results of the present work by comparing the CH\textsubscript{4} linear curve fit of the extinction limit results from the current work to the results from literature. Within the 95% confidence interval is where a curve fit of data from repeat measurements will fall 95% of the time, and can be used to quantify the certainty of the linear curve fit. Within the 95% prediction interval is where a data point from repeat measurements will fall 95% of the time and can be used to characterize the random error associated with these CH\textsubscript{4} extinction limit results.
In Figure 4.1 in Section 4.1, the results from literature only include mole fractions up to \( x_F \approx 0.5 \), so the error analysis of the current work only applies to results obtained when fuel mole fractions were under \( x_F = 0.5 \). Below a mole fraction of \( x_F = 0.5 \), the results appear to be linear, suggesting that a linear curve fit is appropriate for this error analysis.

In Figures 5.8, and 5.9 the linear curve fit of present results shows good agreement to Maruta et al. [39]. In Figure 5.10, the \( \text{CH}_4 \) linear curve fit of the present results shows fair agreement to the results from Tsuji et al. [25]. These linear curve fits suggest that the systematic error was small for the \( \text{CH}_4 \) extinction limit results from the present work. The bias error appears to be smaller between the present work and Maruta et al. in comparison to Tsuji et al.. Perhaps this is because the experimental conditions of the present work is more comparable to that of Maruta et al.. Both the present work and Maruta et al. employed a type I counterflow flame stabilized in the impingement region of two opposed jets from port burners. Tsuji et al. employed a type IV counterflow flame stabilized in the forward stagnation region of a porous cylinder, which differs from the experimental conditions of the present work.

There is a moderate amount of dilution \( \text{CH}_4 \) extinction limit results in literature, but to the author's knowledge there aren't many that can be compared to the present work, other than the work by Maruta et al. and Tsuji et al.. The other works in literature [28, 37, 72, 77] used a local strain rate to characterize the extinction limit, where as the present work used the global strain rate formulation. As discussed earlier, the global strain formulation tends to overestimate the local strain. Other work in literature that used the global strain rate formulation [30] to characterize the \( \text{CH}_4 \) extinction limit investigated the extinction limit as a function of the \( \text{O}_2 \) mass fraction in the oxidizer stream. The current work investigated the \( \text{CH}_4 \) extinction limit as a function of the fuel mole fraction in the fuel stream.

The 95% prediction intervals in Figures 5.8, 5.9, and 5.10, suggest that the results
Figure 5.8: Error analysis on preliminary CH$_4$ results from present work for $x_F < 0.5$.

Figure 5.9: Error analysis on CH$_4$ results from Maruta et al. [39].
Figure 5.10: Error analysis on CH$_4$ results from Tsuji et al. [25].

from the present work have comparable random error to the results from literature [25,39].

5.3.2 Turbulent Conditions in Nozzle

As discussed earlier in Section 3.5.3, it is desirable to keep the flame in the laminar regime. In the present work, the pipe Reynolds number at the exit of the inner nozzles was used to quantify the turbulent conditions. The Reynolds number at the extinction limit for the fuel and oxidizer streams, at various fuel mole fractions are shown in Figures 5.11 and 5.12 respectively. To encourage laminar flame conditions, the inner nozzle exit Reynolds number was kept below 2300, which is the Reynolds number at which a laminar flow regime transitions to a turbulent flow regime.

In Figures 5.11 and 5.12, the inner nozzle exit Reynolds number are shown for the fuel and oxidizer streams respectively. The Reynolds number is calculated using the formulation shown in Section 3.5.3. There was little difference in the Reynolds numbers
between the fuel and oxidizer steams, although it appears that the fuel streams had slightly greater Reynolds numbers for all fuels.

The Reynolds number results shown in Figures 5.11 and 5.12, and the extended range extinction limit results shown earlier in Figures 5.4 in Section 5.2 suggest that the greater the Reynolds number, the greater the spread in data. This spread is most prominent at \( x_F = 1 \), where the strain rate, flow velocity, and Reynolds number are the greatest.

![Figure 5.11: Fuel stream pipe Reynolds number at the extinction limit at various fuel mole fractions.](image)

To explore the effect of Reynolds number on random error, the fuels at \( x_F = 1 \) with Reynolds numbers well above 2300 are investigated (S2, S5, S1, S5M25, and S5M50). S2 has the greatest random error in extinction limit results (Figure 5.4), and the greatest fuel and oxidizer stream Reynolds number (Figure 5.11 and 5.12 respectively). Similarly S5, S5M25, and S5M50 fuels have the second, fourth, and fifth largest Reynolds numbers and random errors in extinction limit results respectively. These results suggest that at
the greater the Reynolds number, the greater the extinction limit random error. This is expected due to the highly chaotic and random nature of turbulent flow.

S1 seems to be an exception to the observed trend that the larger the Reynolds number, the larger the extinction limit random error. S1 has the third largest Reynolds number which is greater than that of S5M25 and S5M50, but the random error of the extinction limit results are smaller than S5M25, and S5M50. This might be because the number of data points recorded for S1 is significantly smaller than the other fuels, which is not sufficient to accurately capture the random error.

![Graph showing oxidizer stream pipe Reynolds number at the extinction limit at various fuel mole fractions.](image)

Figure 5.12: Oxidizer stream pipe Reynolds number at the extinction limit at various fuel mole fractions.

### 5.3.3 Extinction Limit Results - Laminar Regime

In Figures 5.13, 5.14, 5.15, 5.16, 5.17, 5.18, and 5.19 the linear curve fit, the 95% confidence interval, and the 95% prediction interval from the present work’s results are
calculated for S2, S5, S1, S5M25, S5M50, B1, and CH₄ respectively. To remain within the laminar regime, only the results at $K < 1400$ are investigated for this error analysis. $K < 1400$ corresponds approximately to $Re_D < 2300$, in which the flow regime is laminar, for both the fuel and oxidizer stream.

There is little dilution extinction limit experimental data in literature for the gaseous fuels studied in the current work. So to quantify the systematic error of the gaseous fuel extinction limits results, the systematic error of the CH₄ extinction limit results of the current work can be compared to the results from literature [25, 39]. Since the experimental conditions of the gaseous fuel results were the same as the preliminary CH₄ results, it would seem appropriate to equate the systematic error of the gaseous fuel results to the systematic error for the preliminary CH₄ results discussed in Section 5.3.1. The only discrepancy may be the different flow controllers used. Depending on the fuel, either the Brooks or Swagelok flow controllers were used.

The 95% prediction interval, which represents where a data point from repeat measurements will fall 95% of the time, can be used to characterize the random error associated with these extinction limit results.

It is important to consider the different flow controllers used for each of the fuels, as it appears that they had an effect on the observed systematic error of the present work. A Brooks thermal flow controller was used for the CH₄, S1, S5M25, S5M50, and B1 experiments, for data collected at $x_F < 1$. At $x_F = 1$ data was collected using Swagelok flow controllers for all fuels, except for CH₄ which used Brooks flow controllers for all values of $x_F$. Swagelok flow controllers were also used in the S2 and S5 experiment for all values of $x_F$, including $x_F = 1$ results. The error analysis on the data gathered using Swagelok flow controllers may not be comparable to data gathered using Brooks thermal flow controllers due to differences in experimental conditions.

Figures 5.13 to 5.19 suggests that the 95% prediction interval is appropriate to characterize the random error for all the gaseous fuels except for B1. In Figure 5.18 for B1
Figure 5.13: Error analysis on S2 results from the present work.

Figure 5.14: Error analysis on S5 results from the present work.
Figure 5.15: Error analysis on S1 results from the present work.

Figure 5.16: Error analysis on S5M25 results from the present work.
Chapter 5. Results and Discussion

Figure 5.17: Error analysis on S5M50 results from the present work.

Figure 5.18: Error analysis on B1 results from the present work.
Figure 5.19: Error analysis on the preliminary CH\textsubscript{4} results from the present work for all values of $x_F$.

gas, it appears that the $x_F = 1$ data points are outliers in comparison to the data points at all other values of $x_F$. For any given value of $x_F$, including $x_F = 1$, the scatter appears to be fairly small suggesting that the cause of the $x_F = 1$ outlying data points was a bias created by systematic error in the experimental conditions. The only difference in experimental conditions for the data recorded at $x_F = 1$ and all other $x_F$ values was the flow controller. For B1 at $x_F = 1$, Swagelok flow controllers were used. For all other values of $x_F$ for B1, the Brooks thermal flow controllers were used. This suggests that there is a moderate systematic error between the two different flow controllers.

To further investigate the systematic error caused by the two flow controllers, consider S5M50 at $x_F = 1$. Recall that all fuels (except CH\textsubscript{4}) used the Swagelok flow controllers at $x_F = 1$. Considering S5M50 in Figure 5.17, the only other fuel which had laminar conditions ($K < 1400$, or $Re_D < 4500$) at $x_F = 1$, it seems like the $x_F = 1$ data points
have acceptable deviation from the expected trend suggesting that the systematic error is small in this case. The difference between the B1 and S5M50 fuel at $x_F = 1$ was that the flow rates at the extinction limit of B1 was much smaller. This suggests that the systematic error between the Swagelok flow controllers and the Brooks flow controllers is small at higher flow rates, but is more significant at lower flow rates.

As discussed earlier, the systematic error of the S2 and S5 results may not be comparable to the other fuels, as the S2 and S5 results were gathered using Swagelok flow controllers, whereas the results for all other fuels were gathered using Brooks flow controllers for $x_F < 1$. However, the Swagelok flow controllers have insignificant systematic error in contrast to the Brooks flow controllers at high flow rates. Since the S2 and S5 extinction limit occurs at relatively high flow rates, this suggests that the S2 and S5 systematic error may actually be comparable to the other fuels.

In summary, analysis of the results suggest that the systematic error of all the fuels are comparable to each other, regardless of the flow controller used (Swagelok vs. Brooks flow controllers) as long as the fuels which used the Swagelok flow controllers have extinction limits at high flow rates. The exception appears to be B1 at $x_F = 1$, which used Swagelok flow controllers for extinction limits at low rates. B1 results at all other values of $x_F$ are reasonable as the Brooks flow controllers are used for these data points.

As shown in Figures 5.13 to 5.19, the random error characterized by the 95% prediction internal for S2, S5, S1, S5M25, S5M50, B1, and CH$_4$ is approximately ±427, ±505, ±197, ±224, ±129, ±131, and ±123 respectively. It should be noted that this characterization of random error is associated with the extinction limit linear curve fit using the entire domain of fuel mole fractions, and that the random error at any particular fuel mole fraction is significantly less, with the results being very repeatable.
Chapter 6

Conclusions and Recommendations

In this work, the flame extinction limit of various gaseous fuels was investigated in a laminar diffusion counterflow flame. The global strain rate formulation was used to estimate the strain rate at extinction, which was measured at various fuel mole fractions. A new high flow counterflow burner was designed and built for this work. The findings are summarized below:

1. Preliminary work looked at two burner exit flow conditions: top hat exit velocity profile created by an inner nozzle with a sintered porous metal matrix at the exit, and parabolic exit velocity profile from a straight tube inner nozzle. It was observed that the top hat exit condition lead to a lot of inconsistencies. It is speculated that a small recirculation zone was forming in the center of the impingement of the two jets, creating a flame holder that allowed the flame to be stabilized beyond the extinction strain rate. Because of these inconsistencies the decision was made to use the straight tube inner nozzles for the extinction measurements.

2. The preliminary work studying the extinction limit of CH$_4$ for various fuel mole fractions up to $x_F = 1$ showed good agreement with results from literature for fuel mole fractions up to 0.5. There does not appear to be any extinction results in literature for CH$_4$ with fuel mole fractions between 0.5 to 1.0, although there is a
wealth of extinction studies for pure CH$_4$. Pure CH$_4$ results from the present work also showed fair agreement with results from literature.

3. Extinction strain rate results appear to be independent of extinction method used: 1) keeping the mole fraction of fuel in the fuel stream constant while increasing strain, or b) keeping the strain rate constant while slowly decreasing fuel mole fraction in the fuel stream until flame extinction occurs. The data from either of the two cases appeared to deviate very little from the trend. Similarly, Won et al. [66] studied two similar cases of extinction with toluene blended with n-decane, and concluded that the two methods showed good agreement with small error (5%).

4. The gaseous fuel results imply that H$_2$ is dominant in determining the extinction limit conditions. The fuels with the highest H$_2$ concentration had the greatest extinction limit regardless of the concentration of the other combustible species. This may be a result of hydrogen’s high diffusivity compared to the diffusivity of the other combustible syngas species. This seems to suggest that the combustible species with the highest diffusivity in a gas mixture will be dominant in determining the extinction characteristics of a flame burning the gas mixture.

5. Soot was observed in the methane flame as indicated by the orange glow, accompanied with regions of blue within the visible flame. The orange luminosity disappeared as strain rate was increased, or as fuel mole fraction was reduced, leaving only a blue flame. When soot volume fraction measurements were attempted with the laser light extinction system, the soot concentrations were below the detectable limit. The syngas flames were entirely blue in color indicating that no soot was formed in these flames for the strain rates and fuel mole fractions studied.

There are several recommendations to improve on the work presented here. The recommendations are summarized below:
1. A Particle Image Velocimetry (PIV) system is available in the lab that could be used to visualize the flow field. The PIV system has many benefits. First it can be used to obtain the local strain rate by measuring the velocity gradient on the oxidizer side right before the flame, which can be used to validate the extinction strain rate results obtained with the global strain rate formulation.

Second, the PIV system can be used for visualization of the burner exit conditions. The extinction limit results are heavily dependent on the burner exit conditions, and knowing these conditions could help the researcher gain insight into the error and behaviors of the flame at the extinction limit. The PIV system could verify if the flow coming out of the nozzle with the sintered metal at the tip (type II burner) is a top hat velocity profile, or if the flow coming out of the straight nozzle (type I burner) is parabolic. In addition, knowing the flow field could help to gain insight of the observed extinction limit inconsistencies of the sintered metal nozzle, and to confirm if a recirculation zone, which potentially acts as a flame holder, is being formed at the impingement of the two jets.

Third, the PIV system could be used to gain insight on the turbulent condition of the flame. Visual observation, or the pipe Reynolds number, which has been used previously in literature \[35\] to quantify the turbulent condition of a counterflow flame, is not entirely representative of the turbulent conditions in the flame.

2. A numerical combustion modeling research group exists at this research institute, and numerical modeling of the experimental conditions were done in parallel with the experimental work. The results from these numerical studies can be used to gain further insight into the extinction limit conditions of the gaseous fuels used in this work.
Appendix A

Burner Technical Drawings

Figure A.1: Assembly: burner final
Figure A.2: Assembly: burner subassembly

Figure A.3: Assembly: burner upper
### Appendix A. Burner Technical Drawings

#### Section C-C

![Figure A.4: Assembly: burner lower](image)

- **Figure A.4: Assembly: burner lower**

#### Section C-C

![Figure A.5: Assembly: mounting](image)

- **Figure A.5: Assembly: mounting**
Figure A.6: Part: burner upper plate

Figure A.7: Part: burner bottom plate
Figure A.8: Part: inner nozzle - sintered metal

Figure A.9: Part: inner nozzle - smooth bore
Figure A.10: Part: outer nozzle

Figure A.11: Part: base plate mounting
Figure A.12: Part: porous matrix, inner downstream

Figure A.13: Part: porous matrix, inner upstream
Figure A.14: Part: porous matrix, outer

Figure A.15: Part: sleeve, inner downstream
Appendix A. Burner Technical Drawings

Figure A.16: Part: sleeve, inner upstream, press fit

Figure A.17: Part: sleeve, inner upstream, slip fit
Figure A.18: Part: sleeve, outer
Appendix B

Experimental Flow Rates

Table B.1: Flow rates for CH$_4$ experimental results

<table>
<thead>
<tr>
<th>$x_F$</th>
<th>$\dot{Q}_p$</th>
<th>$\dot{Q}_{N_2}$</th>
<th>$\dot{Q}_{FS}$</th>
<th>$\dot{Q}_\Lambda$</th>
<th>$K_{ext}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m$^3$/s</td>
<td>m$^3$/s</td>
<td>m$^3$/s</td>
<td>m$^3$/s</td>
<td>1/s</td>
</tr>
<tr>
<td>0.21</td>
<td>2.68E-06</td>
<td>1.01E-05</td>
<td>1.27E-05</td>
<td>9.96853E-06</td>
<td>44.00</td>
</tr>
<tr>
<td>0.30</td>
<td>8.16E-06</td>
<td>1.92E-05</td>
<td>2.74E-05</td>
<td>1.92753E-05</td>
<td>89.16</td>
</tr>
<tr>
<td>0.40</td>
<td>1.66E-05</td>
<td>2.47E-05</td>
<td>4.13E-05</td>
<td>2.72807E-05</td>
<td>128.99</td>
</tr>
<tr>
<td>0.50</td>
<td>3.82E-05</td>
<td>3.82E-05</td>
<td>7.64E-05</td>
<td>4.71346E-05</td>
<td>228.31</td>
</tr>
<tr>
<td>0.60</td>
<td>5.37E-05</td>
<td>3.60E-05</td>
<td>8.97E-05</td>
<td>5.33028E-05</td>
<td>259.72</td>
</tr>
<tr>
<td>0.70</td>
<td>6.92E-05</td>
<td>2.97E-05</td>
<td>9.88E-05</td>
<td>5.92782E-05</td>
<td>282.34</td>
</tr>
<tr>
<td>0.80</td>
<td>8.58E-05</td>
<td>2.14E-05</td>
<td>1.07E-04</td>
<td>6.7269E-05</td>
<td>306.71</td>
</tr>
<tr>
<td>0.90</td>
<td>1.04E-04</td>
<td>1.15E-05</td>
<td>1.16E-04</td>
<td>7.79203E-05</td>
<td>335.74</td>
</tr>
<tr>
<td>1.00</td>
<td>1.12E-04</td>
<td>0.00E+00</td>
<td>1.12E-04</td>
<td>8.36401E-05</td>
<td>332.37</td>
</tr>
</tbody>
</table>
Table B.2: Flow rates for S2 experimental results

<table>
<thead>
<tr>
<th>$x_F$</th>
<th>$\dot{Q}_F$</th>
<th>$\dot{Q}_{N2}$</th>
<th>$\dot{Q}_{FS}$</th>
<th>$\dot{Q}_A$</th>
<th>$K_{ext}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m³/s</td>
<td>m³/s</td>
<td>m³/s</td>
<td>m³/s</td>
<td>1/s</td>
</tr>
<tr>
<td>Strain Constant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.22</td>
<td>1.48E-05</td>
<td>5.15E-05</td>
<td>6.63E-05</td>
<td>5.42E-05</td>
<td>236.55</td>
</tr>
<tr>
<td>0.36</td>
<td>7.87E-05</td>
<td>1.38E-04</td>
<td>2.17E-04</td>
<td>1.59E-04</td>
<td>730.95</td>
</tr>
<tr>
<td>0.46</td>
<td>1.64E-04</td>
<td>1.95E-04</td>
<td>3.60E-04</td>
<td>2.57E-04</td>
<td>1192.43</td>
</tr>
<tr>
<td>Dilution Constant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.20</td>
<td>8.64E-06</td>
<td>3.50E-05</td>
<td>4.56E-05</td>
<td>3.43E-05</td>
<td>155.12</td>
</tr>
<tr>
<td>0.30</td>
<td>3.10E-05</td>
<td>7.28E-05</td>
<td>1.06E-04</td>
<td>7.78E-05</td>
<td>356.83</td>
</tr>
<tr>
<td>0.40</td>
<td>1.04E-04</td>
<td>1.56E-04</td>
<td>2.60E-04</td>
<td>1.78E-04</td>
<td>850.11</td>
</tr>
</tbody>
</table>

Table B.3: Flow rates for S5 experimental results

<table>
<thead>
<tr>
<th>$x_F$</th>
<th>$\dot{Q}_F$</th>
<th>$\dot{Q}_{N2}$</th>
<th>$\dot{Q}_{FS}$</th>
<th>$\dot{Q}_A$</th>
<th>$K_{ext}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m³/s</td>
<td>m³/s</td>
<td>m³/s</td>
<td>m³/s</td>
<td>1/s</td>
</tr>
<tr>
<td>Strain Constant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.22</td>
<td>1.53E-05</td>
<td>5.42E-05</td>
<td>6.96E-05</td>
<td>5.42E-05</td>
<td>242.11</td>
</tr>
<tr>
<td>0.35</td>
<td>8.04E-05</td>
<td>1.48E-04</td>
<td>2.28E-04</td>
<td>1.59E-04</td>
<td>749.16</td>
</tr>
<tr>
<td>0.47</td>
<td>1.86E-04</td>
<td>2.99E-04</td>
<td>3.94E-04</td>
<td>2.57E-04</td>
<td>1246.66</td>
</tr>
<tr>
<td>Dilution Constant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.20</td>
<td>7.21E-06</td>
<td>2.94E-05</td>
<td>3.87E-05</td>
<td>2.95E-05</td>
<td>131.60</td>
</tr>
<tr>
<td>0.30</td>
<td>3.11E-05</td>
<td>7.28E-05</td>
<td>1.07E-04</td>
<td>7.63E-05</td>
<td>352.89</td>
</tr>
<tr>
<td>0.40</td>
<td>1.13E-04</td>
<td>1.70E-04</td>
<td>2.82E-04</td>
<td>1.93E-04</td>
<td>915.40</td>
</tr>
</tbody>
</table>
# Appendix B. Experimental Flow Rates

## Table B.4: Flow rates for S1 experimental results

<table>
<thead>
<tr>
<th>$x_F$</th>
<th>$\dot{Q}_F$</th>
<th>$\dot{Q}_{N2}$</th>
<th>$\dot{Q}_{FS}$</th>
<th>$\dot{Q}_A$</th>
<th>$K_{ext}$</th>
<th>$\text{m}^3/\text{s}$</th>
<th>$\text{m}^3/\text{s}$</th>
<th>$\text{m}^3/\text{s}$</th>
<th>$\text{m}^3/\text{s}$</th>
<th>$1/\text{s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strain Constant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.37</td>
<td>2.74E-05</td>
<td>4.67E-05</td>
<td>7.41E-05</td>
<td>5.27E-05</td>
<td>249.64</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.44</td>
<td>6.62E-05</td>
<td>8.45E-05</td>
<td>1.51E-04</td>
<td>1.04E-04</td>
<td>500.07</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.48</td>
<td>1.09E-04</td>
<td>1.16E-04</td>
<td>2.25E-04</td>
<td>1.56E-04</td>
<td>746.01</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dilution Constant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.30</td>
<td>7.23E-06</td>
<td>1.69E-05</td>
<td>2.45E-05</td>
<td>1.64E-05</td>
<td>80.25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.41</td>
<td>4.40E-05</td>
<td>6.29E-05</td>
<td>1.08E-04</td>
<td>7.34E-05</td>
<td>355.29</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.50</td>
<td>1.19E-04</td>
<td>1.17E-04</td>
<td>2.36E-04</td>
<td>1.59E-04</td>
<td>775.92</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Table B.5: Flow rates for S5M25 experimental results

<table>
<thead>
<tr>
<th>$x_F$</th>
<th>$\dot{Q}_F$</th>
<th>$\dot{Q}_{N2}$</th>
<th>$\dot{Q}_{FS}$</th>
<th>$\dot{Q}_A$</th>
<th>$K_{ext}$</th>
<th>$\text{m}^3/\text{s}$</th>
<th>$\text{m}^3/\text{s}$</th>
<th>$\text{m}^3/\text{s}$</th>
<th>$\text{m}^3/\text{s}$</th>
<th>$1/\text{s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strain Constant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.33</td>
<td>2.51E-05</td>
<td>5.07E-05</td>
<td>7.58E-05</td>
<td>5.39E-05</td>
<td>250.21</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.44</td>
<td>6.96E-05</td>
<td>8.86E-05</td>
<td>1.58E-04</td>
<td>1.04E-04</td>
<td>500.34</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.52</td>
<td>1.26E-04</td>
<td>1.16E-04</td>
<td>2.43E-04</td>
<td>1.55E-04</td>
<td>750.31</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dilution Constant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.20</td>
<td>4.02E-06</td>
<td>1.60E-05</td>
<td>2.01E-05</td>
<td>1.62E-05</td>
<td>70.96</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.31</td>
<td>1.36E-05</td>
<td>3.01E-05</td>
<td>4.22E-05</td>
<td>3.16E-05</td>
<td>144.11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.41</td>
<td>5.00E-05</td>
<td>7.18E-05</td>
<td>1.14E-04</td>
<td>8.11E-05</td>
<td>380.43</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.50</td>
<td>1.09E-04</td>
<td>1.07E-04</td>
<td>1.95E-04</td>
<td>1.37E-04</td>
<td>647.40</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table B.6: Flow rates for S5M50 experimental results

<table>
<thead>
<tr>
<th>$x_F$</th>
<th>$\dot{Q}_F$</th>
<th>$\dot{Q}_{N_2}$</th>
<th>$\dot{Q}_{FS}$</th>
<th>$\dot{Q}_A$</th>
<th>$K_{ext}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m$^3$/s</td>
<td>m$^3$/s</td>
<td>m$^3$/s</td>
<td>m$^3$/s</td>
<td>1/s</td>
</tr>
<tr>
<td>Strain Constant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.34</td>
<td>2.60E-05</td>
<td>5.04E-05</td>
<td>7.65E-05</td>
<td>5.39E-05</td>
<td>250.11</td>
</tr>
<tr>
<td>0.52</td>
<td>8.52E-05</td>
<td>7.86E-05</td>
<td>1.64E-04</td>
<td>1.03E-04</td>
<td>499.83</td>
</tr>
<tr>
<td>0.74</td>
<td>1.83E-04</td>
<td>6.51E-05</td>
<td>2.48E-04</td>
<td>1.61E-04</td>
<td>746.49</td>
</tr>
<tr>
<td>Dilution Constant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.31</td>
<td>8.65E-06</td>
<td>1.90E-05</td>
<td>2.98E-05</td>
<td>1.97E-05</td>
<td>93.16</td>
</tr>
<tr>
<td>0.41</td>
<td>3.70E-05</td>
<td>5.26E-05</td>
<td>9.28E-05</td>
<td>5.93E-05</td>
<td>285.75</td>
</tr>
<tr>
<td>0.51</td>
<td>7.19E-05</td>
<td>6.99E-05</td>
<td>1.41E-04</td>
<td>8.98E-05</td>
<td>434.48</td>
</tr>
</tbody>
</table>

Table B.7: Flow rates for B1 experimental results

<table>
<thead>
<tr>
<th>$x_F$</th>
<th>$\dot{Q}_F$</th>
<th>$\dot{Q}_{N_2}$</th>
<th>$\dot{Q}_{FS}$</th>
<th>$\dot{Q}_A$</th>
<th>$K_{ext}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m$^3$/s</td>
<td>m$^3$/s</td>
<td>m$^3$/s</td>
<td>m$^3$/s</td>
<td>1/s</td>
</tr>
<tr>
<td>Strain Constant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.48</td>
<td>1.43E-05</td>
<td>1.52E-05</td>
<td>2.95E-05</td>
<td>2.06E-05</td>
<td>99.16</td>
</tr>
<tr>
<td>0.79</td>
<td>3.85E-05</td>
<td>1.03E-05</td>
<td>4.89E-05</td>
<td>3.92E-05</td>
<td>174.22</td>
</tr>
<tr>
<td>0.83</td>
<td>4.60E-05</td>
<td>9.53E-06</td>
<td>5.55E-05</td>
<td>4.56E-05</td>
<td>200.01</td>
</tr>
<tr>
<td>Dilution Constant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.30</td>
<td>4.35E-06</td>
<td>1.01E-05</td>
<td>1.45E-05</td>
<td>1.08E-05</td>
<td>50.14</td>
</tr>
<tr>
<td>0.40</td>
<td>8.52E-06</td>
<td>1.28E-05</td>
<td>2.14E-05</td>
<td>1.52E-05</td>
<td>72.37</td>
</tr>
<tr>
<td>0.50</td>
<td>1.23E-05</td>
<td>1.25E-05</td>
<td>2.49E-05</td>
<td>1.71E-05</td>
<td>83.09</td>
</tr>
</tbody>
</table>
Bibliography


