Measurement of Laminar Burning Velocity of Methane-Air Mixtures Using a Slot and Bunsen Burner

A Major Qualifying Project

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1. Burning Velocity
2. Slot Burner
3. Methane

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Table of Contents

TABLE OF FIGURES

Abstract

The aim of this study is to calculate the laminar burning velocity of a premixed methane-air flame using two different experimental methods -- the slot burner, and the Bunsen burner technique. In both experiments flame angle and flame area are estimated by using a digital camera. The gas flow rates are measured using a flow meter. Results are compared with pre-existing burning velocity data from the literature and good agreement is observed. In addition, the factors that influence the measurement of laminar burning velocity, including equivalence ratio, geometry of the burner, and influence of flame stretch are also analyzed.

1 Introduction

Laminar burning velocity is an important parameter of a combustible mixture as it contains fundamental information regarding reactivity, diffusivity, and exothermicity. Its accurate knowledge is essential for engine design, modeling of turbulent combustion, and validation of chemical kinetic mechanisms. In addition, the determination of burning velocity is very important for the calculations used in explosion protection and fuel tank venting. The burning velocity is defined as the linear velocity of the flame front normal to itself relative to unburned gas, or as the volume of unburned gas consumed per unit time divided by the area of the flame front in which that volume is consumed (Linnett, 1954).

Since the early 1990's the use of natural gas as an energy source has been increasing rapidly. Natural gas is clean burning and consists of approximately 90 percent methane (CH_4). Due to this high percentage it is important to gain as much knowledge regarding the burning properties and attributes of methane as possible. This project will focus on a mixture of methane and air at various ratios, both greater than and less than stoichiometric. The mixture will be burned to simulate natural gas. The physical property under investigation will be laminar burning velocity.

Laminar burning velocity is highly useful for modeling turbulent burning velocity, (Keck 1982). Turbulent flow occurs when a fluid undergoes irregular fluctuations and mixing. Laminar flow is defined as the flow which travels smoothly in regular paths or layers (Laminar Flow, 2007). According to research by Klimov (1975), the relationship between laminar and turbulent burning velocity can be described by the following equation:

$$\frac{U_T}{U'} \sim \left[\frac{U_L}{U'}\right]^{0.3}$$

Equation 1

Where U_T = Turbulent Velocity, U_L = Laminar Velocity. From this equation Klimov concludes that $\frac{U_T}{U'}$ approaches zero according to the limit $\frac{U_L}{U'} \rightarrow 0$.

Another instance where laminar burning velocity is used as an input parameter to model a deflagration is the FLACS Code, developed by GexCon. The FLACS Software Suite is primarily used to model various types of explosions. Specifically, laminar burning velocity is used in the FLACS model for combustion. The model assumes that an explosion can be represented by many small flamelets, which can be considered laminar. Laminar burning velocity models are one of the three input parameters for this program and they are a function of the gas mixture, temperature, and pressure. The second input parameter is a turbulent burning velocity model, which depends upon numerous turbulence parameters, and is determined through experimental data. The final parameter quantifies a model describing quasi-laminar combustion shortly after ignition of the flame, (GexCon, 2007).

There are many experimental techniques used in obtaining the laminar burning velocity of a particular gas-air mixture. A critical review of these methods is available in the literature

(Andrews and Bradley, 1972). Apparatuses for measuring laminar burning velocity can be classified into two categories: constant volume and constant pressure. Examples of these are the spherical bomb technique for constant volume, and the slot-burner for constant pressure. The key differences are the ranges of pressure and temperature that can be included in the tests. The constant pressure methods primarily use atmospheric pressure, and approximately constant temperatures, while the constant volume methods can measure burning velocity under a wide range of temperatures and pressures (Parsinejadet et al., 2006). This project uses the slot-burner and Bunsen burner technique to calculate the flame velocities. The slot burner is chosen due to its advantages involved in the theory of the velocity calculation as well as ease of apparatus construction. The burning velocity obtained using the slot burner method is calculated by multiplying the gas mixture flow rate by the sine of the flame angle.

$$S_u = Usin\alpha$$

Equation 2

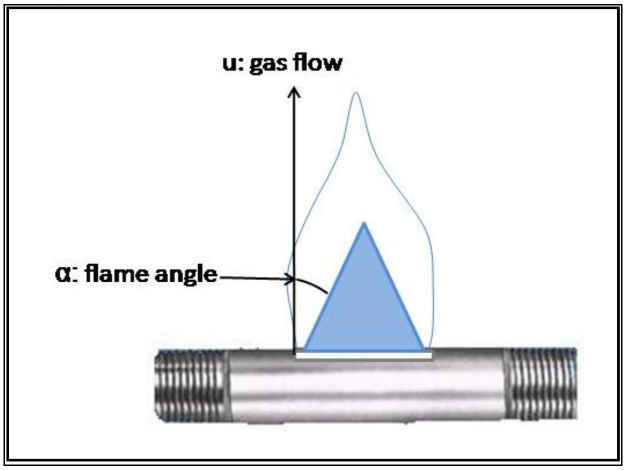


Figure 1: Illustration of experimental parameters used to calculate burning velocity using the slot burner method.

The Bunsen burner apparatus is decided upon because it should provide data that is accurately comparable to previously published data. The Bunsen burner uses the flame surface area and total flow of gas to calculate the laminar burning velocity.

$$v_b = \frac{input\ volumetric\ flow}{total\ flame\ area}$$

Equation 3

The flame produced in both apparatuses is stabilized and adjusted to provide the most uniform, symmetrical flame possible. This is done by increasing or decreasing the flow of fuel and air. The flame will then be photographed using a high resolution camera. Finally, from the pictures of the flames the flame angles and heights will be measured and then the burning velocity will be calculated.

2 Burning Velocity Measurement Techniques

There are a variety of techniques used to measure laminar burning velocity. This section discusses a few of these methods.

2.1 Slot Burner Technique

Description: A flame is stabilized over a rectangular opening. A Mache-Hebra (or similar) nozzle is used to create flat-velocity profile. From the side the flame appears to be tent-like in shape.

Flame Shape: Complex Conical

Advantages	**Disadvantages**
Flame has large flat areas in which curvature is minimized	Angle α is difficult to measure accurately

Experimental Parameters:
α: oblique angle to the primary flow direction of the gas mixture (°)
U: flow of gas mixture (cm/s)

Formula:
$S_u = U\sin\alpha$ (Strehlow 1984)

S_u: Burning velocity (cm/s)

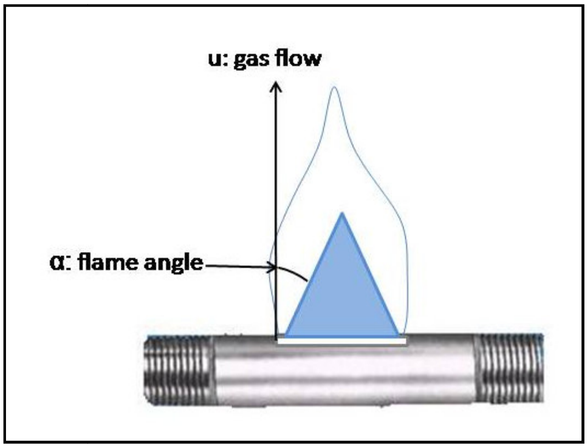


Figure 2: Illustration of Experimental Parameters used to calculate Burning Velocity

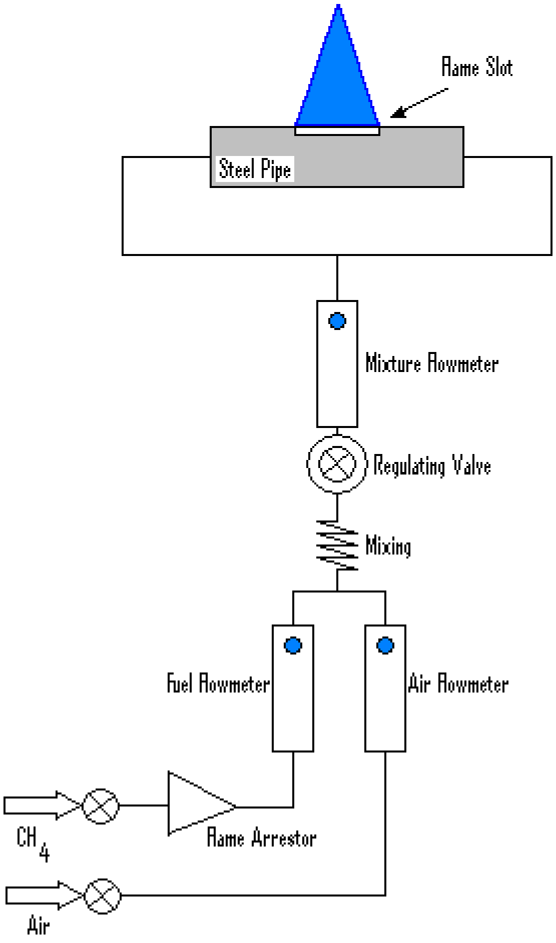


Figure 3: Design of Slot Burner Apparatus

2.2 Bunsen Burner Method

Description: Most commonly performed using a Bunsen burner, the flame surface area is simply measured and divided by the amount of gas mixture consumed per second. There are many ways to perform this experiment; however, it is not known which method is the most accurate, (Vagelopoulos 1998).

- Particle track method
- "Frustrum" Method- Lewis and Von Elbe (base and tip are not included in flame area)
- Angle method with Schlieren cone

Flame Shape: Varying

Advantages	**Disadvantages**
Simple apparatus It is also possible to test the effects of temperature and pressure	Low accuracy Unreliable theory Only avg burning velocity can be obtained Complex flame shapes Not possible with very fast flames

Experimental Parameters:

Volumetric flow (cm^3/s)
Area of flame (cm^2)

Formula:

$$v_b = \frac{input\ volumetric\ flow}{total\ flame\ area}$$ (Fristrom 1965)

v_b: Burning Velocity (cm/s)

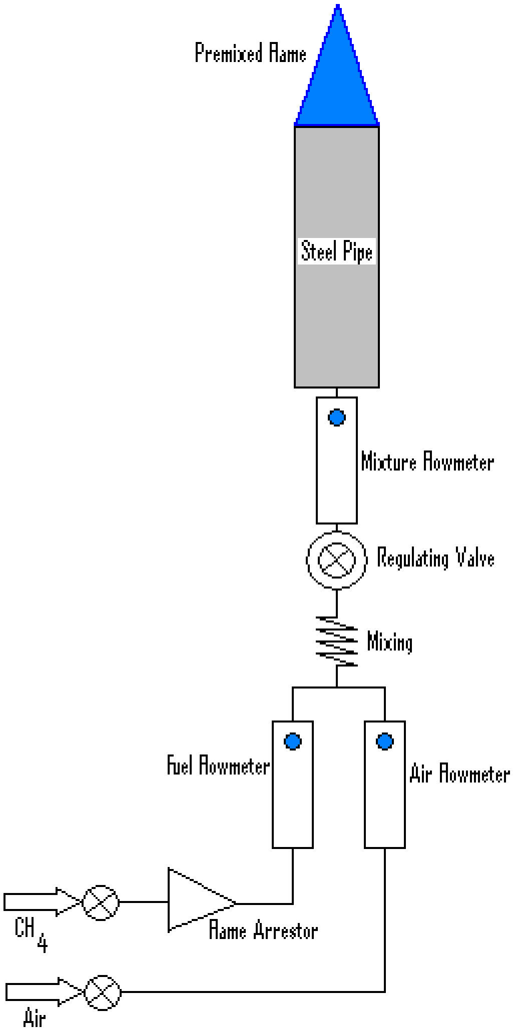


Figure 4: Typical Bunsen Burner

2.3 Tube Propagation Method

Description: A horizontal tube is filled with a gas mixture. One end of the tube is open, the other closed. A flame is ignited at the open end of the tube and a series of snapshots records the flame as it travels down the length of the tube.

Flame Shape: Hemispherical or Ellipsoidal

Advantages	**Disadvantages**
Small quantities of materials needed	Cooling effect of walls create errors
Widely applicable	Measurement of flame area is difficult
Simple apparatus	Only an avg burning velocity can be obtained

Experimental Parameters:

A: area of flame (cm^2)

v_m : speed of flame (cm/s) $\left(\frac{Lengthoftube(cm)}{Timeittakesflametotravelentirelengthoftube(sec)}\right)$

Formula:

$$v_b = \frac{v_m \pi R_2}{A}$$ (Linnett 1954)

V_b = Burning velocity (cm/s)

R_2 = Radius of tube (cm)

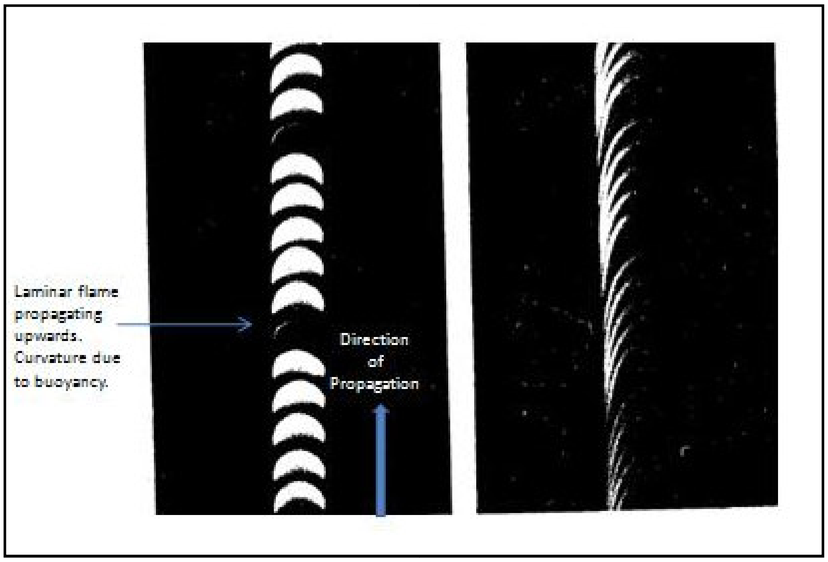


Figure 5: Snapshots of two flames as they propagate along a tube filled with two different fuel types. The picture on the right shows a fuel with a higher burning velocity than that of the picture on the left. This is determined by the spacing between each arc.

2.4 Soap Bubble Technique

Description: A soap bubble is blown with gas mixture and a capacitance spark ignites the flame within the bubble. It then burns as an outwardly propagating spherical flame. The flame is photographed using a rotating drum camera. The initial and final diameters are measured for the expansion ratio.

Flame Shape: Spherical

Advantages	**Disadvantages**
Simple interpretation because explosion occurs at constant temperature Small quantities of materials needed Flame is simple spherical form (spherical)	Gas may diffuse through soap bubble Soap can add water to gas mixture Measuring final bubble diameter is difficult Flames may not retain spherical shape Will not work with slow flames because convection will destroy spherical flame shape

Experimental Parameters:

r_1: Initial radius of soap bubble (cm)
r_2: Final radius of soap bubble (cm)

Formula: $S_u = \left(\frac{r_1}{r_2}\right)^3 S_b$ (Streholow 1984)

S_b: Volumetric flow (cm^3/s)
S_u = Burning velocity (cm/s)

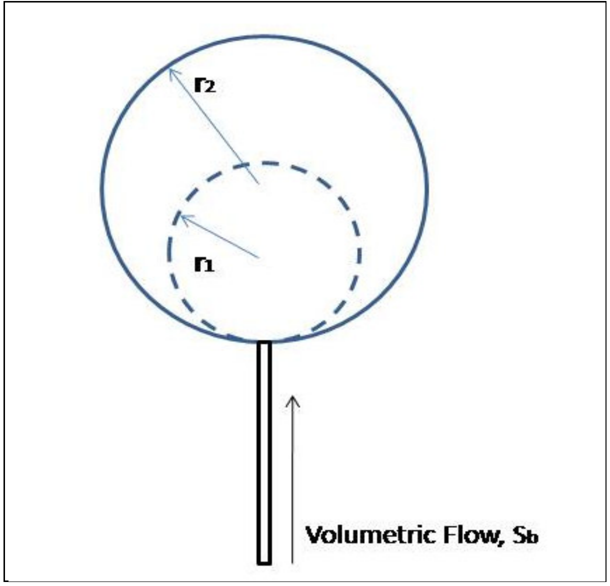


Figure 6: Variables involved in soap bubble technique equation

2.5 Constant Volume Explosion in Spherical Vessel

Description: Gas mixture is ignited at the center of a spherical bomb.

Flame Shape: spherical

Advantages	**Disadvantages**
Simple flame shape	Pressure is inconstant
Small quantities of materials needed	Flame may not remain spherical
Widely applicable	Complicated apparatus
	Theory is uncertain

Experimental Parameters:
p: pressure at time t (Pa)
r: flame radius at time t (cm)

Formula:

$$v_b = \left[1 - \frac{R^3 - r^3}{3p\gamma r^2}\frac{dp}{dr}\right]\frac{dr}{dt}$$ (Linnett 1954)

V_b = Burning velocity (cm/s)

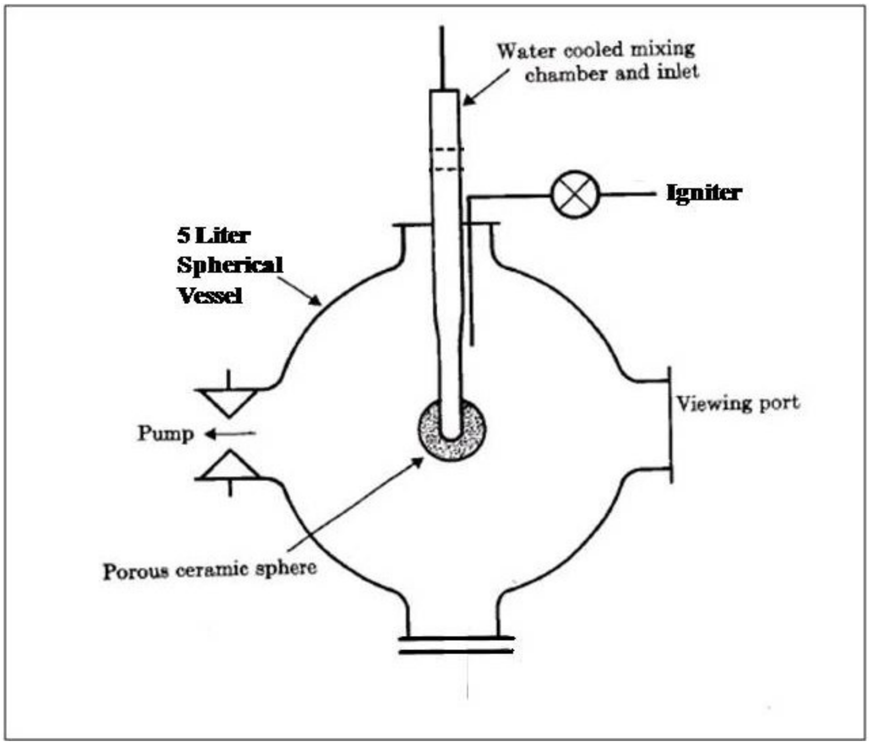


Figure 7: Vessel used for spherical explosion.

2.6 Flat Flame Burner

Description: A low velocity flow of the gas mixture is passed through a series of screens and honeycomb filters to create an even, flat flame, (Gaydon 1970).

Flame Shape: Flat

Advantages	**Disadvantages**
Flat flame profile most closely approaches an infinite plane Useful for mixtures nearing the limits of flammability	Can only be used for slow flames (<15cm/sec) Matrix heats up (sometimes up to 200°C) and preheats gas mixture

Experimental Parameters:

Flame area (cm^2)

Volumetric flow rate (cm^3/s)

Formula:

$$v_b = \frac{input\ volumetric\ flow}{total\ flame\ area}$$ (Gaydon 1970)

V_b = Burning velocity (cm/s)

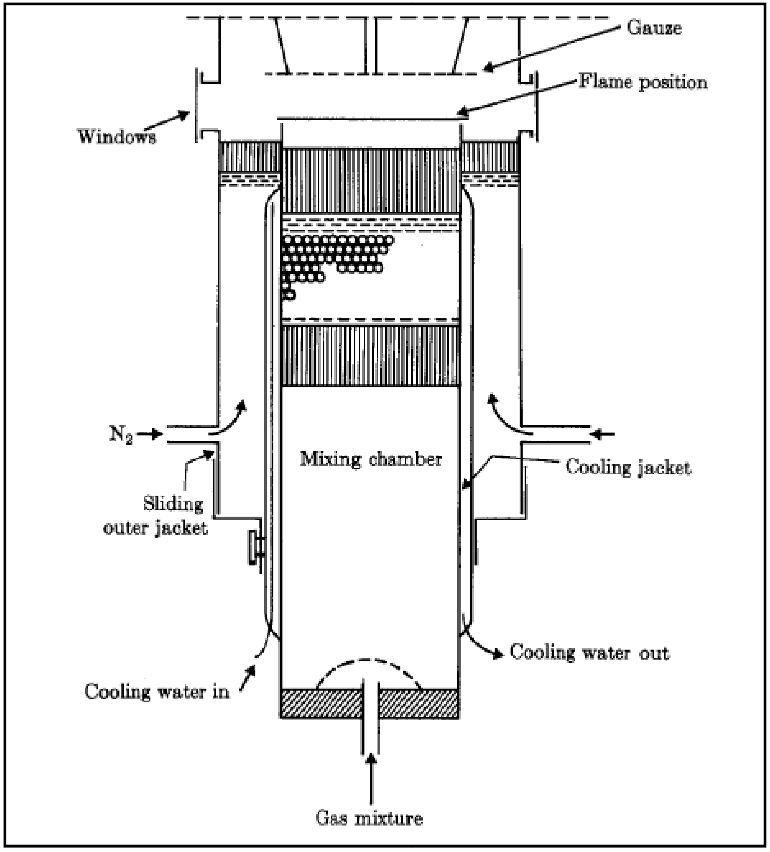


Figure 8: Flat flame burner with a series of filters and honeycombs used to mix the flame and create the flat flame shape

2.7 Counter-flow Diffusion Burner

Description: Two identical combustible mixtures are impinged against each other from two opposing burner nozzles. In this manner, a stagnation plane is generated between the two burners. This configuration forms two identical planar premixed flames (Linnett 1954).

Flame Shape:

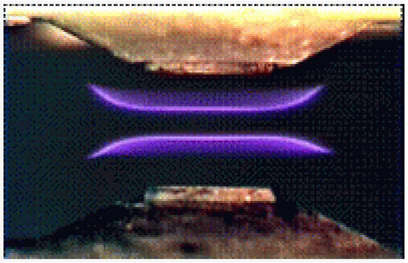


Figure 9: The opposed flame flows create a unique shape shown above (CASE 2007).

Advantages	**Disadvantages**
Conductive heat loss downstream of the flame is basically eliminated due to symmetry	Difficult to create ultralow strain rates Linear extrapolation needed Complicated apparatus

3 Experimental Design

Major Components

- Air Supply
    - In house air supply
- Methane Supply
    - Air Gas Company C.P. Grade (95% pure)
- Braided Steel Tubing
    - 0.635 cm (¼ in) ID
- PVC Tubing
    - Tygon-R 3603 0.925 cm (3/8 in) OD 0.635 cm (1/4 in) ID
- Mixing Chamber with 6mm glass beads
    5.2cm D x 30.48cm L
- (3) Flow Meters
    - (2) King Instrument 7200 Series In-Line Acrylic Flow Meter 7-70 SCFH
    - (1) Key Instrument MR3000 Series Polycarbonate Flow Meter 1-11SCFH
- Flow Regulator Valve
- Steel Pipe or copper pipe for Bunsen burners

3.1 Slot Burner

The slot burner method is chosen for measuring burning velocity for two specific reasons. First, the theory is relatively simple. Burning velocity is calculated by multiplying the gas flow rate by the sine of the acute angle between the direction of gas flow and the flame edge. The second reason for choosing this method is that the apparatus is relatively simple to construct and can be created by satisfying a small number of specifications. The first requirement being that the air and methane must be pre-mixed within the apparatus. Secondly, the gas mixture must exit through a slot of ratio 3:1 (length to width) or greater. Lastly, it is important that the apparatus be capable of creating and maintaining a steady flame characterized by a defined inner triangle.

Air for the experiment is delivered via an in-house compressed air system. A line of steel braided tubing joins this delivery system to the slot burner itself. The methane is stored in a compressed cylinder located approximately one meter away from the apparatus. Another steel braided tube delivers the methane supply to a separate branch of the slot burner, after passing through a methane-rated flame arrestor. Each of these supply sources is equipped with a regulator as well as a pressure gage. The air then passes through a flow meter of scale 7-70 standard cubic feet per hour (SCFH). The methane passes through a flow meter of scale 1-11 SCFH. These flow meters are used for the purpose of identifying the resulting gas mixture composition. The supplies then flow through approximately 30 cm (equidistantly) to a T-union where they simultaneously flow into a 5.2cm (3 in) diameter clear plastic tube. This tube is filled with glass beads of diameter 6mm (0.326 in) meant to mix the air and methane into an approximately uniform distribution.

The newly mixed gas then passes through a regulator valve. The purpose of this valve is to manage the flow exiting the slot thereby reducing turbulence. This is followed by a third flow meter of scale 7-70 SCFH to measure the actual gas flow exiting the slot burner. This value is used in calculation of the burning velocity. The gas mixture is then split once again at a T-union and delivered via PVC tubing to opposite ends of a 1.27 cm (½ in) diameter, 15.24 cm (6 in) long steel pipe. The inner wall of which has a fine mesh used to pressurize flow within the pipe, thereby reducing turbulence through the slot which is located at the top center of the pipe.

3.2 Bunsen Burner

Only a few alterations are made in order to convert the slot burner design to a Bunsen burner design. For the first test a 1.524cm diameter by 30.48cm long (1/2” x 12”) pipe is oriented vertically directly above the regulator valve. This way the flow no longer splits into two directions and exits directly at the top of the steel pipe where the laminar flame forms. Experimental parameters measured are the height and base of the flame as well as the volumetric flow exiting the pipe. Other burner diameters tested are 0.76cm and 1.016cm. The burning velocity is found by dividing the volumetric flow by the area of the flame.

3.3 Experimental Procedure

A leakage test is performed before every experiment to minimize the risk of a methane leak. This is done by first opening the air supply line and applying a leak identifying agent (Snoop) to every point with the potential for leakage. Connections are tightened until bubbles caused by Snoop are no longer present. The same process is completed along the methane line. A flame is lit at the top of the apparatus during this time to ensure that the methane is consumed rather than let out into the atmosphere.

The apparatus is located underneath a fumigation hood which is switched on throughout the duration of experimentation. A camera, approximately one meter away from the apparatus, is positioned for optimal flame photography. A visual scan is performed to ensure that no flammable objects are within close proximity to the apparatus. Next, a commercial lighter is lit and held over the flame opening as the methane supply is opened. Once the methane ignites the flow is adjusted to a relative desired rate measured by the 1-11 SCFH scale flow meter. Air supply is then turned on at a very gradual rate until the flame appears steady with a defined blue cone within the center. The regulator valve is adjusted to ensure that flow through the slot is not overpowering and causing turbulence.

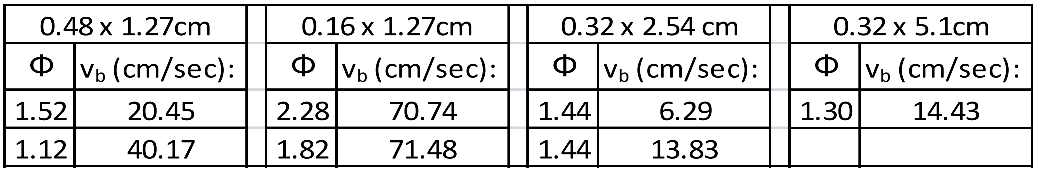
Once the flame is steady and the flow meters show a desired mixture ratio, the flow meter values are recorded. The flow meters directly in line with the air and gas lines will be used to determine ratio of methane-air mixture. The flow meter located above the mixing chamber will be used to define the gas flow used in the burning velocity calculation. Several photos are then taken of the flame which will later be used to measure the angle α for the slot burner, and conical surface area for the Bunsen burner. These parameters are later used to calculate the laminar burning velocity.

4 Results

For the slot burner method a total of 4 slot sizes are used for experimentation:

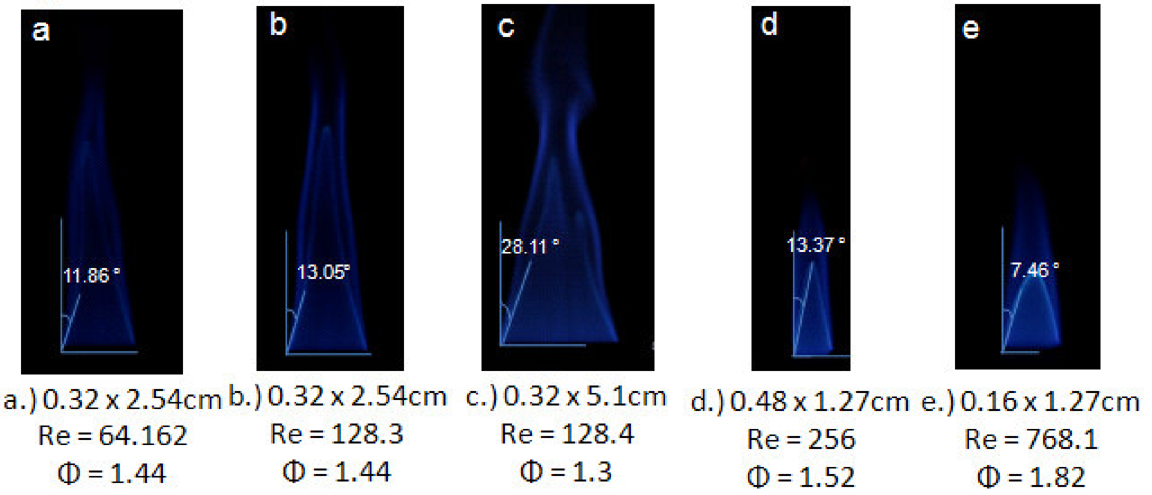
- 0.16 x 1.27cm
- 0.48 x 1.27cm
- 0.32 x 2.54cm
- 0.32 x 5.1cm

Figure 11 shows photographs taken of each flame for each slot burner size. For the slot burner of size 0.32 x 5.1cm there are two noticeable peaks within the flame. This result is presumed to be caused by a lack of pressurization across the slot, thereby creating multiple peaks. Full laminar flames are obtained for the other three slot sizes. Burning velocity results for slot size 0.16 x 1.27cm are unusually high (Figure 10 & Figure 12). This could be due to the fact that the slot is too small for this slot burner design, and high pressures are causing an abnormal increase in burning velocity.



0.48 x 1.27cm		0.16 x 1.27cm		0.32 x 2.54 cm		0.32 x 5.1cm	
Φ	v_b (cm/sec):	Φ	v_b (cm/sec):	Φ	v_b (cm/sec):	Φ	v_b (cm/sec):
1.52	20.45	2.28	70.74	1.44	6.29	1.30	14.43
1.12	40.17	1.82	71.48	1.44	13.83		

Figure 10: Experimental results for Slot Burner Method.



a.) 0.32 x 2.54cm
Re = 64.162
Φ = 1.44

b.) 0.32 x 2.54cm
Re = 128.3
Φ = 1.44

c.) 0.32 x 5.1cm
Re = 128.4
Φ = 1.3

d.) 0.48 x 1.27cm
Re = 256
Φ = 1.52

e.) 0.16 x 1.27cm
Re = 768.1
Φ = 1.82

Figure 11: Photographs of flames for each slot burner size tested.

Figure 11 shows that the angles are similar for all slot sizes and flames. The only anomaly is that the flame shown in picture (c) is slightly turbulent and a full laminar flame is not obtained.

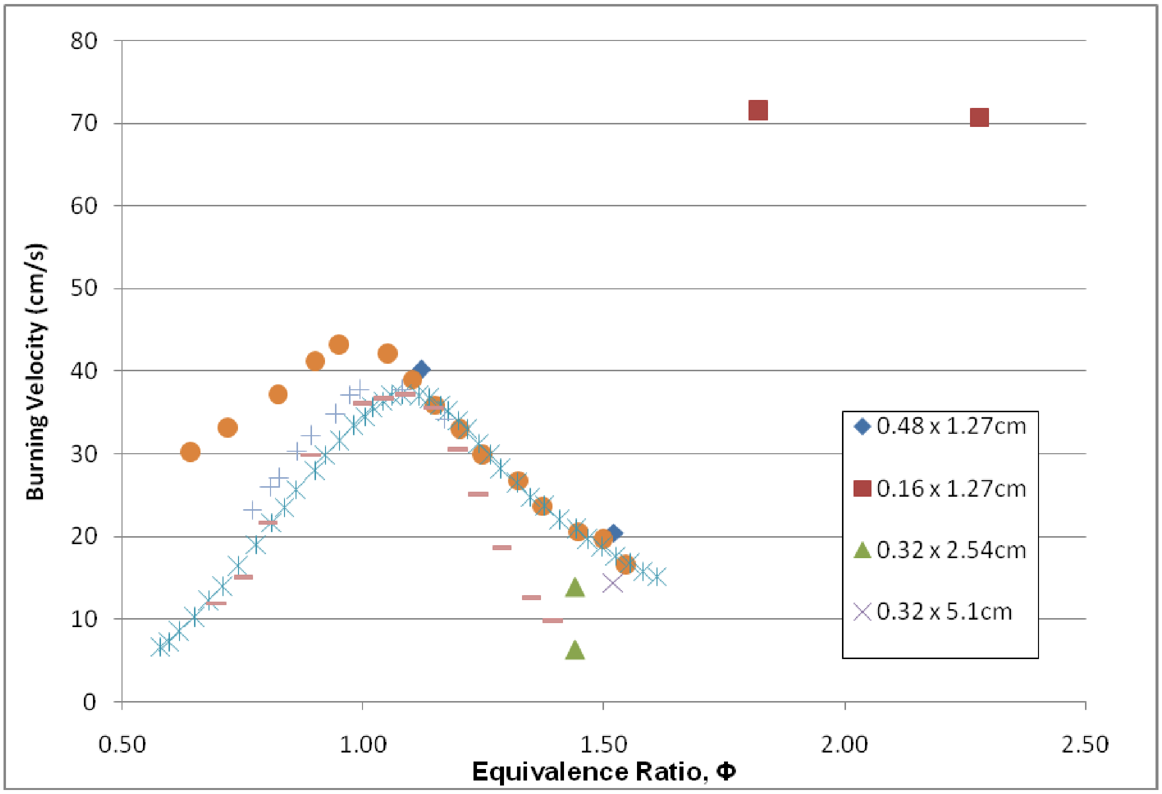
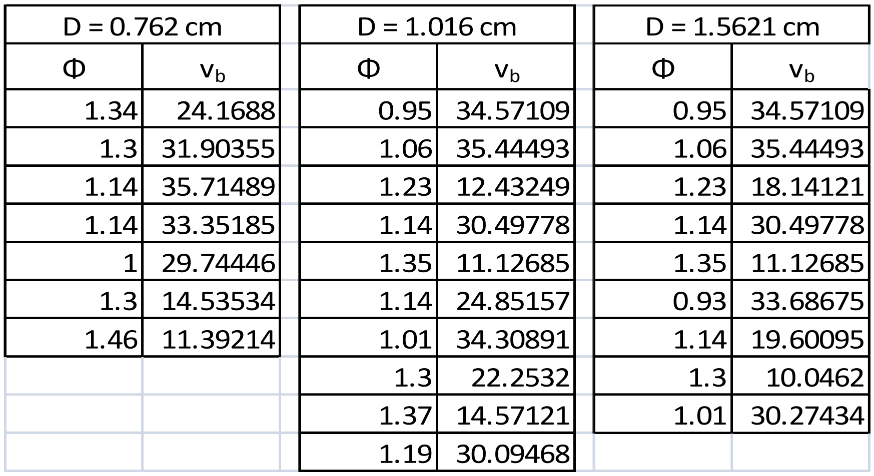


Figure 12: Slot burner experimental results plotted against published data for Methane and Air burning velocity

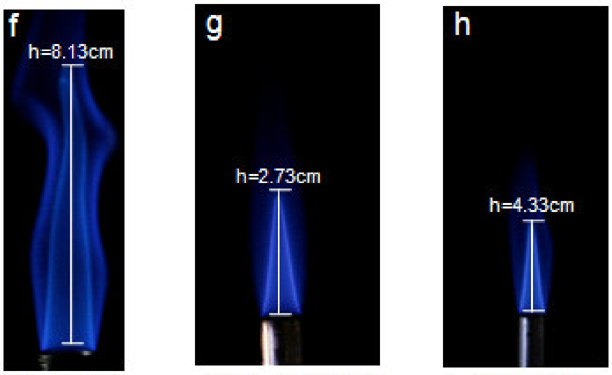
Figure 14 shows photographs taken of each flame for each Bunsen burner diameter tested. For the Bunsen burner diameter of 1.524 there is some noticeable turbulence. Reasons for this disturbance are unknown, as the Reynold's number is calculated to be 84.77 which is far below Re = 2300 where the flame is defined as turbulent. Burning velocity results for all three diameters are found to be within an accurate range of pre-published methane-air burning velocities. Figure 15 shows the Bunsen burner data and slot burner data plotted with published data by Strehlow, Lewis, Natrajan et. al. and Vagelopoulos.



D = 0.762 cm		D = 1.016 cm		D = 1.5621 cm	
Φ	v_b	Φ	v_b	Φ	v_b
1.34	24.1688	0.95	34.57109	0.95	34.57109
1.3	31.90355	1.06	35.44493	1.06	35.44493
1.14	35.71489	1.23	12.43249	1.23	18.14121
1.14	33.35185	1.14	30.49778	1.14	30.49778
1	29.74446	1.35	11.12685	1.35	11.12685
1.3	14.53534	1.14	24.85157	0.93	33.68675
1.46	11.39214	1.01	34.30891	1.14	19.60095
		1.3	22.2532	1.3	10.0462
		1.37	14.57121	1.01	30.27434
		1.19	30.09468		

Figure 13: Experimental results for Bunsen Burner Method.

Figure 13 shows the equivalence ratios that are achieved and their related burning velocities for each laminar flame achieved in the Bunsen burner tests.



f.) D=1.524cm
Re=84.77
Φ=1.14

g.) D=0.762cm
Re=325.525
Φ=1.14

h.) D=1.016cm
Re=439.45
Φ=1.14

Figure 14: Photographs of flames for each Bunsen burner diameter tested.

The data shows that the heights of the flames for the Bunsen burner tests vary within a minimum of ~2cm and a maximum of ~9cm. The average is approximately 4.5cm. Figure 15 shows a plot of Bunsen burner experimental results with pre-published data by Strehlow, Lewis, Natrajan et. al. and Vagelopoulos.

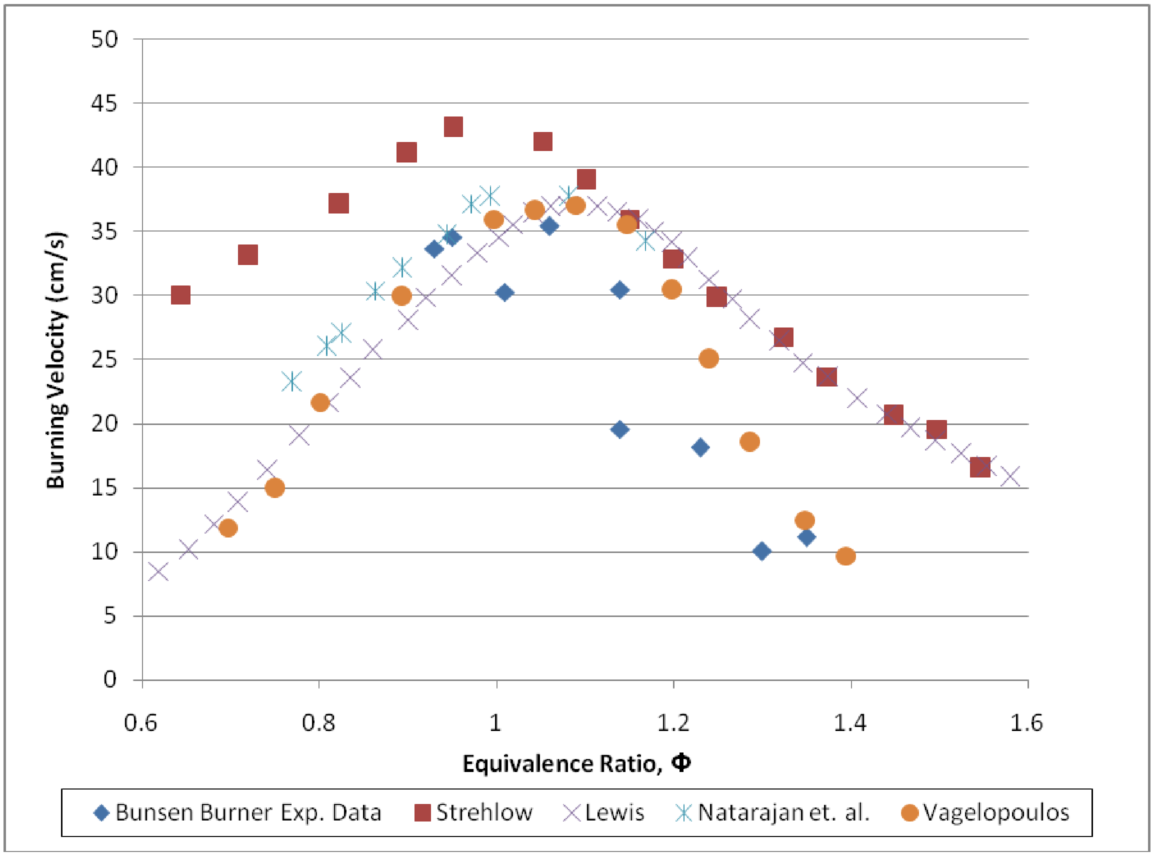


Figure 15: Plot of experimental results for the Bunsen burner plotted with published data by Strehlow, Lewis, Natrajan et. al., and Vagelopoulos.

5 Analysis

5.1 Factors Influencing Flame Velocity Results

There are multiple physical factors which will affect the results of a burning velocity experiment. Some of these factors are discussed below.

5.1.1 Equivalence Ratio

The main focus of this study is to calculate burning velocity at various equivalence ratios, Φ. A variety of previously published literature including Lewis, Streholow, Vagelopolous among others have found that the relationship between equivalence ratio and burning velocity is in the form of a bell curve approximately centered on Φ=1. An example of Lewis's data curve is shown below in Figure 16.

In order to calculate the equivalency ratio, Φ, for this experiment a series of calculations are necessary. The first step is to take the volumetric flow rate of both methane and air and multiply these values by their respective densities (Figure 17). This changes the units to mass flow rate. These numbers are then divided by their respective molecular weights so that the remaining units are in moles per hour. Also, air is multiplied by 0.21 so that only the number of moles per hour of oxygen remains. Next, the methane value is divided by the oxygen value (both in moles per unit time). This number is then divided by the fuel to oxygen stoichiometric ratio of 0.5 (Equation 4 & Equation 5). The subsequent value is the equivalency ratio, Φ (Equation 6).

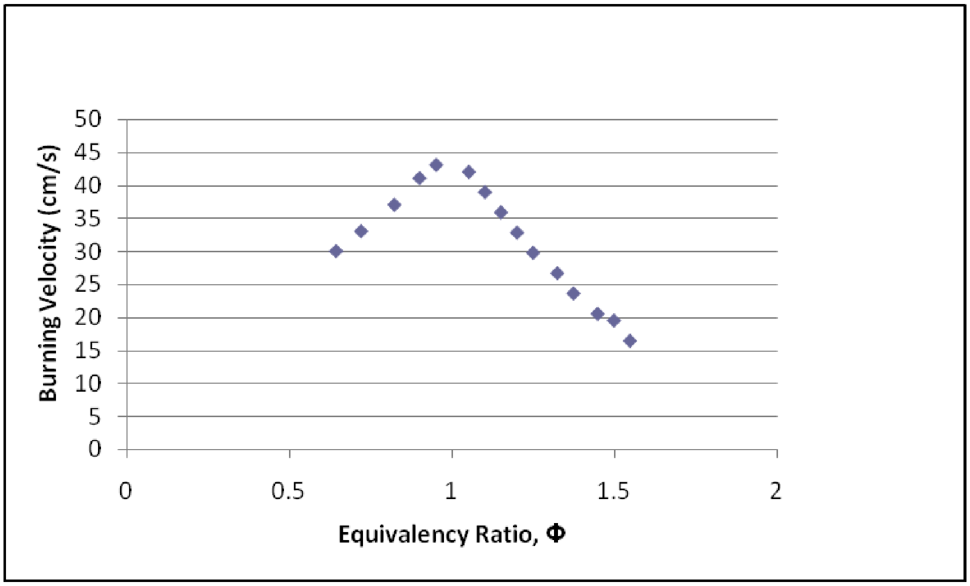
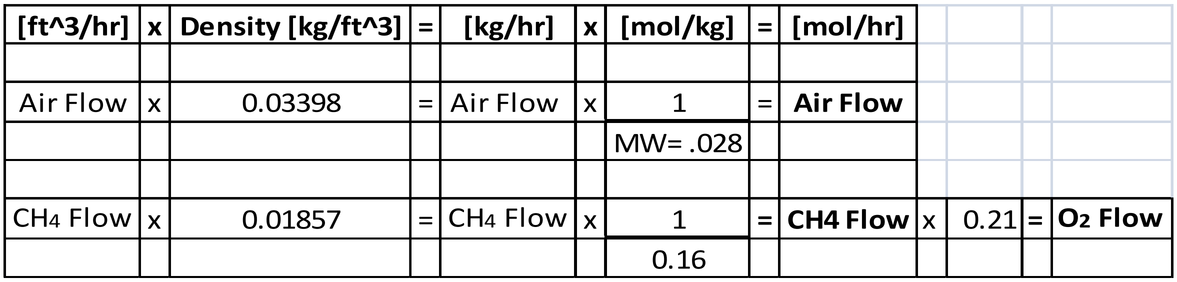


Figure 16: Lewis's bell-shaped correlation between burning velocity and equivalence ratio.



[ft^3/hr]	x	Density [kg/ft^3]	=	[kg/hr]	x	[mol/kg]	=	[mol/hr]				
Air Flow	x	0.03398	=	Air Flow	x	1	=	**Air Flow**				
						MW= .028						
CH4 Flow	x	0.01857	=	CH4 Flow	x	1	=	**CH4 Flow**	x	0.21	=	**O2 Flow**
						0.16						

Figure 17: Converting volumetric flow rate to molecular flow rate.

$$CH_4 + 2O_2 + 2.79N_2 \rightarrow 2H_2O + Co_2 + 2.79N_2$$

Equation 4

$$\text{Fuel/Air Stoichiometric} = 1 \text{ mol } CH_4 / 2 \text{ mol } O_2 = 0.5$$

Equation 5

$$\phi = \frac{\left(\frac{fuel}{air}\right)_{actual}}{\left(\frac{fuel}{air}\right)_{stoich}}$$

Equation 6

5.1.2 Reynolds Number Calculations

A significant characteristic that affects burning velocity is the degree of turbulence in the flame. Ideally, the flame being measured should be laminar. A laminar flame has parallel flow lines, and therefore results in a uniform, steady flame. The Reynolds number (Re) is used to determine the state of the flow for a given apparatus. The equation for the Reynolds number is

$$Re = \frac{vd\rho}{\eta}$$

Equation 3

where

$v = average\ gas\ velocity$

$d = diameterofthe\ tube$

$\rho = densityofthegas\ stream$

$\eta = dynamic\ viscosityofthegas\ stream$

Most importantly, for Re<2300 the flow is laminar, and for $Re > 3200$ Re > 3200 it is typically turbulent. A laminar flame is precise and sharply defined which is necessary to accurately determine burning velocity using the Bunsen burner method.

For this project, the average gas velocity is determined by dividing the volumetric flow by the cross-sectional area of the pipe. The density and viscosity are calculated by determining the percentage of air and percentage of methane present after mixing, and multiplying these percentages by the particular gas properties. The following is an example of this calculation for total viscosity after mixing methane and air.

$$Viscosity = \frac{\frac{ft^3}{hr}Air}{Total\frac{ft^3}{hr}} * ViscosityAir + \frac{\frac{ft^3}{hr}Methane}{Total\frac{ft^3}{hr}} * ViscosityMethane$$

Equation 4

$$Viscosity = \frac{14.00}{16.25} * (1.82 * 10^{-5}) + \frac{2.25}{16.25} * (1.10 * 10^{-5})$$

$$Viscosity = 1.72 * 10^{-5}\ {}^{kg}/_{m-s}$$

In conclusion, for all of the chosen pipe diameters for this project, the Reynolds numbers are between 60 and 760. These are all well below the critical value of Re<2300, which confirms laminar flow. The detailed results for each flame recorded are shown in Figure 18.

Pipe Size (cm)	Test Number	Reynolds Number
0.762	Flame 1	346.8822
0.762	Flame 2	238.5255
0.762	Flame 3	325.5198
0.762	Flame 4	260.4158
0.762	Flame 5	238.8830
0.762	Flame 6	433.6826
0.762	Flame 7	238.3401
1.016	Flame 1	521.3073
1.016	Flame 2	472.1934
1.016	Flame 3	390.4425
1.016	Flame 4	439.4517
1.016	Flame 5	308.9329
1.524	Flame 1	84.77077
1.524	Flame 2	69.64522
1.524	Flame 3	86.70889
1.524	Flame 4	98.06858
1.524	Flame 5	86.80545
0.738x1.27	Trial 1	256.0087
0.738x1.27	Trial 2	276.2050
0.159x1.27	Trial 1	596.2010
0.159x1.27	Trial 2	768.0920
0.318x5.08	Trial 1	128.4080
0.318x2.54	Trial 1	64.16200
0.318x2.54	Trial 1	128.3240

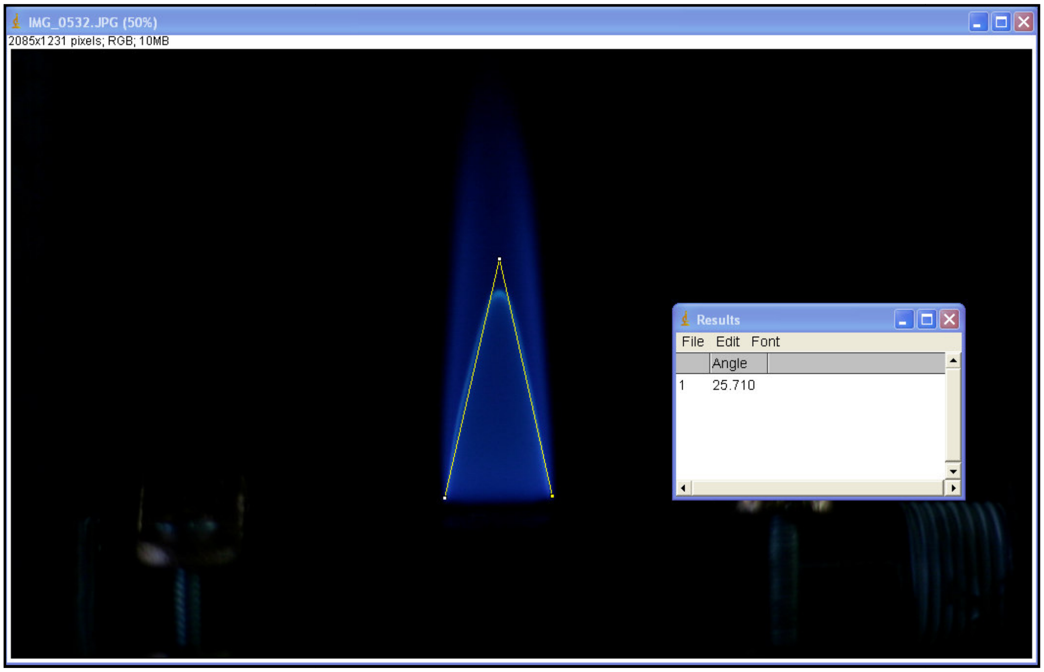
Figure 18: Reynolds Number Results

5.1.3 Measurement Error

For the measurement of burning velocity using the slot burner method there are two experimental parameters which could contribute to possible calculation error. The flow rate of the gas being consumed, *u*, is measured in cubic feet per hour using an appropriate flow meter. The rates are indicated by markings along the side of the flow meter at increments of two cubic feet per hour. Alpha is measured by uploading pictures of the flame onto a computer and using ImageJ software to measure the angle (shown in Figure 19). For each flame three pictures are measured and the angle is averaged. The standard deviation between the measurements is approximately 0.44 degrees.

$$\propto = \frac{MeasuredAngle}{2}$$

Equation 7



	Angle
1	25.710

Figure 19: An example of the measurement of angle alpha using ImageJ freeware.

For the measurement of burning velocity using the Bunsen burner method there are three variables which could contribute to possible calculation errors. The surface area of the conical flame is calculated by measuring the height and the base diameter of the cone. Both of these lengths are measured using a metric ruler with one millimeter increments. The volumetric flow rate for this method is also measured using the aforementioned flow meters.

5.1.4 Unburned Gas Temperature

The temperature of the unburned gases in a pre-mixed flame can have a substantial influence on the burning velocity measurement. Andrews and Bradley (1972) have developed an empirical correlation (Equation 8) to evaluate the affect of flame temperature on stoichiometric Methane-Air flames. Figure 20 shows a graphical representation of this correlation. All experiments in this study are conducted in a room temperature environment. As tests are conducted over the course of several days it is possible that the temperature of the room may have varied as much as 2°C on any given day.

$$v_b\left[\frac{cm}{s}\right] = 10 + 0.000371(T_u[K])^2$$

Equation 8

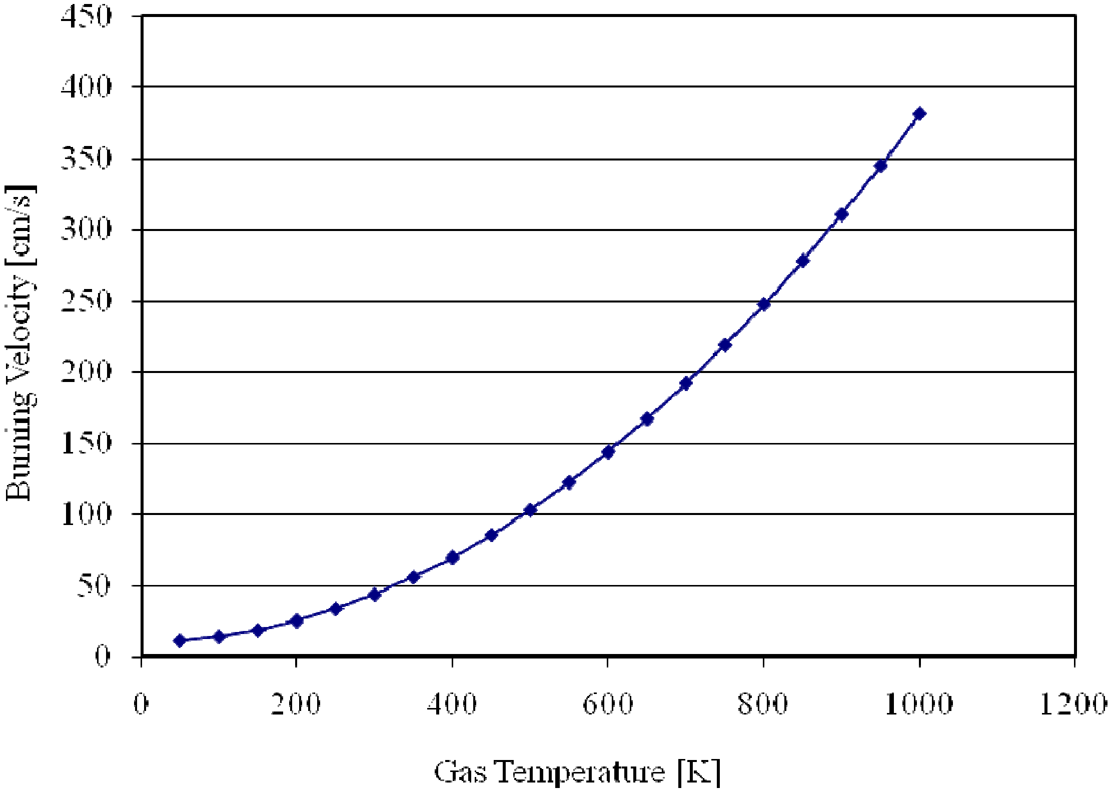


Figure 20: Andrews and Bradley correlation for temperature and burning velocity in Methane-Air stoichiometric flames.

5.1.5 Pressure

Pressure is also an important factor in the measurement of the burning velocity for a pre-mixed flame. For pressures greater than 5atm Andrews and Bradley (1972), found that the burning velocity for Methane-Air stoichiometric mixtures can be approximated using the equation shown below. All experiments conducted in this study took place in an environment of standard atmospheric pressure.

$$v_b\left[\frac{cm}{s}\right] = 43(P[atm])^{-0.5}$$

Equation 9

5.1.6 Flame Stretch

Flame stretch can also cause error in the calculation of burning velocity. In the case of the Bunsen burner technique, the flame stretch is negative oftentimes causing a slight increase in burning velocity.

5.2 Comparison of Bunsen Burner Method and Slot Burner Method

Both the Bunsen burner and slot burner techniques for measuring burning velocity have been proven experimentally and theoretically to be reasonably accurate. Our experimental data shows that the slot burner method over predicts burning velocities when compared with data published in the literature (Vagelopoulos and Egolfopoulos, 1998). The reason for this discrepancy could be due to differences in flame shapes (experiments by Vagelopoulos and Egolfopoulos had a flat flame formed in a stagnation plane). Figure 15 also shows that the value of the burning velocity depends on the diameter of the Bunsen burner tube. A detailed analysis of the effect of tube diameter on burning velocity measurements is part of a future study related to this work. It can be hypothesized that changing the size of the tube affects external air entrainment causing the flame shape to vary. This is also the reason why there is an increased scatter in the s data as the mixture becomes fuel rich (equivalence ratio increases).

6 Conclusions

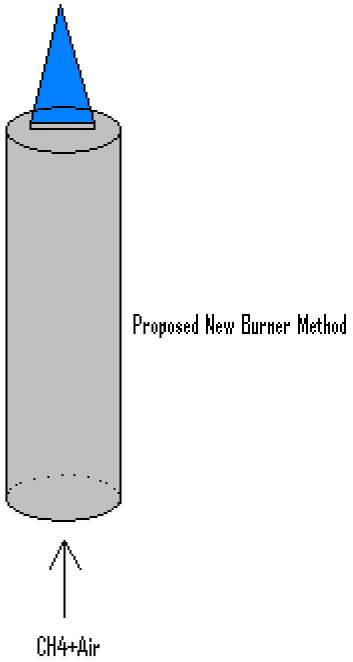
The primary goal of this project is to design two burning apparatuses to evaluate the laminar burning velocities with a variety of flame sizes. The slot burner used three different slot sizes and provided unsatisfactory results when compared to previously published data. The velocities obtained using the slot burners are much higher than previously published data. This could be due to air entrainment from the sides of the flame which cools to flame temperature and affects its burning velocity. The group also experienced problems of turbulence with this set up. The Bunsen burner data is reasonably accurate as shown in Figure 15.

The highest burning velocities occurred when the equivalence ratio is approximately equal to 1 where the fuel and air mixture is equal to stoichiometric conditions. Thus there is complete combustion which in turn maximizes the flame temperature. Flame temperature and burning velocity are directly related, and therefore at Φ=1 the flame should have its highest possible burning velocity.

7 Future Experimentation

The experimental setup for this project had several flaws that are significant sources for the margin of error in the data. Although reasonably accurate, the data varies from previous results found in the literature. For example, burning velocities calculated from a slot burner apparatus are typically slightly lower than those calculated using the Bunsen burner method. This is not shown in our results, and further testing should be done to justify this variation.

Particular focus should be on a redesign of the apparatus for the slot burner. Possible improvements should include a section of greater vertical distance prior to the slot itself to attempt to induce a flow that is more laminar, and generally less twists and turns in the tubing and adapters.



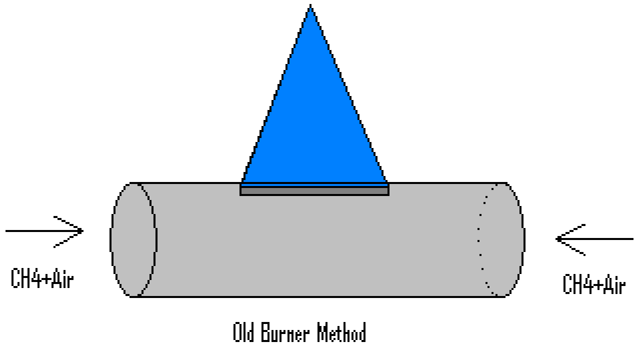


Figure 21: (Above) Actual burner used for testing. (Left) Proposed method for a new burner with flow that is more laminar.

For the Bunsen burner apparatus the most significant improvement would be to add a second tube to the apparatus. The tube would surround the existing burner tube, and it would provide a flow of an inert gas, such as nitrogen. This flow would stop the leakage that occurs in a horizontal direction under atmospheric conditions. This is ideal to provide an exact cone-shaped flame, which will in turn provide a more accurate measurement for surface area and finally burning velocity.

An additional benefit of the inert gas environment will be the flame stability that it will provide. This will allow the data to cover a complete range of equivalency ratios, from lean to rich. Current apparatus designs experience flame blow-out during lean mixtures, causing burning velocities below stoichiometric to be nearly impossible to record.

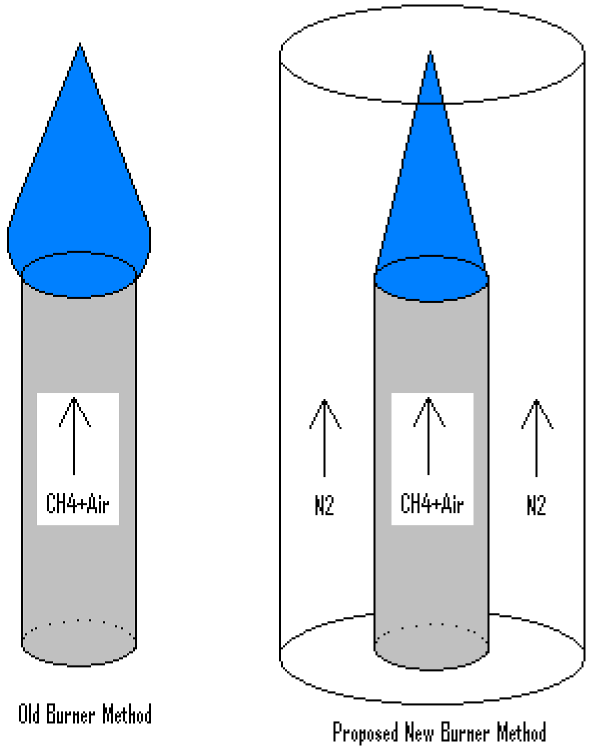


Figure 22: (Left) Current burner design used. (Right) Proposed new burner design, with added inert gas environment to control horizontal fuel leakage.

In addition to these improvements particular focus should be on repeatability. The data collected during this project is comparable with experimental data found in literature, however many more data points are needed to improve accuracy. With a large set of data points, averages could be taken at each equivalence ratio to provide an accurate curve of laminar burning velocity.

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