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Laminar Burning Velocities Of Gas Mixtures

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Dedication

This thesis is dedicated to my family, my Mother and Father and my Brother

LAMINAR BURNING VELOCITIES OF GAS MIXTURES

by

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THESIS

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Abstract

In this study, burning velocities of hydrogen-carbon monoxide (H_2-CO) mixtures, which are primary constituents of syngas fuels, are measured. The effect of different burner systems, H_2 concentration, and different measurement techniques on the burning velocities of H_2-CO mixtures is also discussed. The burning velocities of H_2-CO mixtures increase with the increase in H_2 content in the mixture. When compared with different burner systems using different methods, the burning velocity data almost coincide in the lean condition, but at rich condition the data stray away from each other. The burning velocities of actual syngas compositions (based on different sources of coal) are then measured and analyzed to determine the effects of diluents on the burning velocities of syngas mixtures. As diluents, carbon dioxide (CO_2) plays a dominating role on the burning velocity when compared to nitrogen (N_2). Finally, the burning velocities of H_2-methane (CH_4) mixtures are measured to determine the effect H_2 on the burning velocities of H_2-CH_4 mixtures.

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1.0 Introduction

Demand for clean energy production leads to the rise of new technologies. One such example is the development of Integrated Gas Combined Cycle (IGCC) plants. These plants are capable of combusting both low and high calorific fuels while maintaining high efficiencies and low pollutant emissions. Coal gasification is one of the most efficient and clean ways of producing energy when compared to coal and natural gas power plants. Coal when gasified produces synthesis gas (syngas), which is used as fuel for power generation. Syngas primarily consists of hydrogen (H_2) and carbon monoxide (CO), little amounts of methane (CH_4), carbon dioxide (CO_2), nitrogen (N_2), and other higher hydro carbons [1].

Turbine combustors of advanced power systems have goals to achieve very low pollutants emissions (NO_x < 2-ppm), fuel variability, and fuel flexibility [3]. Future generation gas turbine combustors should tolerate fuel compositions ranging from natural gas to a broad range of syngas without sacrificing operational advantages and low emission characteristics [2]. Understanding the combustion characteristics of syngas will help in designing better combustion chambers and a safer environment.

Flame speed or laminar burning velocity is defined as the speed of unburnt fuel-air in the combustion chamber and is an important property of gaseous air-fuel mixture. The value of flame speed determines the tendency of the flame to flashback or blow off. Measuring flame speed also provides information regarding the exothermicity, reactivity and diffusivity of the air-fuel mixtures.

Most of researchers have restricted their research to limited compositions and equivalence ratios. This study focuses on the determination of flame speed of different compositions of H_2-CO mixtures at wide range of equivalence ratios. Different burner methods and various experimental techniques were employed in determining the flame speed of H_2-CO mixtures. The effects of N_2 and CO_2 on the flame speed of H_2-CO mixtures are also discussed.

1.1 Research Objectives

The increase in demand for energy and imposition of strict regulations on the emission of pollutants triggered the development of higher efficiency gas turbine combustors. The primary objectives of this research are:

1. To develop a series of test matrix to study the effect of H_2 on the laminar burning velocities of syngas fuel;
2. To determine the burner effect on the laminar burning velocities of syngas fuels;
3. To understand the effect of diluents, such as N_2 and CO_2, on the laminar burning velocities; and
4. To find the laminar burning velocities of syngas using different techniques.

1.2 Thesis Organization

Chapter 1 provides an outline of the increased demand for clean energy production that fuelled the rise of new technologies, such as IGCC plants. These plants are capable of combusting both low and high calorific fuels while maintaining high efficiencies and low pollutant emissions. Moreover this chapter deals with low calorific fuels, namely syngas fuels, which were derived from coal, biomass, sewage, etc. Further, this chapter discusses the objectives and scope of study.

Chapter 2 provides a summary of the technical background on hypothetical basis by which conclusions of the experimental data will be drawn.

Chapter 3 provides an outline of the detailed methodology involved in determining the laminar burning velocities of syngas fuels using different experimental techniques and different burner systems. The instrument used to carry out the research includes flashback burner, nozzle burner, Intensified CCD camera, optical instrumentation and Digital SLR camera.

Chapter 4 presents the comparison and justification of the results for laminar burning velocity profiles of different syngas fuels with respect to varying fuel compositions.

Chapter 5 concludes the results and provides the scope for further research.

1.3 Practical Relevance

Syngas is considered the most reliable alternate fuel for natural gas, since there has been depletion of natural gas resources around the world. Therefore a need to understand the combustion characteristics of syngas fuels has become an important aspect of research for the gas turbine combustor in ultra lean mixture compositions. Gas turbine combustor technology can lead to lower pollutants and a low cost of production with high efficiency. This research will provide the laminar burning velocities of different compositions of syngas fuels over a wide range of equivalence ratio that will eventually lead to a better design of gas turbine combustor.

1.4 Combustion and Propulsion Research Laboratory

The Combustion and Propulsion Research Laboratory (CPRL) is located in Mechanical and Industrial Engineering Department at The University of Texas at El Paso. The Laboratory provides computational and experimental research related to the field of combustion, fluid mechanics and propulsion with a wide range of software and equipment. The primary focus of the research is in the development of micro-propulsion and micro-combustion technologies. CPRL also provides a wide range of facilities, such as flat flame burner, counter flow burner and flashback burner systems. These systems are used to determine the combustion characteristics (i.e. flame speed, flashback propensity and flame extinction limits). Apart from these, the laboratory also provides a collection of optical instrumentation; high speed Cameras; intensified CCD camera; laser based measurement techniques, such as Particle Image Velocimetry (PIV); and a vacuum chamber to replicate the space atmosphere, which completes the necessary equipment for propulsion systems development.

2.0 Literature Review

2.1 Syngas

Syngas gas is a mixture of varying amounts of H_2 and CO. Moreover it has less than half the energy density of natural gas. Table 2-1 shows different compositions of syngas produced by gasification of coal and wood.

Table 2.1 Composition of Syngas Produced by Gasification of Coal and Wood

Gasification	Type of coal	CO (%)	H_2 (%)	CH_4 (%)	N_2 (%)	CO (%)	Calorific Value (MJ/m^3)
COAL	Brown coal	16	25	5	40	14	6.28
	Bituminous	17.2	24.8	4.1	42.7	11	6.13
	Lignite	22	12	1	55	10	4.13
	Coke	29	15	3	50	3	6.08
Wood		21	21	1.83	43	12	7.07

Syngas is either used as a fuel source or intermediates for producing ammonia or methanol. In the Fisher-Tropsch process, syngas is used as an intermediate for production of synthetic petroleum, which can be either used as fuel or lubricant.

2.2 Laminar Burning Velocities of Mixtures

Flame speed or laminar burning velocity is defined as the speed of unburnt fuel-air in the combustion chamber and is an important property of gaseous air-fuel mixture. The value of flame speed determines the tendency of the flame to flashback or blow off. From the basic point of view, information regarding the laminar burning velocity of fuel mixtures is the key factor in understanding the fundamental combustion mechanisms.

The limited resource of fossil fuels forced researchers to explore alternative fuels and find a way for fuel replacement and emission reduction. CH_4 is considered the best alternative fuel because of its high octane number and less pollutant emission. Several experiments have been conducted to identify the combustion characteristics of CH_4. Agnew and Graiff [4] have studied the laminar burning velocities of CH_4-air and propane-air mixtures at different pressures ranging from 0.5 to 20 atmospheres and concluded that as the pressure increases the flame speed of the air-fuel mixture decreases. J. P. Botha and D. B. Spalding [5] investigated laminar flame speed of propane-air mixtures using a flat flame burner by the heat extraction method. The major limitation in using CH_4 as fuel is: elevated ignition temperature and poor lean burning ability, which leads to incomplete combustion. Blending H_2 with CH_4 is the most efficient way to improve the combustion since H_2 has high flame speed, low ignition temperature and high reactivity. Blending H_2 with CH_4 not only increases the burning velocity but reduces the ignition temperature. The presence of H_2 in the fuel mixture alters diffusivity, flame reaction to stretch kinetics, and transport properties of the fuel. At this time, there is no experimental relation available to calculate the laminar flame speeds of fuel blends, although it has been predicted that laminar burning velocities of blended fuels fall in between the primary fuels.

Le Chatelier's rule is commonly used to approximate the flammability limit of fuel blends. It uses straightforward method to verify the flammability limits of fuel blends by limiting the mole fractions Xi of each species "i". The lower flammability limit (LFL) of the gas fuel is given by

$$\mathrm{LFL} = \frac{100}{\frac{M1}{LF1}+\frac{M2}{LF2}+\frac{M3}{LF3}+\cdots}$$

where LFL is the lower flammability of the blended fuel $M_1,M_2,M_3,\ldots$. are the volumetric percentage of each fuel in the fuel gas mixture and ($M_1+M_2+M_3,\ldots=100$) and LF1 +LF2 LF3+… are the lower flammability limit of individual fuels. The flammability

limit of a fuel mainly depends on complex non-linear interactions of burning velocity, energy release and external loss mechanism. [6]

2.3 Laminar Burning Velocities of H_2-CO Mixtures

Until recently many researchers have shown interest in determining the flame characteristics of CO and H_2. They have carried out numerous laboratory experiments and field observations to illuminate the darkness of this field. Their findings and suggestions are reviewed in this section. Yumlu [7] measured adiabatic burning velocities of various H_2-CO mixtures for an equivalence ratio of 0.6 using a flat flame burner with direct cooling. Laminar flame speed and extinction strain rates of H_2-CO mixtures using the counter flow were investigated by Vagelopoulos and Egolfopoulos [8] using the twin-flame technique in conjunction with laser Doppler velocimetry. Natarajan [9] not only investigated the effect of diluent addition but also determined reactant preheating on laminar flame speeds of syngas mixtures by the cone surface method based using an intensified CCD camera. McLean et al. [10] and Brown et al. [11] studied flame speeds that were acquired by the isobaric expanding spherical flame method. Flame stretch and laminar burning velocity effects were investigated by Hassan et al. [12] for pressures between 0.5-4 atmospheres. Scholte and Vaags [13] studied the laminar flame speed of rich syngas mixtures using nozzle burner using schlieren technique. N. Bouvet1 et al. [14] investigated laminar flame speeds of undiluted syngas mixtures. A wide range of lean syngas mixture compositions have been studied using straight cylindrical burner apparatus Flame speeds near extinction have been studied very recently by Love, Subramanya, and Choudhuri [15] on a water-cooled N_2-stabilized flat flame and a twin flame counter flow burner respectively. According to the findings listed above, the researchers have limited their research to limited compositions of syngas fuels. In addition to that no one really determined the effect of burner, diluent and various experimental techniques on laminar burning velocities. Due to the limited literature available on this subject, this study was conducted. The primary objectives of the experiment is to

a) Determine laminar burning velocities for a wide range of syngas compositions experimentally;

b) Study the effects of diluents on laminar burning velocities; and

c) Determine laminar burning velocities for various coal derived syngas compositions.

2.4 Methods to Determine the Laminar Burning Velocity

Various experimental and computational methods have been employed to determine the laminar burning velocity. The experimental methods to determine the laminar flame speed is provided in the following sections.

2.4.1 Burner Method

In this method, the premixed flame is sent through a cylindrical tube that is long enough to ensure the streamline flow at the mouth of the burner. When the flame is stabilized at the burner mouth, the burner cone is recorded and measured using various techniques. Shaped nozzles were used instead of long tubes in order make the flow laminar.

The burning velocity obtained in this method is not accurate since the burning velocity measured at different points on the cone is different. This is mainly because of the energy loss near the walls of the burner, which leads to a lower temperature when compared to the higher temperatures on the top of the cone. The advantages of this technique are that it is very unambiguous and simple to construct; therefore, it was chosen to measure the laminar flame speed of syngas in the study.

2.4.2 Flat Flame Burner Method

This method provides the close approximation to one dimensional flat flame. It was initially developed by prowling and was only applicable for mixtures having the flame speeds less than 15 cm/sec or less. Botha and Spadling [5] extended the previous work by cooling the porous plug to achieve greater flame speeds. The flame is stabilized over a wide range of air-fuel mixtures, and adiabatic flame speeds are calculated by extrapolation.

2.4.3 Soap Bubble Method

In this method, the premixed fuel mixture is contained in the spherical bubble with a spark gap at the center. By considering the expansion of the gas is not resisted by the soap bubble, ignition of the gaseous mixture results in the spread of the spherical flame front at constant pressure. The results are recorded with the high speed camera. The flame propagation velocity in the soap bubble at constant pressure is called as Spatial velocity denoted by U_r. The rate at which the amount of unburnt gas is consumed is equal to the spatial velocity.

$$S_L*A*\rho_u = U_r*A*\rho_b$$

From the above relation, the laminar burning velocity, which is equal to density ratio times the spatial velocity, can be calculated. One of the greatest drawbacks in this method is due to the large uncertainty in calculating the density ratio as it is dependent on the initial and final temperatures. Moreover this method is only applicable for fast flames and cannot work for dry mixtures.

2.4.4 Closed Spherical Bomb Method

This method is quite similar to the soap bubble method except the combustible mixture is kept in a thick spherical vessel, keeping the volume of the mixture constant. When the mixture is ignited the flame propagates from the center to the wall, where the unburnt gas mixtures tend to expand, since the volume of the vessel is constrained. This results in the increase of both pressure and temperature. The laminar burning velocity is given by the equation:

$$S_L = \left[1- \frac{R^3 - r^3}{3p\,r^2}\frac{dp}{dr}\right]\frac{dr}{dt}$$

where R is the sphere radius and r is the radius of the spherical flame front at any moment. This method can be extensively used only when the pressure and temperature changes are measured accurately with the position of the flame front. Brown, M. J.et al. [10] determined Markstein lengths of CO/H_2/air flames, using expanding spherical flames.

2.4.5 Cylindrical Tube Method

In this method, the combustible mixture is contained in the long cylindrical tube opened at one end; then the mixture is ignited at the open end. The flame propagates inside the cylindrical tube following the unburnt gas. The laminar flame speed is calculated from flame propagation (S) and the area of the flame front. Due to the buoyancy effects, the flame front is no longer geometric to the area of the cylinder, which makes it difficult to measure flame area. If the flame front presumes the shape of a hemisphere, the flame speed is given by the equation:

$$S_L = \frac{S\pi R\hat{}2}{A}$$

Because of the pressure wave developed in the tube due to the flame propagation, the unburnt gas attains some velocity and tries to move away from the flame front. Therefore, a small hole is drilled at the end of the tube and the pumped out gas is measured using the soap solution. The rate of growth of soap bubble determines the unburnt gas velocity (V).The laminar burning velocity is calculated by:

$$S_L = \frac{(S-V)\pi R\hat{}2}{A}$$

The errors dude to buoyancy cannot be completely eliminated but can be controlled by turning the tube vertically.

3.0 Experimental Facilities

All the gases (H_2, CO, CO_2, N_2, and Air) are stored separately in gas cylinders under 1600 psi pressure. The purity of these gases is 99%. Different flow meters are used in this experiment to maintain volumetric flow rate ranges from 0 to 10 LPM. Manual precision metering valves in conjunction with low-torque-quarter-turn plug valves are used to control and meter fuel and air flow rates. Prior to each experiment mass flow meters are calibrated using a laser based mass flow meter calibrator.

3.1 Burner System

3.1.1 Reduced Burner

The schematic of reduced burner system shown in Figure 3.2 has four primary components:

a) Mixing manifold;

b) Flow excitation hub (base, speaker and speaker housing);

c) Flow conditioner (honeycomb, honeycomb housing and wire mesh); and

d) Burner tube assembly (converging nozzle, glass tubes, glass tube adapters, adjustable supports, and c-clamps).

The converging nozzle section seamlessly merges with the adapters to accommodate glass tubes of different diameters (10.6 mm, 7 mm and 6 mm). The fuel and air enter into the manifold through four alternate injection holes. The fuel-air mixture then passes through the flow conditioning section to eliminate injection induced flow irregularities and to ensure laminar flow through the burner tube.

Figure 3.1 Reduced Burners

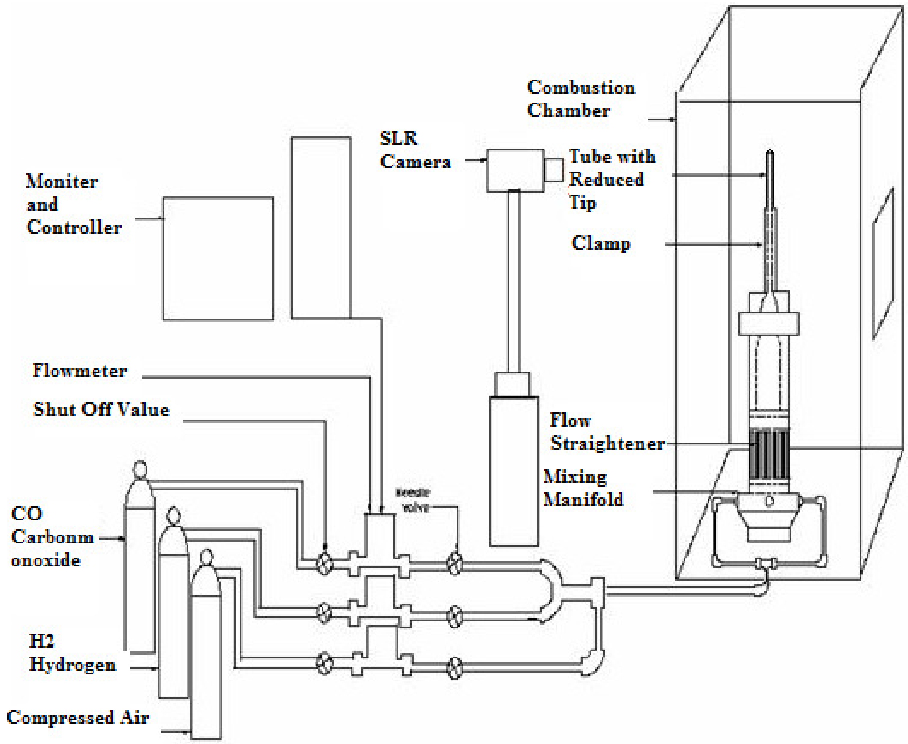


Figure 3.2 Experimental Setup: Reduced Burner

The burner is located in a vertical combustion chamber that has a window opening over one side for the ignition system. The top of the combustion chamber was open to atmosphere through an exhaust duct.

3.1.2 Flat Flame Burner

The burner system consists of a 6-cm diameter sintered stainless steel porous disk. N_2 flowing through a concentric 0.5-cm wide porous metal strip shields the flame from the surroundings. The burner cooling system extends throughout the porous disk system to vary the heat loss rate from the burner. The amount of heat extracted is determined by the thermocouples, which were placed at the inlet and exit of cooling circuit. The temperature readings were acquired from the data acquisition device. The cross sectional view of flat flame burner is shown in Figure 3.4

Figure 3.3 Flat Flame Burner

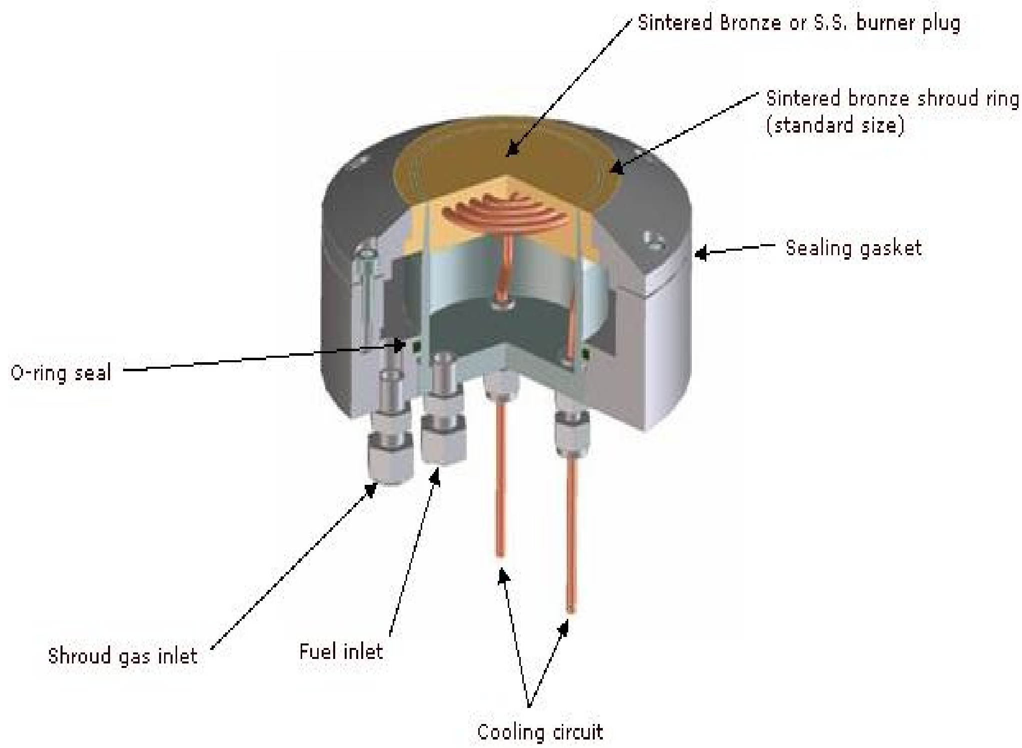


Figure 3.4 Cross Sectional View of Flat Flame Burner

3.1.3 Nozzle Burner

The nozzle burner assembly consists of four major components:

a) Manifold,

b) Stem,

c) Connecter, and

d) Burner nozzle.

The burner nozzle was machined to fit a fifth degree polynomial curve to provide a top hat exit flow velocity profile. The air-fuel mixture is fed to the burner manifold by four symmetric inlets. To avoid stratification effects, homogeneous mixing of air and fuel is ensured by mixing the streams far upstream from the burner. The fuel air mixture is then fed through a series of honeycomb matrices that acts as flow straightner. The measured velocity at the burner exit shows the top hat velocity with minimum wall effects and turbulent fluctuations. The nozzle burner is shown in Figure 3.5 and its cross-sectional view is shown in Figure 3.6.

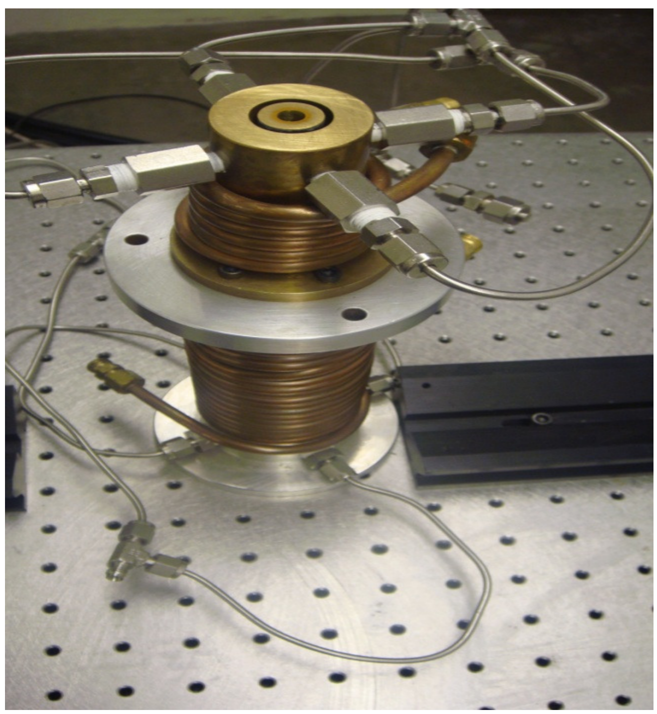


Figure 3.5 Nozzle Burner

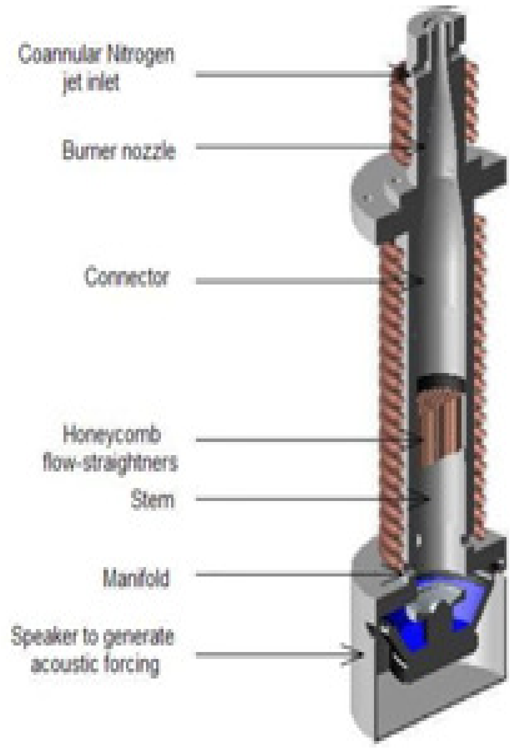


Figure 3.6 Cross Sectional View of the Burner

3.2 Measurement Techniques

3.2.1 Schlieren Method

In this approach, the light is emitted from Dolan-Jenner (900 W) (Figure 3.7) through a fiber optic wire and then passes through the slit of 1000 microns. The diverging light emanating from the slit is assumed as a point source for the first achromatic lens. The burner tip is placed in the middle of the test region defined by the collimated rays that are formed between two achromatic lenses. A knife edge is placed on the focal point of the second lens that blocks the deflected light to reach the focusing screen of the camera. The resulting images called Schlieren images are captured on the CCD camera (Figure 3.10). The camera records the video onto the onboard memory at the desired frame rate. The conceptual Schlieren system is shown in the Figure 3.8.

Figure 3.7 Dolan-Jenner 900 W Light Source

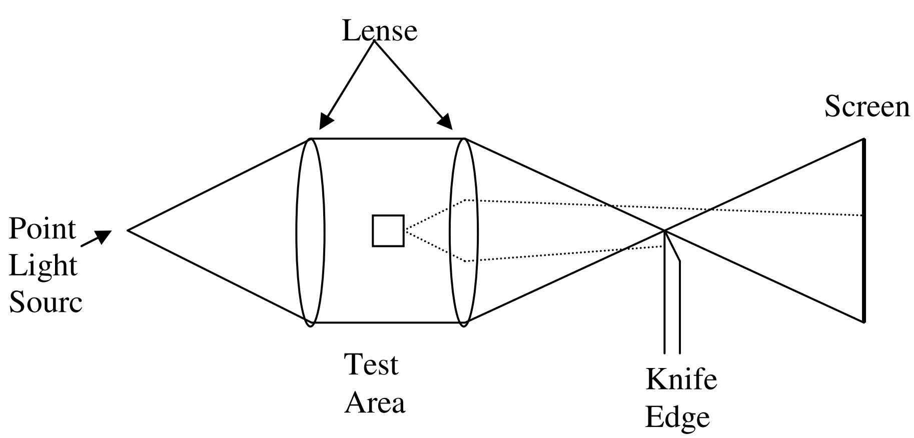


Figure 3.8: The Conceptual Schlieren System

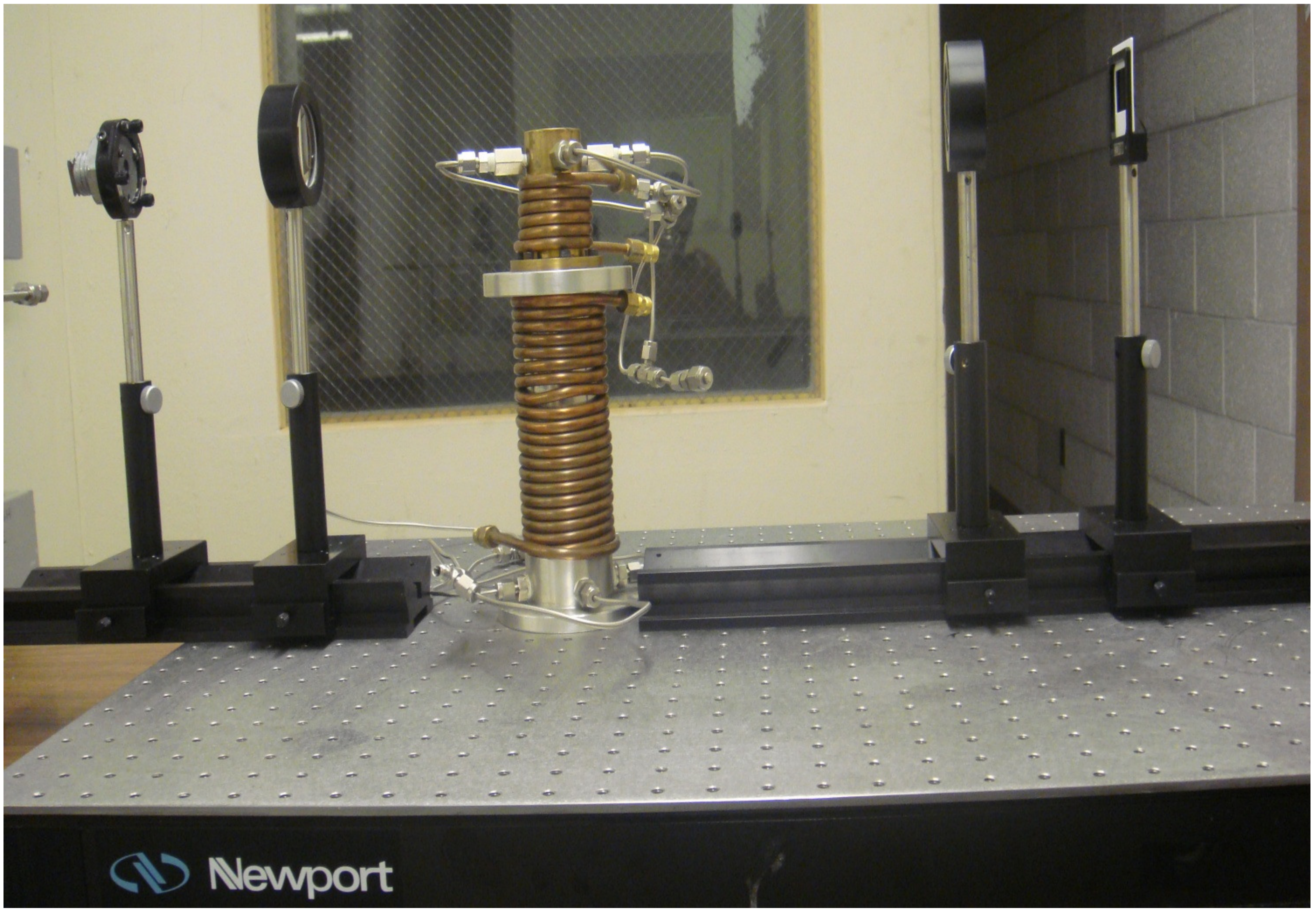
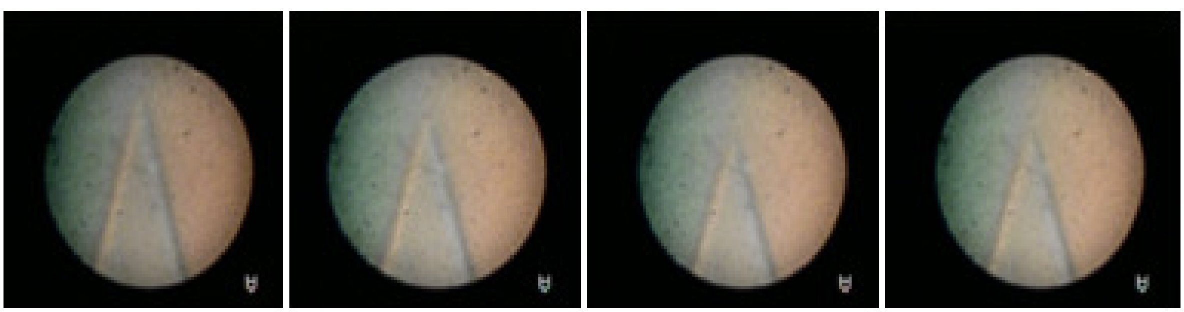


Figure 3.9 Experimental Setup for Schlieren Imaging System



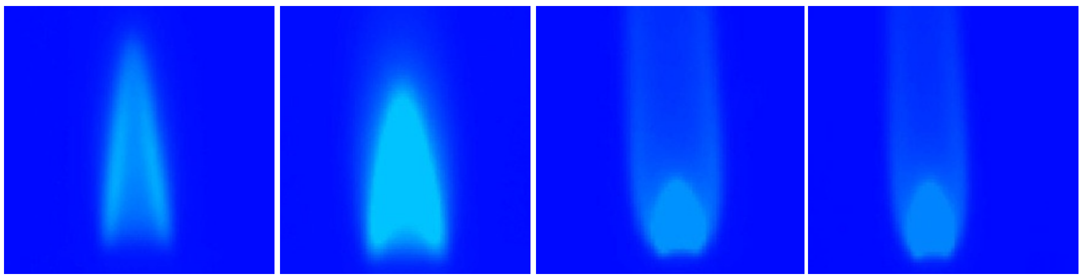
a) φ=.7 b) φ=.8 c)φ=1 d)φ=1.4

Figure 3.10 Flames using Schlieren Technique

3.2.2 Intensifier Method

Digital images of the flame are taken with a 12-bit intensified CCD (2048 x 2048 pixels). The

built in first image intensifier is available with a multialkali photocathode having a wide range of spectral response range from ultra-violet (UV) through near infrared, and hence capable of identifying the OH* chemiluminescence from the flame region zone. The ICCD system operates with a minimum gate time of 10 nanoseconds and a maximum gate repetition frequency up to 200 KHZ and also allows multi-exposure. The Schematic diagram of the experimental set up is shown in Figure 3.12, and the images taken by the intensifier are shown in Figure 3.11.



Φ=.7 Φ=.8 Φ=1 Φ=1.4

Figure 3.11 Flames using Intensifier Camera

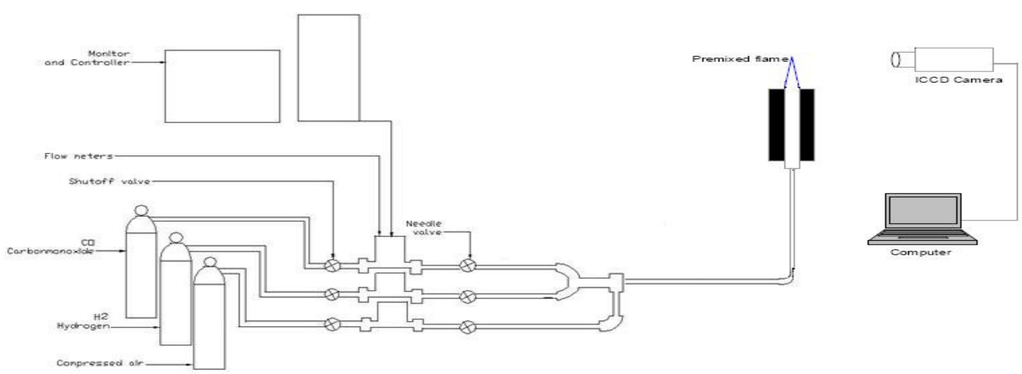
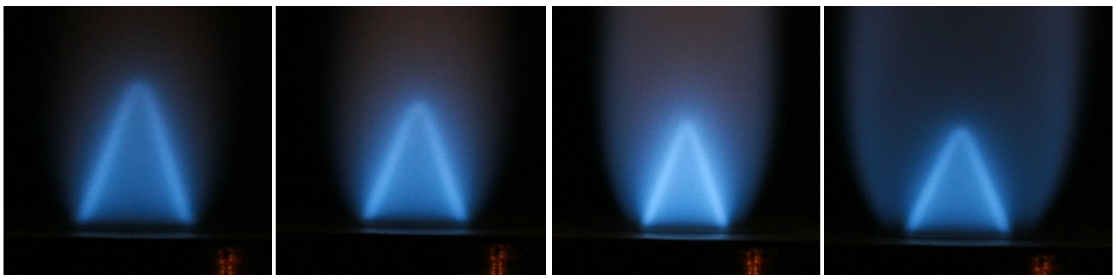


Figure 3.12 Schematic Representation of Intensifier Method

3.2.3 Direct Imaging Method

In this method, the digital images of the flame are captured by 12-bit A/D DSLR camera

(3504 x 2336 pixels) with a focal length of 100 mm, f/2.8 camera lens and with minimum aperture of f/32. Images of flame at equivalence ratios are shown in Figure 7. Experimental uncertainties (bias + random errors) of present measurements are less than ±0.5% of the mean value. All H_2-CO mixture compositions reported in this article are volumetric percent.



Φ=.7 Φ=.8 Φ=1 Φ=1.4

Figure 3.13 Flames using Direct Imaging Technique

3.3 Flow Measurement Devices and Data Acquisition

3.3.1 Flow Meter

Digital mass flow meters (Omega FMA 1700/1800 series in Figure 3.14) were used to measure the mass flow rate of air and fuel. The mass flow meters are designed to withstand temperatures ranging from 0° C to 50° C, pressures up to 500 psig and relative humidity of 70%. The mass flow meters used in the present study varied in full scale from 0-200 mL/in, 0-2L/min, 0-5L/min, and 0-10L/min. For all cases the accuracy is ±1.5% of full scale. The mass flow meter is shown in Figure 3.14. These flow meters are calibrated by Dry Cal Meter Calibrates as shown in Figure 3.15.

Figure 3.14 Digital Mass Flow Meter

Figure 3.15 Dry Cal Calibrator

3.3.2 Metering and Shutoff Valves

Precision metering values (SS-SS4VH in Figure 3.16) were used to regulate the air and fuel mixtures. The shutoff values (SS-4P4T4 in Figure 3.17) were used to shut off the fuel flow from the pressurized gas cylinders.

Figure 3.16 Swagelok SS-SS4VH Metering Value 1

Figure 3.17 Swagelok SS-4P4T4 Shutoff Value 1

3.3.3 Data Acquisition

For temperature measurement a National Instruments Lab View data acquisition system was constructed to attain signals from the individual sources. The input module is shown in Figure 3.18,

Figure 3.18 NI USB 9263

The NI USB 9263 is a four channel, 16 bit analog voltage output module and ranges from -10 volts to +10 volts. Two s-type thermocouples are connected to the two channels by means of long connecting wires. The s-type thermocouple is generally comprises of platinum and platinum-10% rhenium (Figure 3.19).

Figure 3.19 S-type Thermocouple

The USB data acquisition is capable of recording data at 12 samples per second. For this experimental purpose it is more than sufficient to get the temperature readings. The virtual instrument (.vi) designed for this purpose is shown in Figure 3.20; the related block diagram is shown in Figure 3.21.

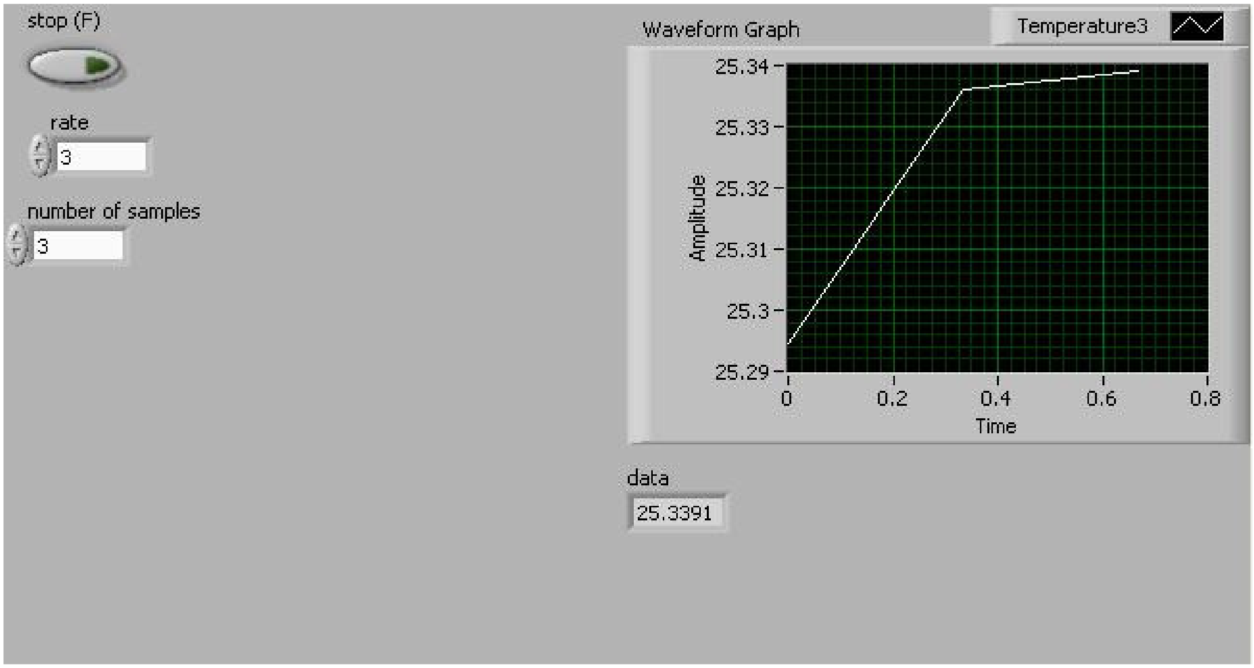


Figure 3.20 Front Panel for Data Acquisition

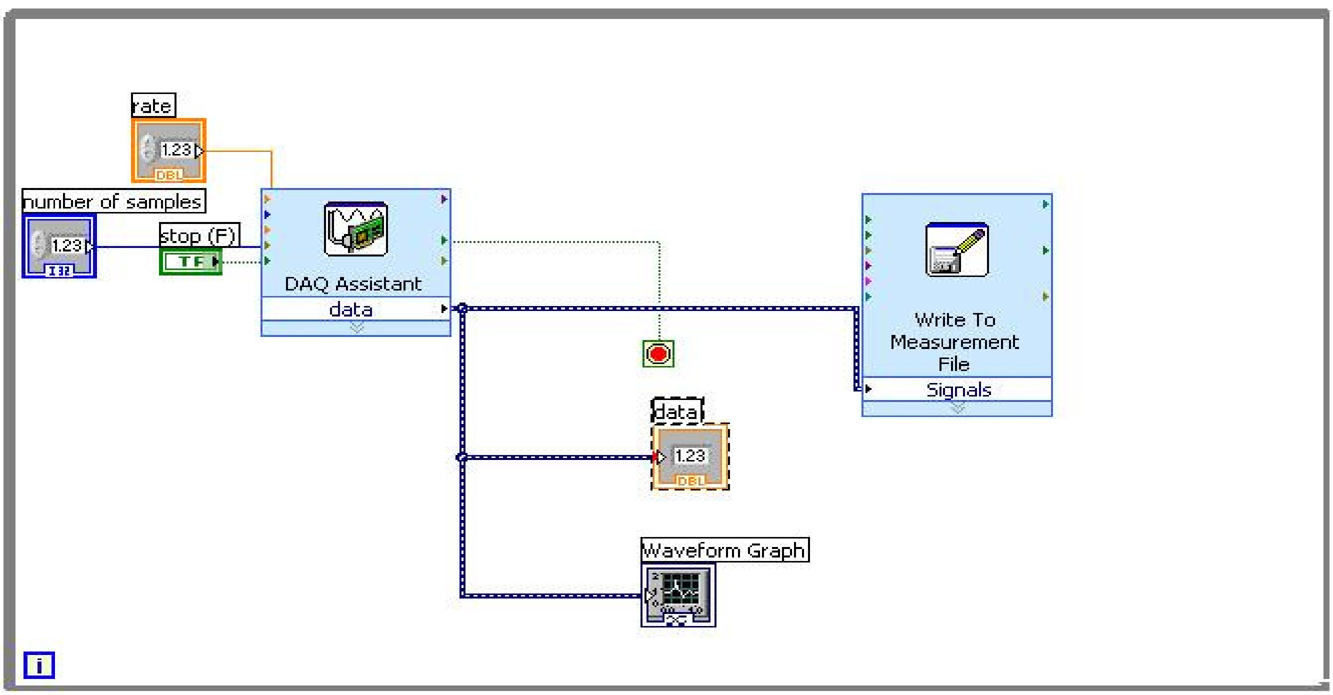


Figure 3.21 Block Diagram for Data Acquisition

4.0 Results and Discussion

4.1 H_2-CO Mixtures

The premixed fuel is comprised of H_2-CO. The laminar burning velocity of air-fuel mixtures was determined at wide range of equivalence ratios. The variability of percentage employed in H_2-CO mixtures was 10%-90%, 15%-85%, 20%-80%, 25%-75%, and 30%-70%. These combinations are then compared to evaluate the laminar burning velocity with increase in H_2 content.

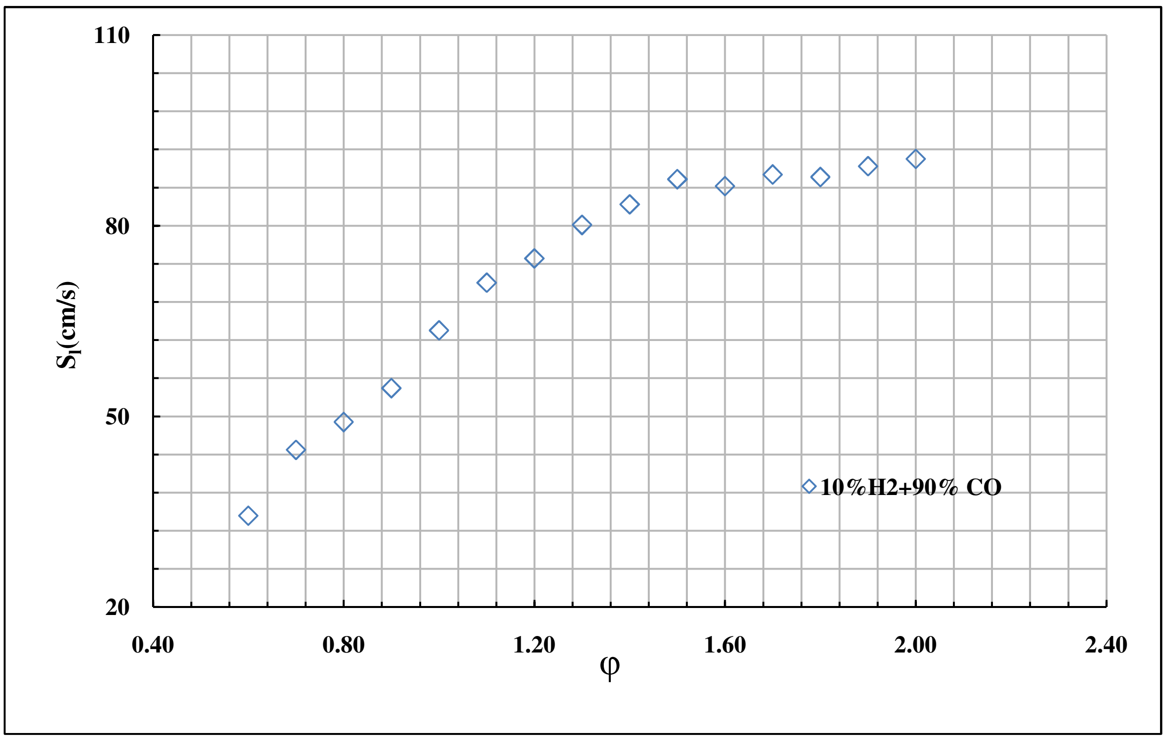


Figure 4.1 Laminar Burning Velocities 10% H_2- 90% CO

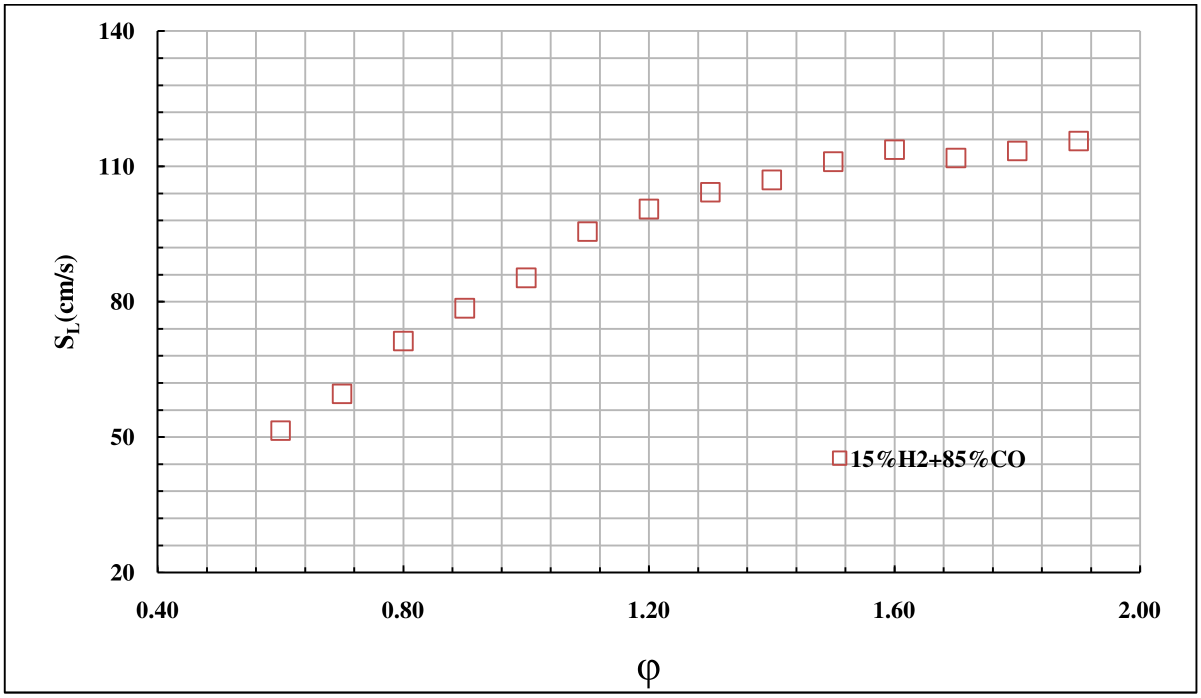


Figure 4.2 Laminar Burning Velocities for 15% H_2 - 85% CO

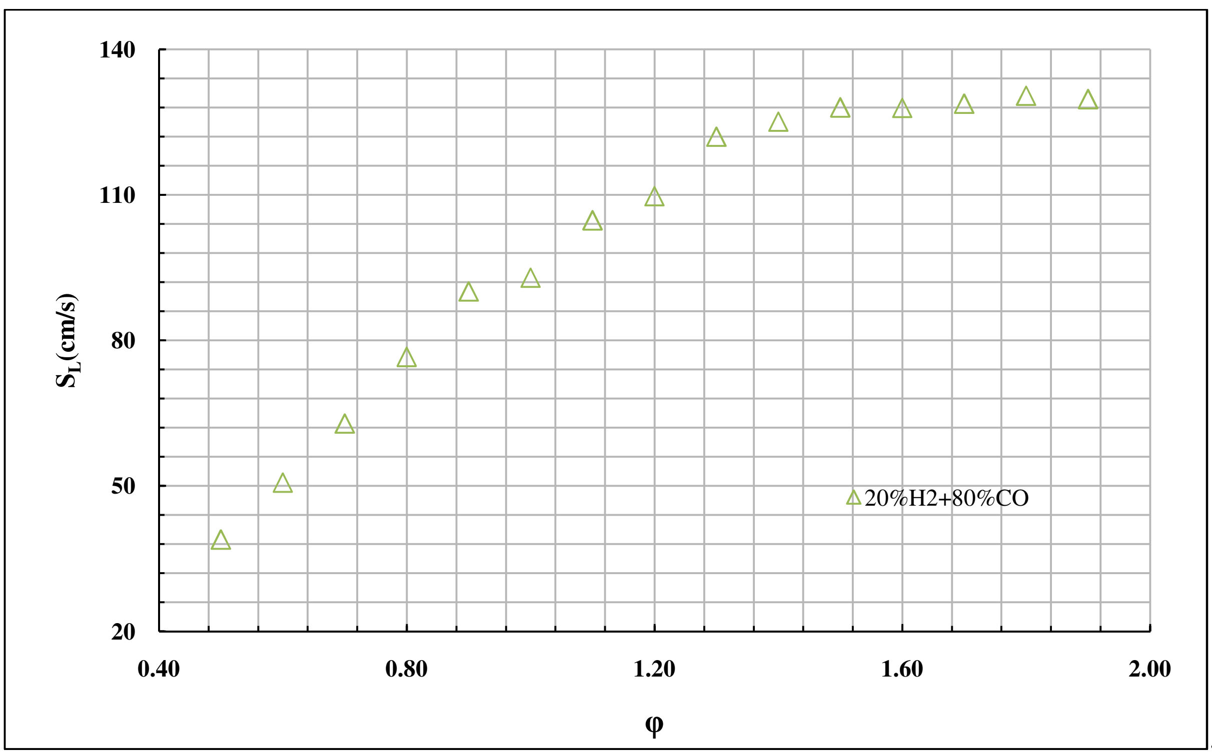


Figure 4.3 Laminar Burning Velocities for 20% H_2 - 80% CO

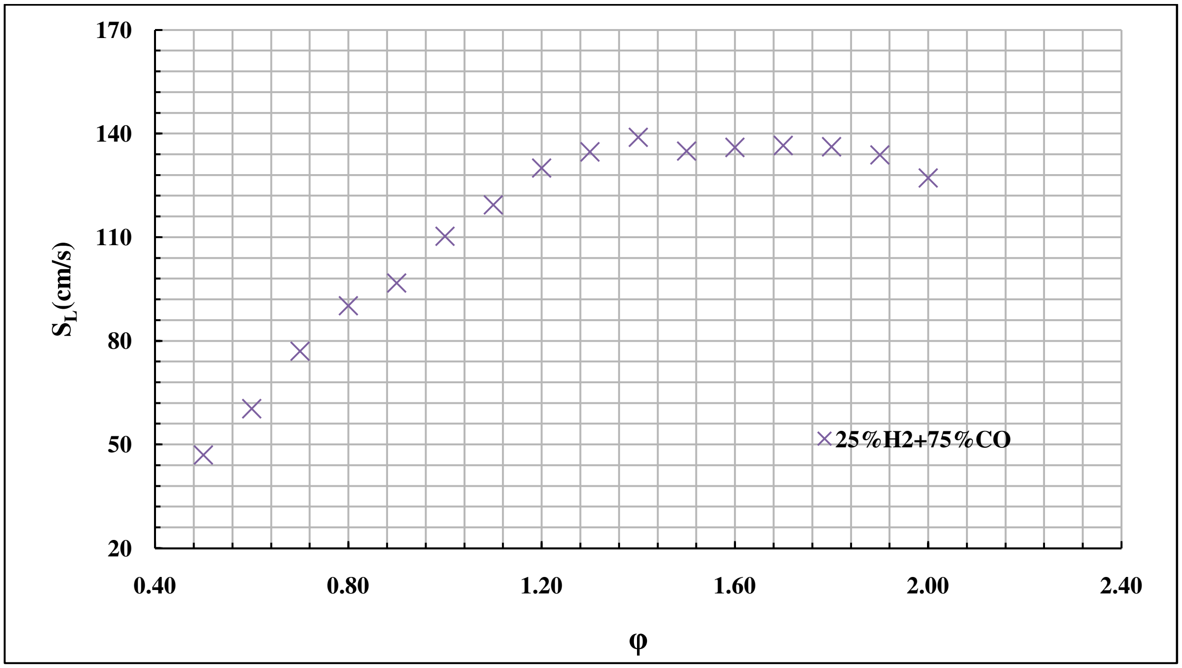


Figure 4.4 Laminar Burning Velocities for 25% H_2 - 75% CO

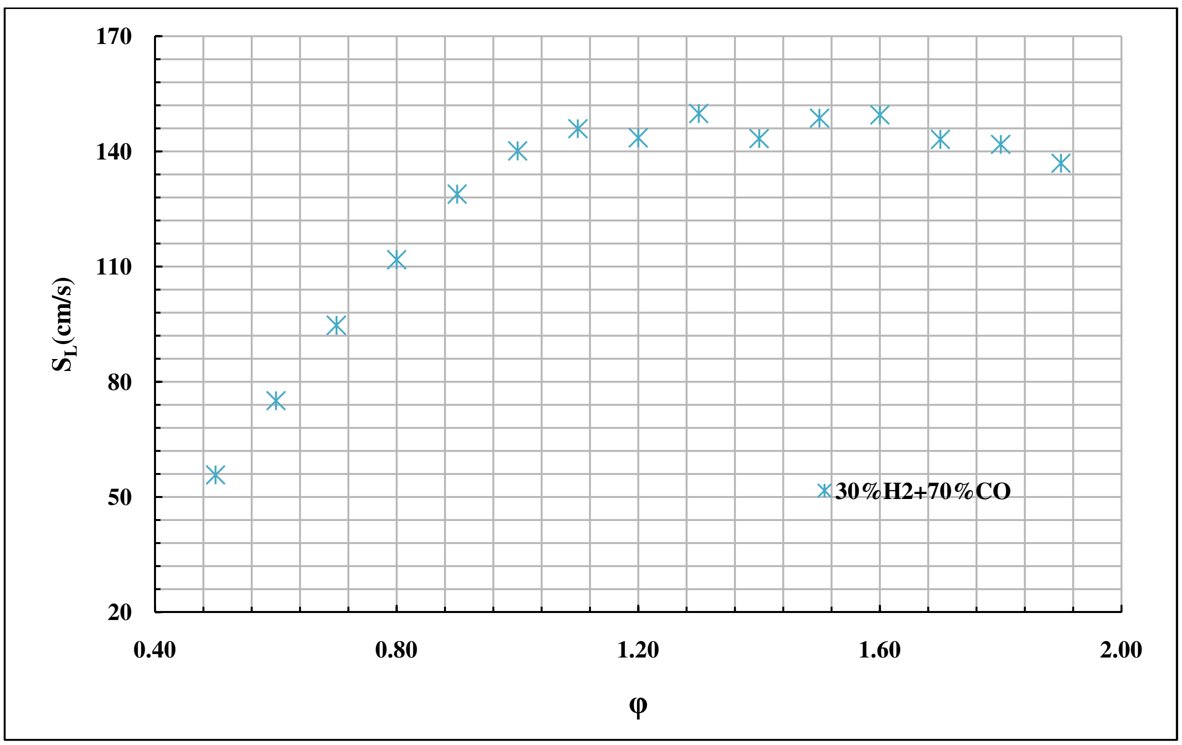


Figure 4.5 Laminar Burning Velocities for 30% H_2 - 70% CO

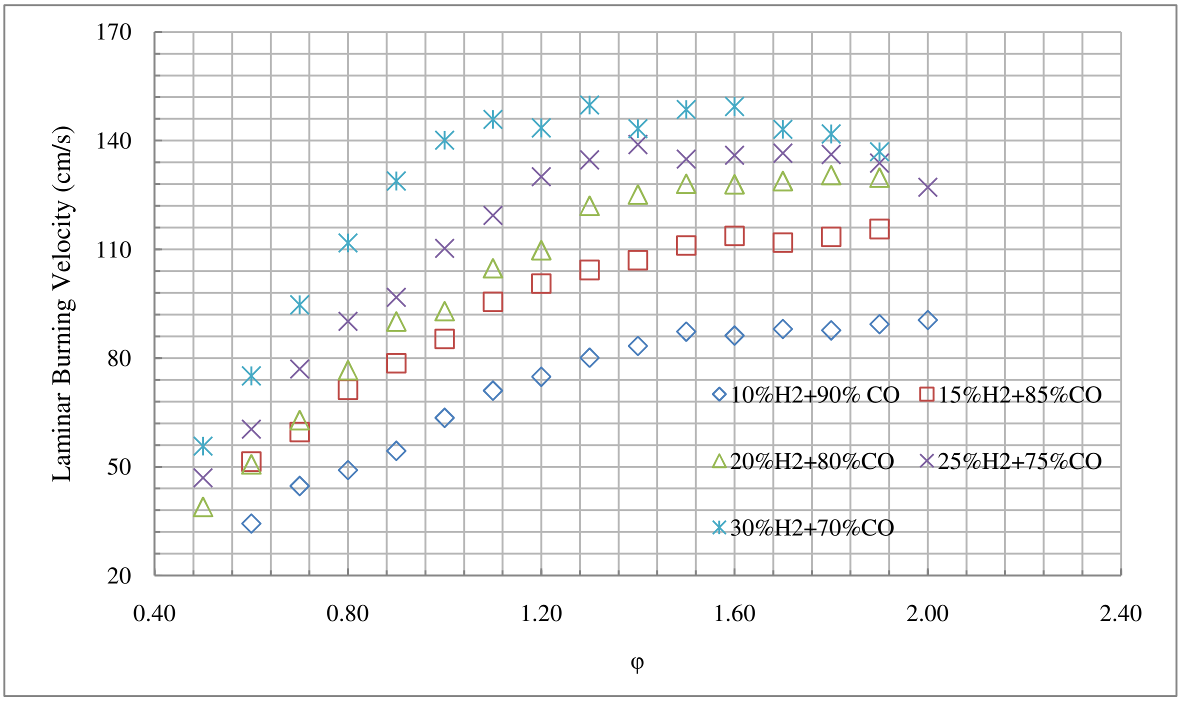


Figure 4.6 Comparison of Burning Velocities of Syngas at Different Mixture Compositions

Figures 4.1 through 4.5 show the laminar burning velocities of all compositions of % CO - % H_2 with respect to the equivalence ratio. Figure 4.5 shows burning velocities of H_2-CO mixtures at different H_2 concentrations and mixture equivalence ratios (%F). As expected, burning velocity increases with the increase of H_2 contents in the mixture. The effect of H_2 addition is especially significant at lean conditions. The presence of H_2 in fuel mixtures creates the necessary branched chain reactions to accelerate the flame propagations. The H_2 in the mixtures supplies the necessary active radicals and atoms, such as OH_2 O and H_2, and their diffusion rates into the unburned gas determines the magnitude of flame burning velocity. However, it is interesting to note that the maximum burning velocity of H_2-CO mixtures shifted back to lean condition with the increase of H_2 concentration in mixtures. The stoichiometric of 100% CO is at equivalence ratio 2 [13]. As H_2 percentage increases in the mixtures the stoichiometric condition shifted back because H_2 has higher thermal diffusivity and higher mass diffusivity. The rapid reaction kinetics also compares to the relatively slow CO=>CO_2 step that is the termination step in 100% CO as well as hydrocarbon combustion. In order to get burning velocities at

lean condition (phi < .5) flat flame burner introduced. Table 4.6 shows the burning velocities at lean condition (phi < .5) using flat flame burner system.

Table 4.6 Burning Velocities at Lean Condition using Flat Flame Burner

Composition	Phi	Burning velocity(cm/s)
5% H_2+95%CO	0.45	10.4
	0.48	11.1
15%%H_2+85%CO	0.39	9.2
	0.45	10.66
	0.48	12.13
20%H_2+80%CO	0.39	13
	0.45	13.88
	0.48	16.66

4.1.1 Burner Effect on Laminar Burning Velocity of H_2/CO/Air

As described in the experimental setup, two types of distinguishable burner (nozzle and reduced burner) systems were used to measure burning velocities of various compositions of syngas. The laminar burning velocities are determined at 30% H_2 - 70% CO composition and the results were plotted as shown in Figure 4.7.

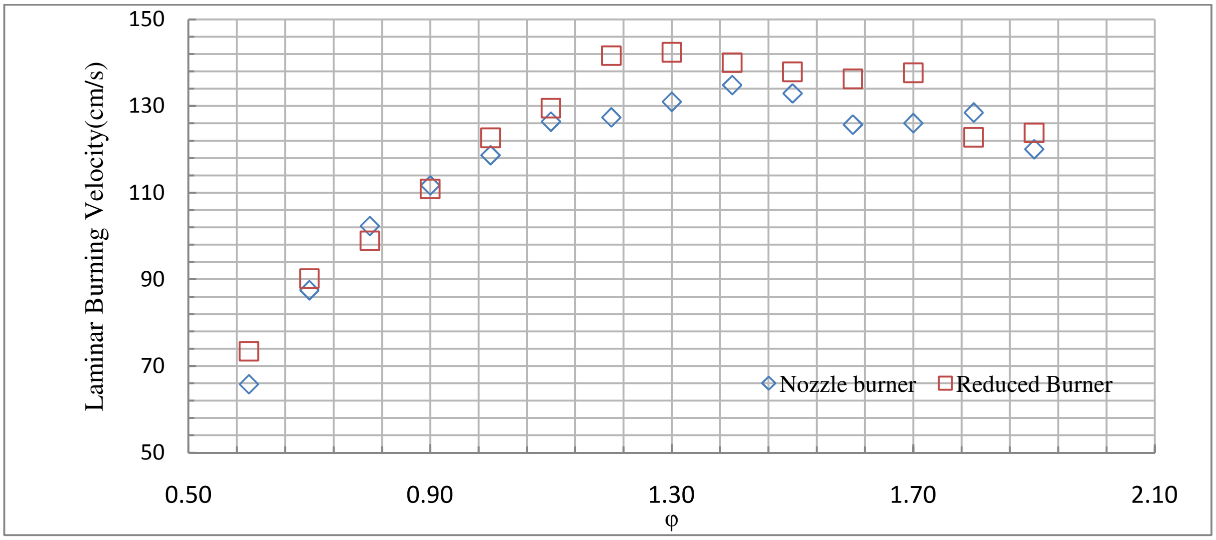


Figure 4.7 Laminar Burning Velocity Comparison between Different Burner Systems (30% H_2)

Figure 4.7 shows a good agreement between the two burner systems at lean conditions, but at rich condition it deviates from each other. Bunte and Litterscheidt [18] investigated burner diameter effect on the burning velocity and found that over a wide range of burner diameter the results were identical.

4.1.2 Comparisons between Different Measurement Techniques (30% H_2)

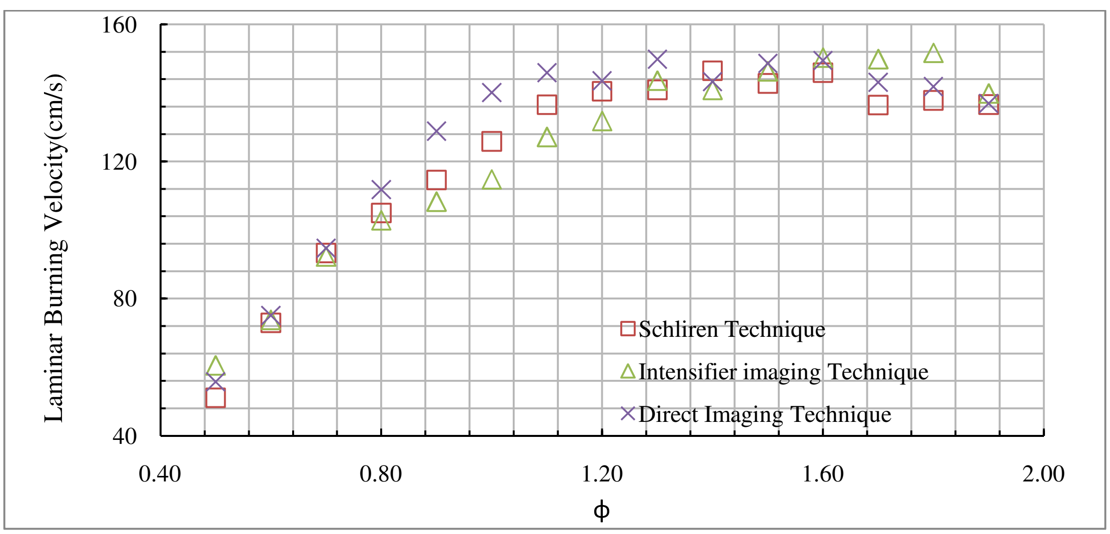


Figure10 Comparisons between Different Measurement Techniques (30% H_2)

Figure 10 shows the burning velocity of syngas fuels (30% H_2 + 70% CO) using different measurement techniques. At lean condition, the results are almost the same, but as it moves to the rich limit the results disagree with this alignment.

4.2 Effects of Diluents on Burning Velocity of Syngas

The effects of N_2 and CO_2 dilution (a minor constituent of syngas fuels) on the burning velocity of H_2-CO mixtures were investigated at Tad=1900K temperature.

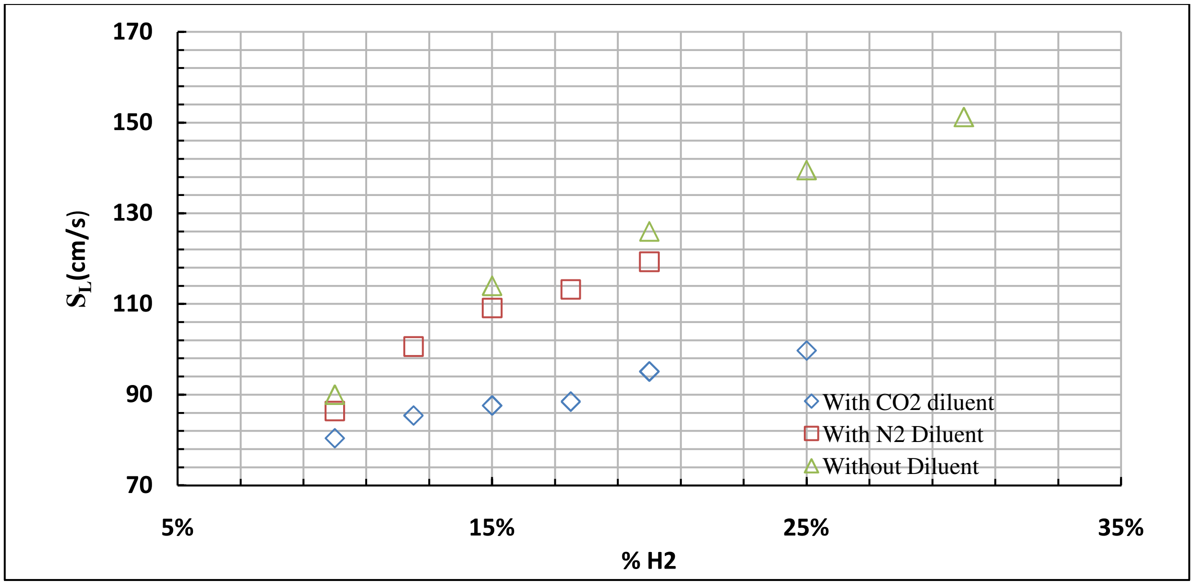


Figure 4.8 Effect of Diluents on Burning Velocity

Experiments were performed with a simultaneous increase in both H_2 and diluents (N_2 and CO) concentrations individually to understand the activity of N_2 and CO_2 concentrations on burning velocity of syngas fuel flames. Figure 4.8 shows the addition of CO_2 in H_2-CO mixtures. Burning velocity plays a dominant role compared to the addition of N_2 in the mixtures. The addition of more diluents to the mixtures, the recombination ($H+H+M \rightarrow H_2+M$) reaction is faster compared to the chain branching ($H+O_2 \rightarrow O+OH$) step. And also if the diluents (CO_2, N_2) of higher heat capacity are present in sufficient quantities, it will reduce temperature, thereby reducing the rate of energy release and eventually decrease the burning velocity [18]

4.3 Compositions of Syngas Fuels

Calculations of the laminar burning velocity were performed for syngas fuels (derived from gasification of brown coal, bituminous coal, lignite, and coke, which are comprised of different compositions of CO, H_2, N_2, CO_2, and CH_4) and air mixture at varying equivalence ratios. The relationship between equivalence ratio and laminar burning velocity of syngas- air mixtures is shown in Figures 4.9- 4.12, respectively.

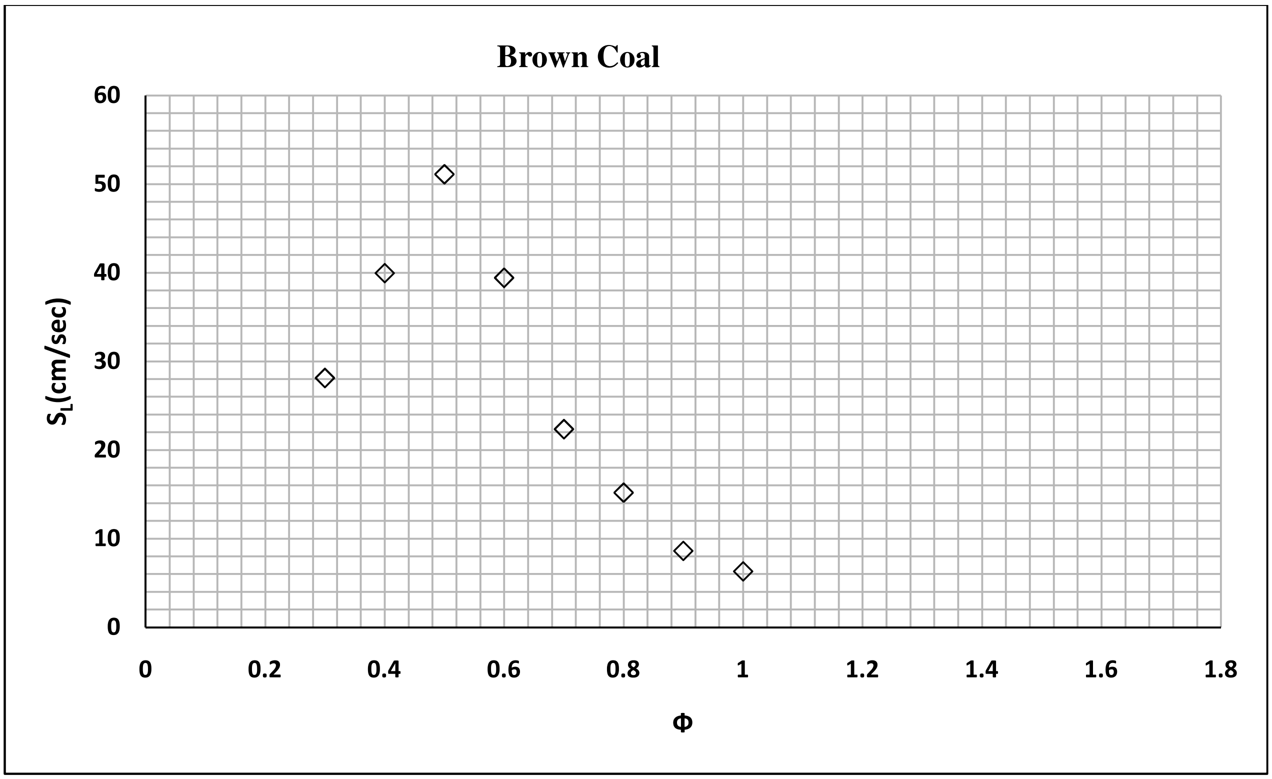


Figure 4.9 Laminar Burning Velocities of Brown Coal

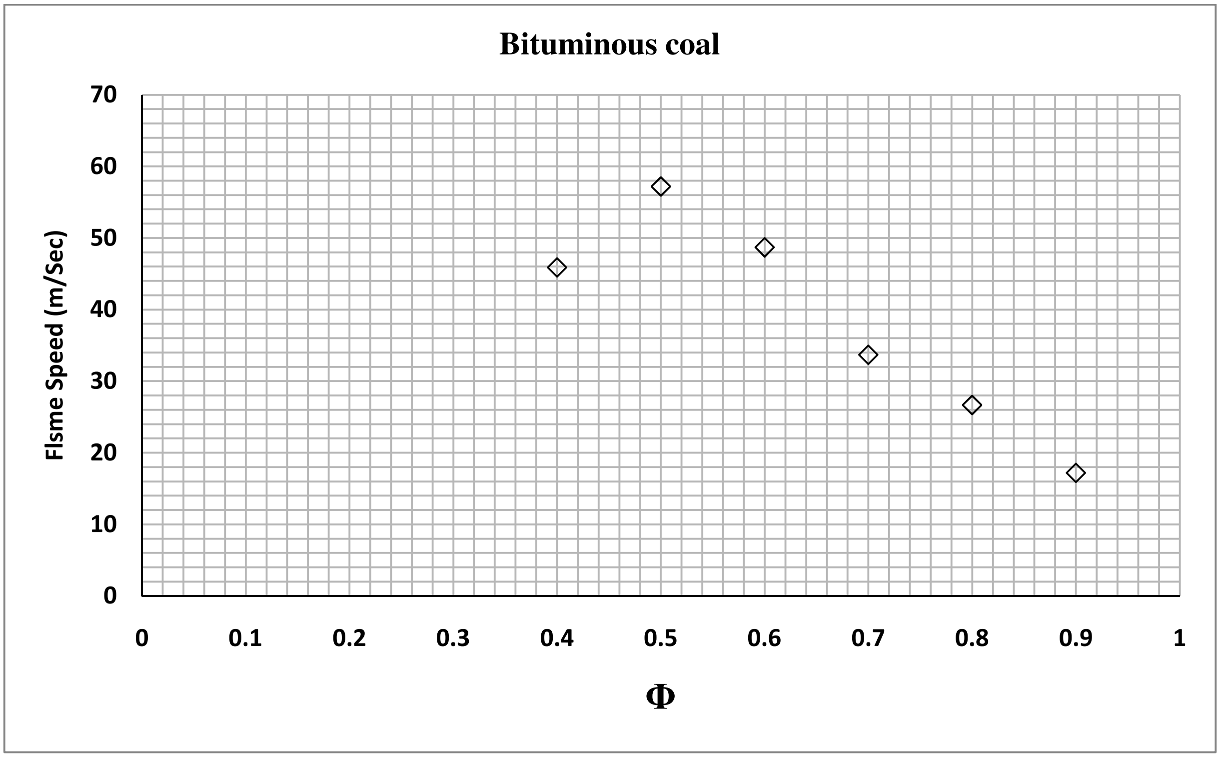


Figure 4.10 Laminar Burning Velocities of Bituminous Coal

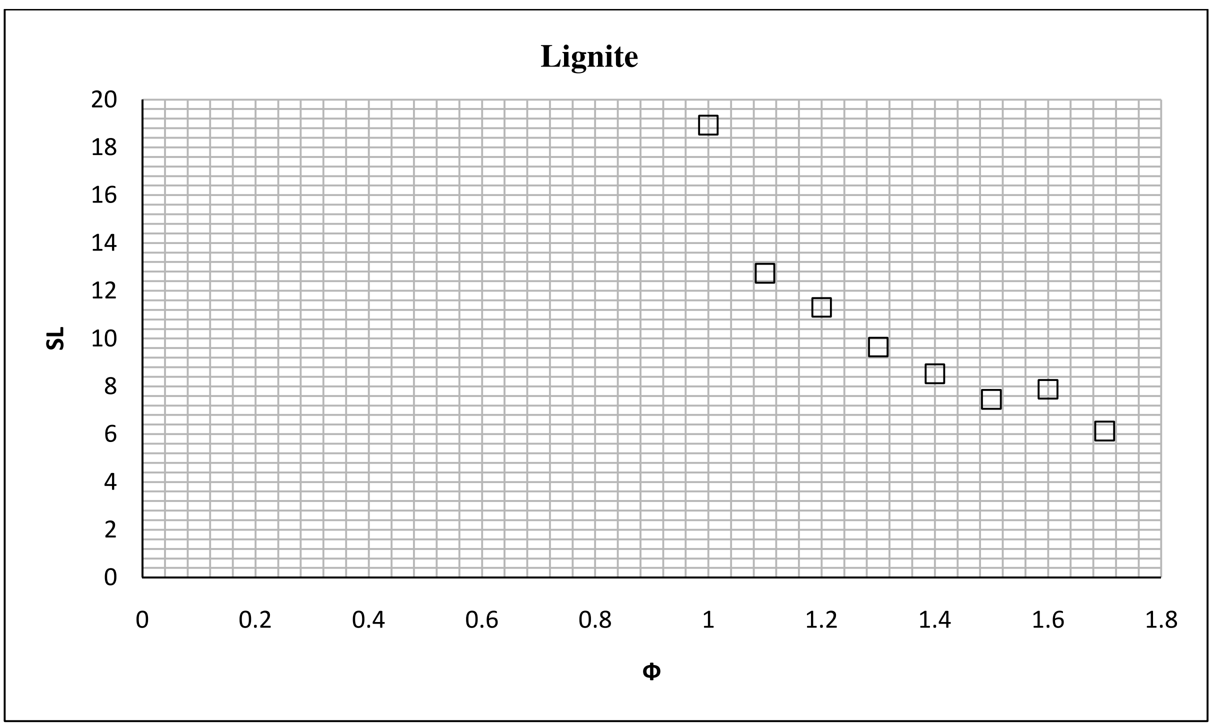


Figure 4.11 Laminar Burning Velocities of Lignite

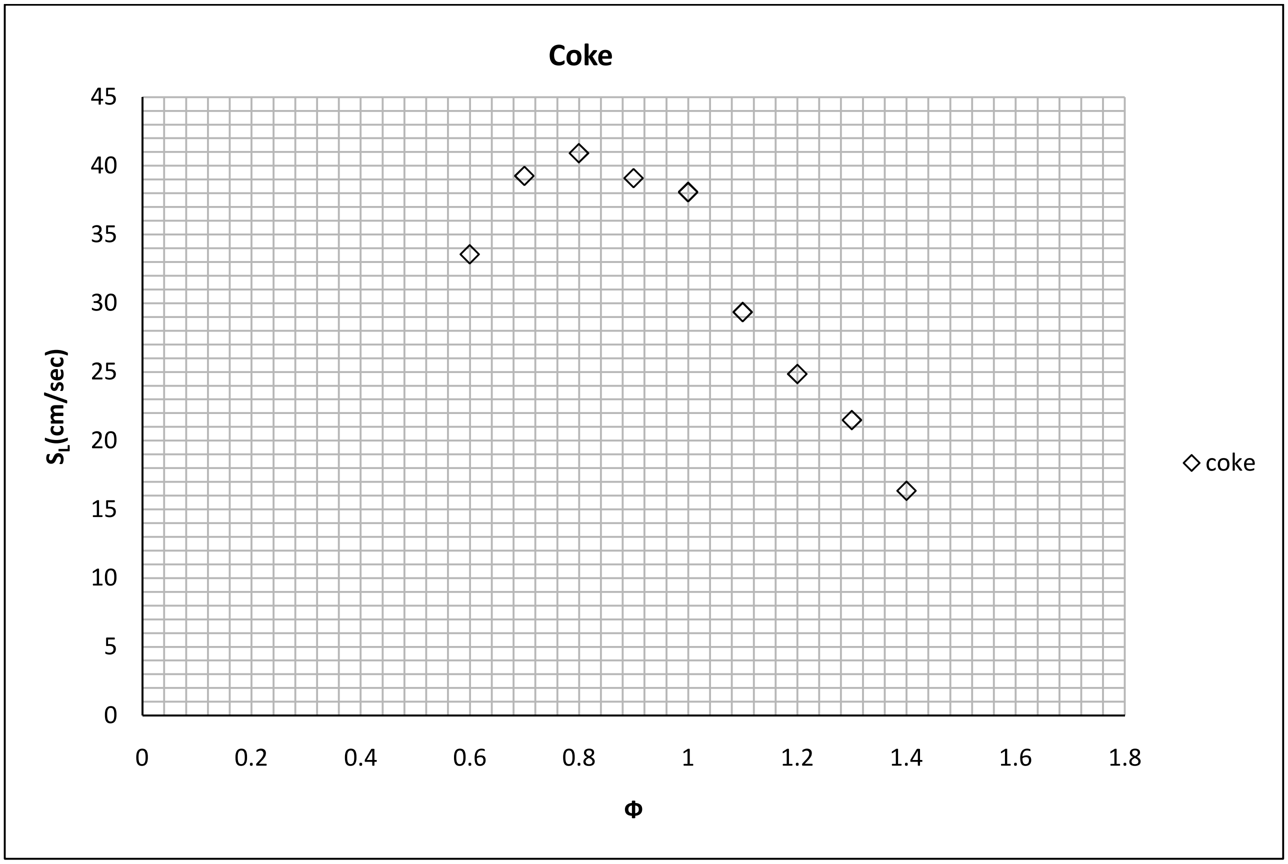


Figure 4.12 Laminar Burning Velocities of Coke

Table 4.7 Compositions of Synthesized Gases

Comparisons of Synthesized Coals						
Gasification	Type of coal	CO (%)	H_2 (%)	CH_4 (%)	N_2 (%)	CO_2 (%)
Coal	Brown coal	16	25	5	40	14
	Bituminous	17.2	24.8	4.1	42.7	11
	Lignite	22	12	1	55	10
	Coke	29	15	3	50	3
Wood		21	21	1.83	43	12

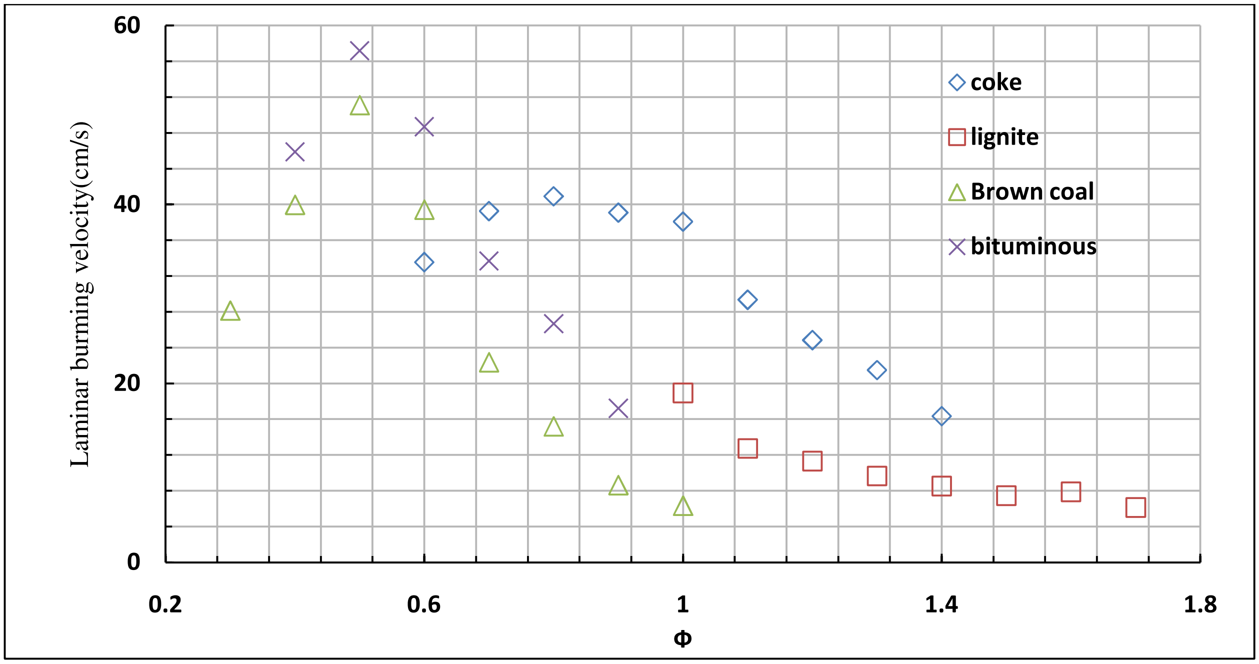


Figure 4.13 Burning Velocity of Actual Syngas Compositions

Figure 4.13 shows the burning velocity of actual syngas composition depending on the source of coal. It is interesting to note that the maximum burning velocity point of brown and bituminous coal synthesized gas is in the lean condition due to the presence of more H_2 percentage than CO in the mixtures. Another observation is the effect of CO_2 diluents on the burning velocity of these two mixtures. Although the H_2 and CO percentage is almost same, bituminous coal derived syngas composition has higher burning velocity than brown coal derived syngas composition due to the presence of less CO_2 concentration. The maximum burning velocity of lignite and coke derived syngas composition fuels shifts to the right due to the presence of a higher CO percentage than H_2 concentration. Also the diluents' effect is dominant here; due to the high CO_2 concentration in lignite, the burning velocity of coke is higher than lignite coal derived syngas compositions.

4.4 CH_4-H_2 Mixtures

The dual fuel blend comprised of CH_4 and H_2. The laminar burning velocity of air-fuel mixtures was determined at wide range of equivalence ratios. The percentages applied were 10% H_2 - 90% CH_4, 15% H_2 – 85% CH_4, 20% H_2- 80% CH_4, 25% H_2 - 75% CH_4 and 30% H_2 - CH_4. These combinations are then compared to evaluate the laminar burning velocity with an increase in H_2 content.

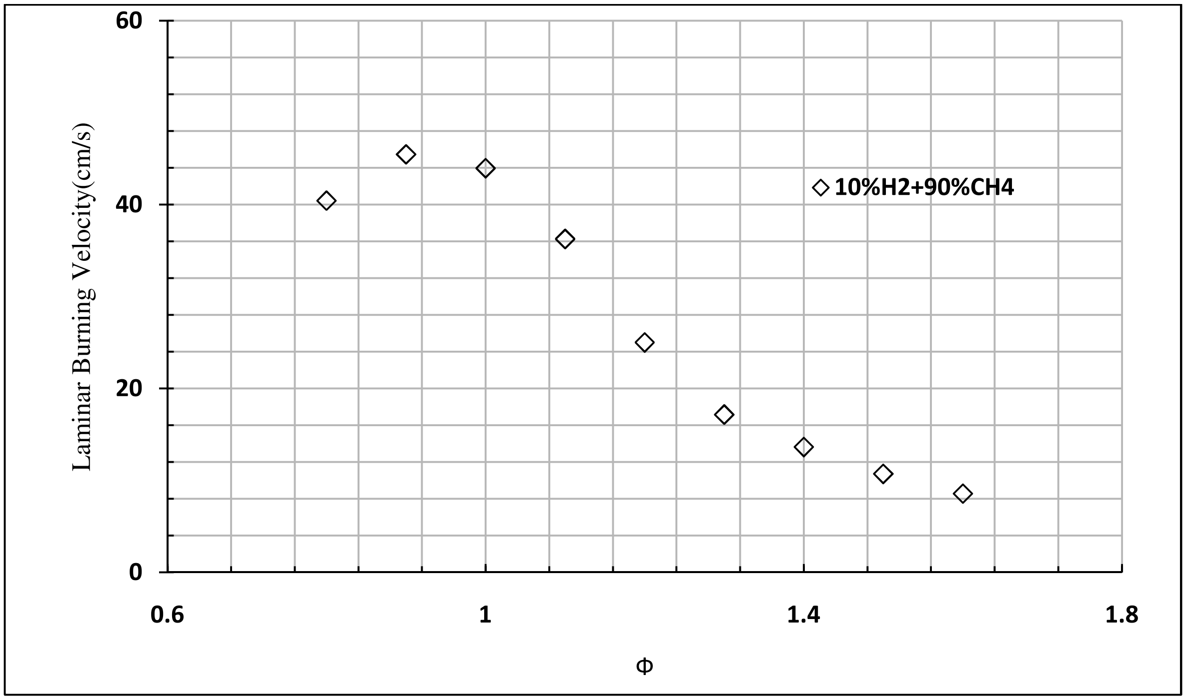


Figure 4.14 Laminar Burning Velocities for 10% H_2 - 90% CH_4

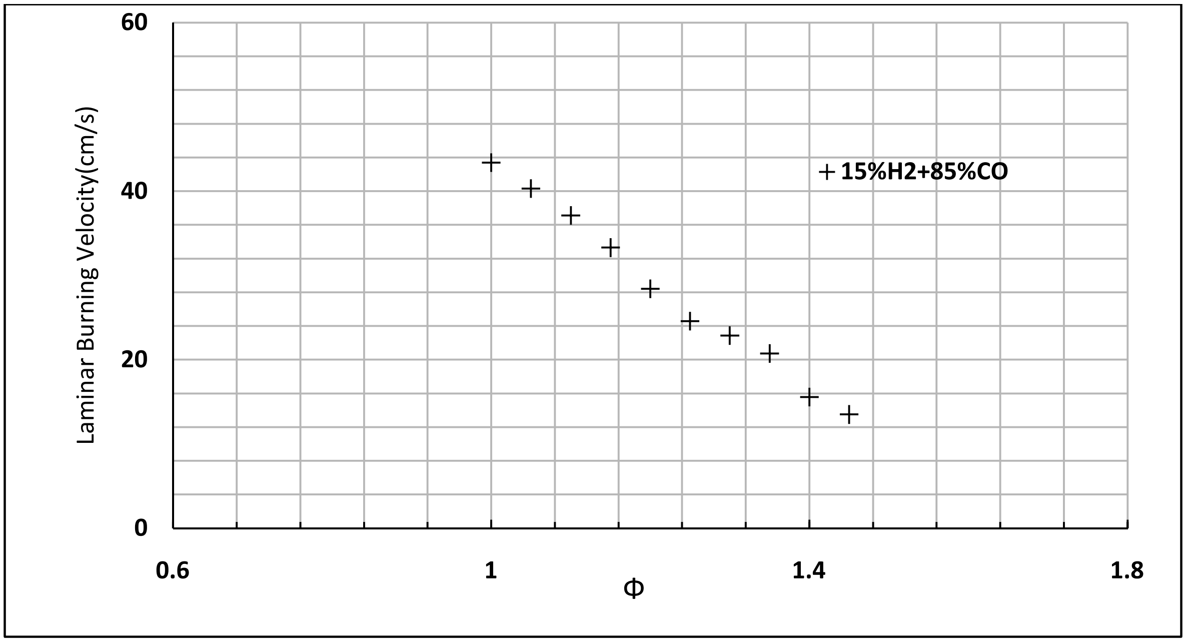


Figure 4.15 Laminar Burning Velocities for 15% H_2 - 85% CH_4

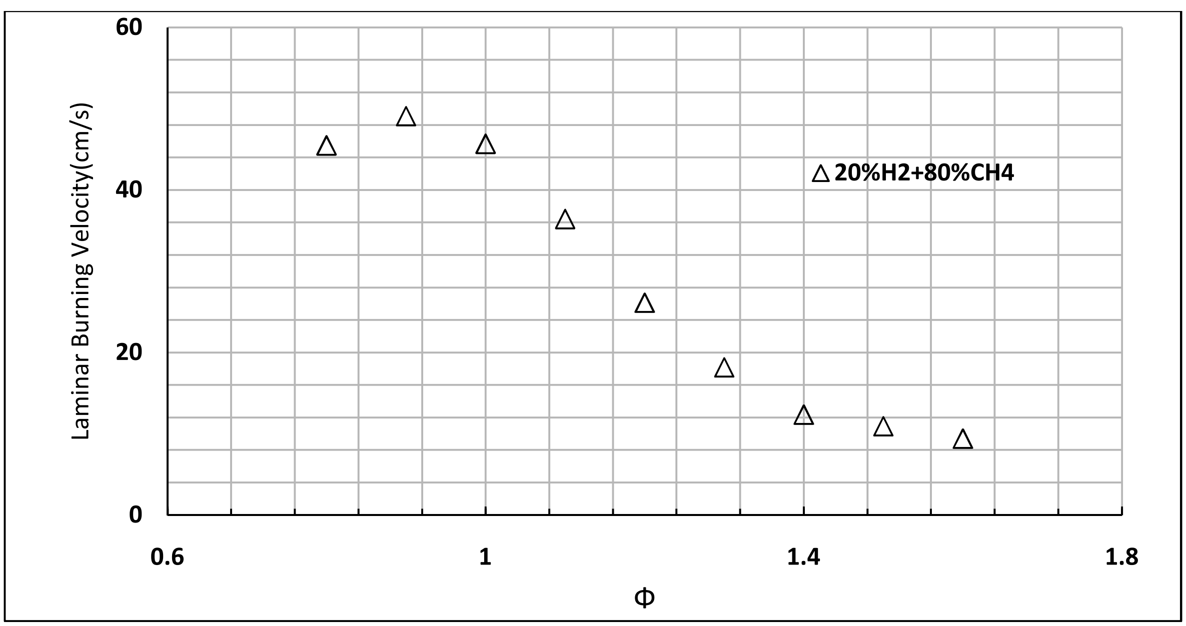


Figure 4.16 Laminar Burning Velocities for 20% H_2 - 80% CH_4

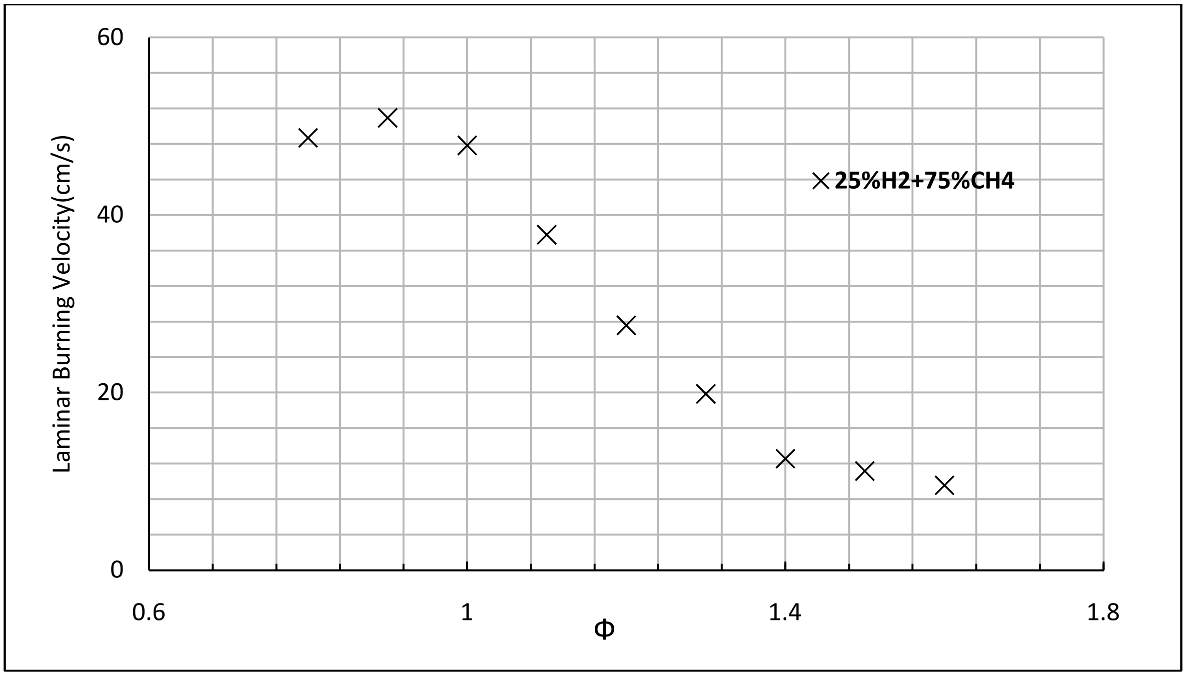


Figure 4.17 Laminar Burning Velocities for 25% H_2- 75% CH_4

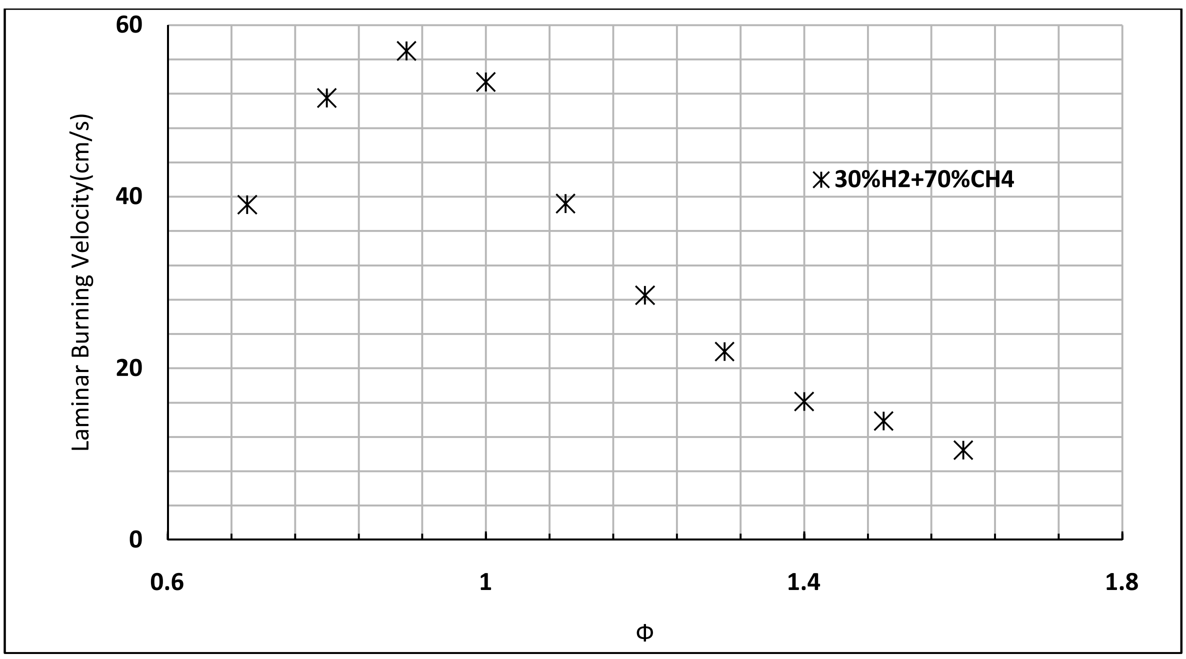


Figure 4.18 Laminar Burning Velocities for 30% H_2 - 70% CH_4

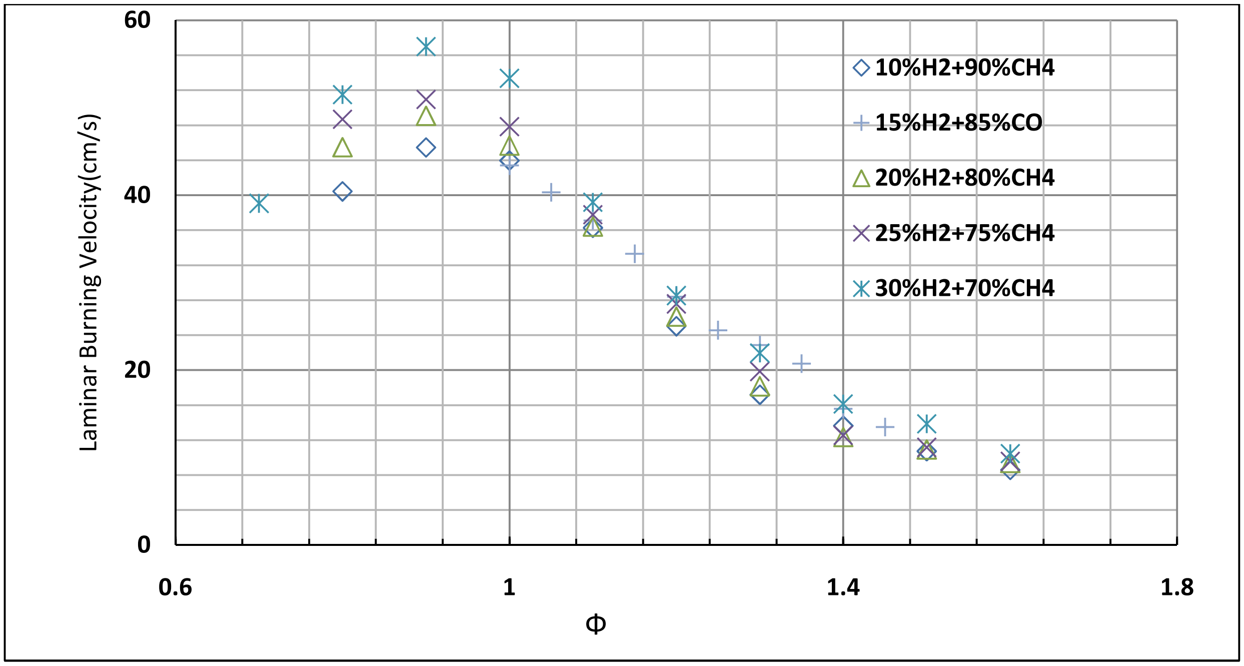


Figure 4.19 Laminar Burning Velocity of H_2-CH_4 Mixtures

Tables 4.8 through 4.12 display the flow rates of all compositions of % CH_4 - % H_2, and Figures 4.8 through 4.12 display the laminar burning velocity of variable syngas compositions of % CH_4 - % H_2. All the compositions demonstrate that, as the H_2 content in the compositions increase the laminar burning velocity also increases. In rich compositions of % CH_4 - % H_2, even with the increase in H_2 content there are no big variations in the laminar burning velocities, but the lean mixtures the burning velocities differ significantly.

4.5 Quantification

The burning velocity of CH_4 was measured to reproduce the data provided by Gibbs and Calcote's data [7]. Table1 shows the measured S_L in the present study plotted with the Gibbs and Calcote's measurements and the CHEMKIN (GRI mechanism) data. Present measurements agree fairly well with the previously reported data and the CHEMKIN data.

Table 4.13 CH_4 Quantification

Methane Quantification at ϕ=1				
Present observation			Gibbs and Calcote(J.Chem .Eng.Data)	Chemkin(GRI mechanism)
	Direct Imaging	Intensifier Technique		
Laminar Flame Speed(cm/s)	45.4	44.4	43.4	40.3

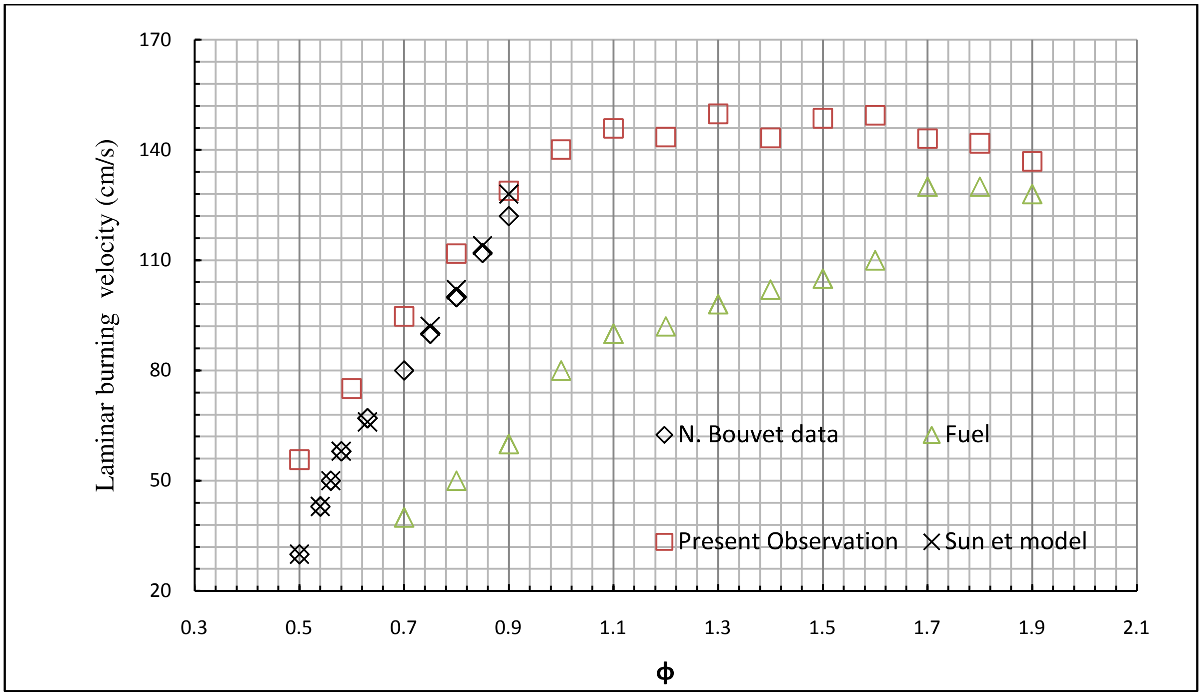


Figure 4.16 Comparison with Other Measurements (30% H_2 +70% CO)

Figure 4.16 shows the comparison of this study and N. Bouvet and Sun et al. model data. The experimental results of laminar burning velocity of 30% H_2 + 70% CO compositions show a good agreement with the works of N. Bouvet and Sun et al.

5.0 Conclusions

It is concluded that (i) The burning velocities of H_2-CO mixtures increase as H_2 increases in the contents of the mixture; (ii) the burning velocity of coke derived syngas fuel is higher than others; (iii) CO_2 as a diluent is more prominent than N_2; (iv) the increase of CO_2 in the syngas mixtures decreases the burning velocity; and (v) the burning velocities of H_2-CH_4 mixtures align with each other at rich condition.

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Curriculum Vita

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