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Investigation Of The Radiative Heat Release Factor Of Premixed Oxy-Syngas Flames

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INVESTIGATION OF THE RADIATIVE HEAT RELEASE FACTOR OF
PREMIXED OXY-SYNGAS FLAMES

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Martin de la Torre

2013

Dedication

This dissertation is dedicated to my family and my cSETR colleagues at the University of Texas
at El Paso

INVESTIGATION ON THE RADIATIVE HEAT RELEASE FACTOR OF PREMIXED OXY-
SYNGAS FLAMES

by

MARTIN DE LA TORRE, B.S. Mechanical Engineering

THESIS

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ABSTRACT

The majority of the United States is being powered by combustion devices relying on coal since it is abundant and is a high emitting source of electricity per unit energy. The U.S. accommodates about one quarter of the world's coal reserve, however; the burning of this abundant fuel is responsible for a significant contribution for the pollutant emissions causing global warming. Because coal is not likely to be replaced as the main source of energy in the U.S. any time soon, the scientific community has been dealing with the emissions problem in order to meet current and future governmental emission requirements. With the strict regulations governmental agencies have imposed on the greenhouse gas emissions, this thesis work looks to provide a study of the radiative heat release rate of premixed oxy-syngas flames. It is now well established that radiating heat from the flame is a major contributor of the heat flux going into the combustor walls. Oxy-combustion is a promising CO₂ capture technique that would allow a simplified carbon capture and storage process and the use of coal-derived synthesis gas in turbines. This would allow for the reduction of greenhouse gas emissions by eliminating the N₂ presence from the combustion process. In order to be able to retrofit the existing technology with oxy-combustion or design a new turbine combustor system a deeper understanding of factors like heat transfer and combustion kinetics is needed to successfully accommodate for this new technology. Motivated by the change in the radiative properties when conducting oxy-syngas combustion and the much needed fundamental oxy-syngas combustion characteristics data, this thesis work aims to contribute on the study of the global radiation of oxy-syngas combustion. The effects of CO₂ acting as a diluent, percentage of H₂ in the fuel and the effects of equivalence ratio on the flame's radiative heat release are investigated. The work reveals that the radiative heat release factor of syngas flames decreases at higher firing inputs and high hydrogen concentrations while increasing at lower ones. An increase in heat release factor is noted when increasing the equivalence ratio and the recirculation ratio of diluents, in this case CO₂.

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CHAPTER 1

INTRODUCTION AND BACKGROUND

The United States has the largest accessible coal reserves in the world [1] and it is projected that coal will remain the United States main energy contributor for the century due to its high emitting source of electricity per unit energy [2] for a long time. Since coal is readily available and very abundant in the U.S. the technology has buried its roots deep down into the U.S. economy and lifestyle. The coal-power generating industry is responsible for thousands of jobs and the technology has been implemented in most of the power generating plants. With 75% of the United States being powered by combustion devices relying on coal [3] as the main fuel and the strict regulations governmental agencies have imposed; these and other contributing factors have pushed the engineering community to develop ways to control the greenhouse gas emissions.

When combustion takes place with air as an oxidant the high concentration of N_2 present dilutes the CO_2 concentration in the flue gases producing NO_x , H_2O and the dominant contributor of the greenhouse gases, CO_2 [4]. In order to minimize and put into good use the exhaust gases coming out of the combustion process different approaches have been taken, the most promising one consist on the post-combustion capture process: Carbon Capture and Storage (CCS). CCS's main goal is to eliminate CO_2 emissions from power generation into the atmosphere as much as possible. The process consists of three parts: capture, transport, and storage of CO_2 . Storage can be done in deep saline aquifer formations, underground or can be used for enhanced oil recovery [4].

Currently there are two types of disposal being defined [36]:

- Sequestration: Carbon capture and sequestration implies a permanent disposal of the CO_2 . The sequestered CO_2 can be used to recirculate and control combustion temperatures in the combustion process.

- Storage: Refers to the disposal of the CO₂ for a significant time period. The storage options available include the injection into depleted oil reservoirs to conduct enhanced oil recovery, injection into deep saline aquifers, coal beds, etc.

In order to efficiently capture CO₂ one must first decrease its dilution in NO_x thereby increasing its concentration in the flue gases. There exists a variety of different innovative ways in which CCS can be achieved for coal combustion and gasification. Most of these methods have been investigated and can be found in more detail in literature [4]. The three most promising methods to achieve an efficient CCS technology are:

- Post-combustion capture
- Pre-combustion capture
- Oxy-fuel combustion
- Emerging technologies

1.1 Post-combustion Capture

Post-combustion capture refers to the removal of CO₂ after combustion has taken place. The process usually is performed utilizing chemical absorption from the flue gas. Amine absorption is a proven technology and is utilized in the process industry. Post combustion capture of CO₂ utilizing chemical solutions poses a reduction of plant efficiency of 10-14% points. The scientific community has been looking for alternative absorbents that are much more efficient so that the efficiency loss when implementing the technology can be mitigated [31]. Other technologies like membrane post-capture ones have also been widely used. A coal-fired power plant produces vast amounts of CO₂ in the flue gas but it's very diluted by the different products generated due to the presence of N₂ in ambient air. The post combustion process aims to generate a highly concentrated CO₂ flue gas ready for capture which is usually later pressurized to 100 atm for transport and storage [5]. The CO₂ obtained from the flue gas can later be used to be recirculated into the combustion process, can be stored underground or in deep saline aquifers, it can be used to increase the amount of crude oil acquired out of oil fields by the process of enhanced oil recovery or it can also be used in many other commercial and industrial applications.

A popular emerging technique and one of the most researched on is the use of membrane gas separation technologies. Membranes are usually a thin film made out of a polymer and work on the basis of the rates at which the species in question permeate. The polymeric films are manufactured in such a way as to have the desired permeability based on the molecule spaces with which they are designed, their solubility and diffusion coefficients [5],[6]. The films are usually made as thin as possible to allow for permeability to take place but at the same time meet the mechanical properties required [5]. A schematic of a two-stage membrane capture system is depicted in Fig. 1.1.

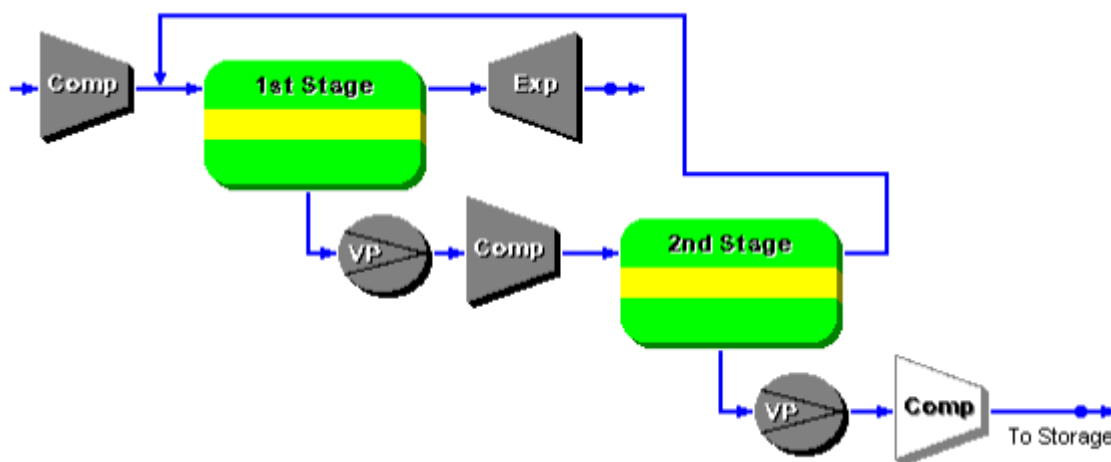


Figure 1.1. Two-stage membrane capture system. (NETL IECM Technical Documentation: Membrane-based CO₂ Capture Systems for Coal-fired Power Plants, September 2012. Prepared by Zai Haibo and Rubin S. Edward)

Another widely used technique common to refineries is the amine gas treating process. This process utilizes various alkylamines or amines, to remove H₂S and CO₂ from a gaseous solution. The most used solvents for this process include alkanolamines which are used in the form of aqueous solution. The amines used for this process can be divided into two main categories: chemical and physical solvents. The chemical solvents are used when the flue gas has low/moderate CO₂ content with partial pressure while the physical solvents are used for high pressure gas streams [7]. This process has received wide attention due to the possibility of mixing different types of amine solutions in order to attain process advantage over the single amine process [7]. The system consists of two main components: an absorber which will remove the CO₂ from the flue gas and a regenerator where the CO₂ will be released and the original solvent will be recovered [8]. In order to recover the CO₂ from the absorber heat needs to be applied to it which is usually leached from the power system resulting in decreased efficiency; also additional power will be drawn in order to pressurize CO₂ for transport. A flow schematic for a CO₂ capture from flue gases using amine-based system can be seen in Fig. 1.2.

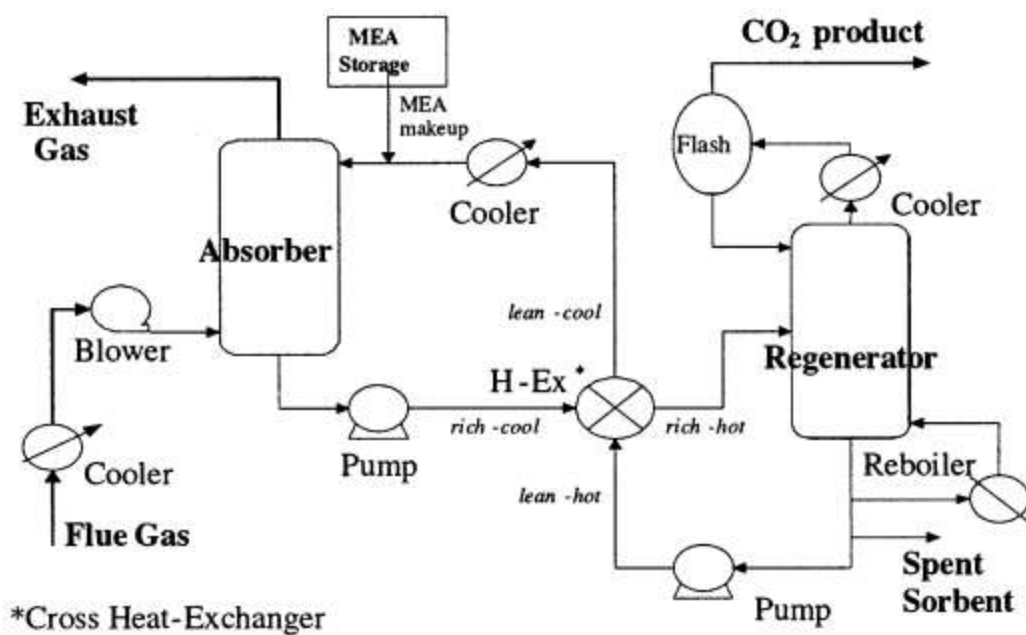


Figure 1.2. Flow schematic diagram for a CO₂ capture from flue gases using amine-based system (Anand B. Rao and Edward S. Rubin. A Technical, Economic, and Environmental Assessment of Amine-Based CO₂ Capture Technology for Power Plant Greenhouse Gas Control. "Environ. Sci. Technol." 36 (2002): 4467-4475)

1.2 Pre-combustion Capture

Pre-combustion capture aims to remove as much CO₂ as possible before combustion takes place. The most promising technology for pre-combustion capture is the integrated gasification combine cycle (IGCC). This process involves the decomposition into its most basic chemical constituents of coal or any carbon based fuel being fed by means of a thermo-chemical reaction. With IGCC coal is first gasified into synthesis gas, which is composed mainly of CO, H₂ and CO₂, in the presence of oxygen. The resulting gas is then mixed with steam and sent to a shift converter where the CO from syngas gets converted into CO₂ and additional H₂ by the water gas shift reaction ($\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2$). The CO₂ is then separated from H₂ and sent along with steam or N₂ to the combustion turbine. The flue gas acquired from the combustion turbine is then used to generate more steam for the water gas shift reaction process to take place [9], [10]. There have been calculations that show IGCC has promising process economics and plant efficiency characteristics [36]. The downside of this technology lies in the high capital cost associated with the plant's construction. It has also been determined that they are much more complicated systems than suspension-fired boilers [32, 33]. Due to their increased complexity and high capital costs associated with construction IGCC plants are scarce and are not viable for retrofit existing power plants. A simplified scheme of the IGCC plant configuration is shown in Fig. 1.3.

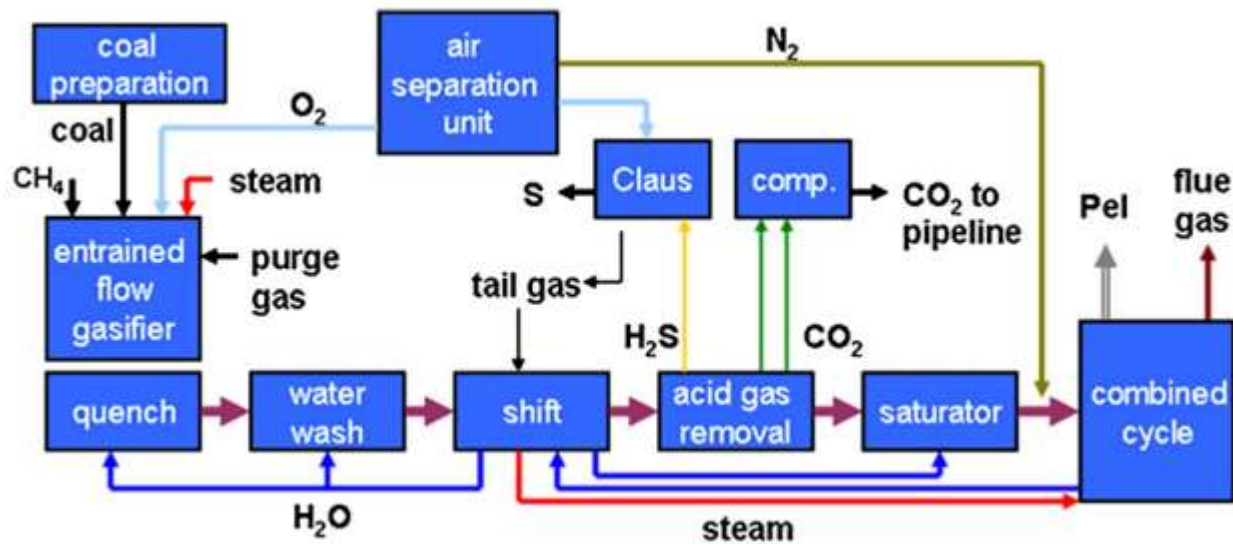


Figure 1.3. Simplified IGCC plant configuration (Kunze Christian, Spliethoff Hartmut. Modeling of an IGCC Plant with Carbon Capture for 2020. “Fuel and Processing Technology” 91,8 (2012): 934-941)

There have been models that prove a 38.5 and 41.9% efficiency for hard coal and lignite respectively however the results are considered to be too optimistic when compared to other major studies [33].

1.3 Oxy-fuel Combustion

Oxy-fuel combustion refers to the process of burning a hydrocarbon fuel with pure oxygen instead of air. Conventional combustion processes use air for combustion which end up producing mainly NO_x , H_2O and CO_2 in the flue gases. Since air is mostly composed of N_2 and a small fraction is composed of O_2 the resulting flue gases obtained from combustion end up emitting a small amount of CO_2 when compared to NO_x . When pure oxygen is introduced as an oxidant accompanied by recycled flue gas in the combustion process, a high concentration of CO_2 ready for sequestration is produced in the flue gases along with steam [4]. The steam can be later condensed to allow for easy separation of the CO_2 . The recycled flue gases introduced along with oxygen serve to act as diluents and to make up for the volume missing from the absence of N_2 [4].

Usually flue gases are recirculated into the plant's combustion process in order to maintain the flame temperatures within the material's limits of the furnace/combustor. By implementing oxy-fuel combustion the flame temperatures increase dramatically when compared to conventional combustion. The higher temperatures lead to a greater change in the plant configuration when compared to post and pre-combustion capturing technologies [36]. This is mainly due to the change in chemistry obtained by replacing N_2 from air combustion by flue gases.

The main disadvantage for implementing oxy-fuel combustion relies in the need of utilizing almost pure oxygen. The available large scale for air separation unit utilize cryogenic distillation which would consume considerable amounts of energy from the plant [34]

In order to be able to introduce oxy-fuel combustion in today's power generating equipment, an in-depth and detailed study on oxy-fuel combustion must be conducted. Factors like heat transfer and combustion kinetics must be investigated in order to successfully accommodate for this new technology. Density, heat capacity, diffusivity and the radiative properties of the equipment's gases will be different when switching from air to oxygen combustion [4].

The flame temperatures generated when conducting oxy-fuel combustion with coal are extremely high due to the lack of N_2 in the process. Unlike combustion processes that use air as an oxidant, oxy-fuel is very dependent on the need to be diluted with flue gases in order to control the flame temperatures. If a retrofit technology is needed, a retrofit is considered in order to minimize changes in the current combustion system, extensive heat transfer investigations are needed. Furnace heat transfer is dependent on flame temperature, heat transfer properties of gases and particles, water cooling, wall temperature and properties of the materials, and the aerodynamic fluid field established, including the flame types [4].

1.4 Emerging Technologies

Some of the emerging technologies for carbon capture and sequestration include membrane separation, chemical looping combustion, carbonation-calcination cycles, and enzyme-based systems among others. Some of these technology concepts claim to have 100% CO₂ capture including pressurization to 100 bar [35]. The AZEP is an efficient and cost-effective process that utilizes a combination of a mixed conducting membrane reactor and a conventional gas turbine based combined cycle. The chemical looping combustion is one of the most recent ways in which fuel is oxidized in order to produce useful energy, however; combustion has been studied extensively and adequate resources are needed in order to make chemical looping a competitive technology.

The separation of CO₂ at high temperatures is being studied since it would lead to lower energy penalties in the separation step [35].

The implementation of these technologies depends mainly on the economic feasibility and efficiency of the system. Other factors are also taken into consideration such as retrofit possibilities, local circumstances, expected availability etc.

CHAPTER 2

LITERATURE REVIEW

Conventional coal-fired boilers and furnaces that use air produce a much diluted CO₂ stream in the flue gases; this is due to the high N₂ concentration present in air making the capturing process a relatively expensive one. Some of the differences between air based combustion include temperatures, flue gases composition, and recirculation of flue gases needed among others. The main differences can be summarized by the following [11]:

- In order to generate a similar adiabatic flame temperature than that of air, about 60% of the flue gases is need for recirculation in an oxy-fuel process, a substantial increase than that for air for which is about 21%.
- CO₂ and H₂O (steam) have higher emissivity and when that is combined with the high proportion of both gases present in the combustion process the radiative heat transfer properties will differ from conventional combustion. This will affect not only the adiabatic flame temperature but also the way the materials will react to the process. In order to generate similar heat transfer properties that those attained by conventional combustion, the O₂ proportion of the gases passing through the burner should be less than 30%. The amount of O₂ needed to attain similar temperatures as those from conventional combustion can be offset by recirculating a greater amount of flue gases. Further investigation is needed to understand the effects this measure would cause since the radiative heat transfer properties could change drastically.
- After recycling the volume of the flue gases will be reduced by approximately 80%. The remainder could be captured and implemented in other industries or processes.
- In the conventional combustion a 20% excess air is supplied to the process. In oxy-fuel combustion an O₂ excess is required as well in order to obtain this excess oxygen from the flue

gases from 3% - 5%. This requirement would have its most impact on the air separation unit which would in turn draw more energy from the plant's cycle.

- Due to the flue gases being recycled, corrosive species concentrations will be increased if not removed prior to recycling.
- Oxy-fuel combustion will result in a less efficient process since some power will be diverted to air separation units and other additional equipment needed in order to make oxy-fuel combustion happen.

Oxy-fuel combustion has been investigated in many other available technologies including boilers which in turn would produce CO₂ rich flue gas ready for sequestration. Other studies include the investigation of oxy-fuel combustion in oil and gas fired power plants. In metal heating furnaces it was proposed to use coal-fired oxy-fuel combustion to recycle the flue gas which would result in a reduction in the furnace size and the NO_x emissions [11].

Due to the extremely high temperatures the stoichiometric oxy-fuel combustion produces, a recycle of the flue gases to act as diluents is needed. Due to the presence of the high temperatures along with the high concentration of CO₂ gases in the combustion process, it is expected that radiative heat transfer will play a much greater role in oxy-fuel combustion than in conventional air combustion. Since the temperature of a combustor walls are limited by its material properties, special attention must be given to the study of the radiative properties of oxy-fuel flames [12].

Conventional combustion utilizes air as an oxidant which produces negligible radiative heat transfers due to the low emissivity of the highly N₂ diluted flue gases. Oxy-fuel's flue gases are mainly composed of radiating species (CO₂ and H₂O) which greatly affect the radiation heat transfer properties of the flame making them strong enough to be of concern when designing a combustor/furnace/boiler. Studies have been conducted in the past using propane in an oxy-fuel fired boiler and they show that the flame with 27% O₂ diluted with CO₂ has a similar behavior as in air but with an increase in radiative

heat flux of up to 30% [13]. The radiation emissions of a flame are greatly influenced by the fuel's propensity to produce soot. In previous studies it has been concluded that the increase of radiative heat transfer in oxy-fuel combustion can be attributed to the inflame soot volume fraction [14].

Even though soot generation contributes a great deal in increasing the radiative heat transfer of an oxy-fuel flame it is important to look at the species produced by the combustion process as well. When running at equivalence ratio of one the generation of soot is greatly decreased leaving the bulk radiative heat transfer generation to the species in the oxy-fuel combustion flue gases (CO_2 and H_2O). In order to accurately predict the radiative heat fluxes that will be generated by oxy-fuel combustion models that take into account the special conditions oxy-fuel presents need to be generated and/or modified. Spectral radiation models are needed in order to accurately predict the mentioned heat fluxes since the absorptivity of the major species present in the flue gases is a strong function of wave number [15].

The two main byproducts produced in oxy-fuel are CO_2 and H_2O , which are strong emitters in the infrared region at 2 and 2.3 μm for CO_2 and 1.38 and 1.87 μm for H_2O with an overlap at 2.7 μm . In a gas turbine the banded spectra from H_2O and CO_2 is its strongest at temperatures of up to 3000 K. At higher temperatures these two byproducts are depleted by dissociation leaving CO with the strongest banded spectra [16]. Other effects on the operating conditions of gas turbine combustors have been studied. It is relevant to study the rich fuel mixtures since combustion chambers that utilize atomized fuel delivery are affected by an increase in pressure since it tends to conglomerate the center of the flame tube near the spray nozzle. This condition allows for a fuel rich zone that would increase the soot formation [16]. In previous studies it has been shown that the radiation emitted by oxy-syngas flames is much higher than that of syngas air and hydrocarbon air flames, and when compared to turbulent premixed methane air flames the flame is about 1.6 times stronger due to the high concentrations of CO_2 in the combustion process [17, 18]. These studies have also shown how radiation increases significantly

at high pressures. The results in the present study corroborate the reported tendency for syngas radiation to increase as the amount of CO_2 increases. It is important to note that higher syngas firing inputs result in a decrease of radiative heat release factor even when the temperature increases as depicted in Fig. 11.

Researchers have proposed several ways to minimize radiation generated in gas-turbine combustion chambers. One of the proposed ways lies in the design of the flame tube and the fuel injector. These two components should be designed as to keep the primary combustion zone fuel weak in order to keep the fuel rich zones generated by the high pressure from developing [16]. The present study corroborates this claim by looking at the behavior of the radiative heat release factor decrease at low equivalence ratios and increase at higher equivalence ratios. This would mean that at oxy-syngas conditions fuel rich regions should be avoided while fuel lean mixtures would work to reduce the radiative heat release rate.

Many studies have investigated the burning of synthetic fuels in air under many different conditions [19-27]. Few authors, however, have focused on experimental measurements of oxy-syngas combustion and its fundamental characteristics. Kobayashi et. al. investigated highly CO_2 diluted oxy-syngas turbulent flame characteristics in a high-pressure environment [18]. The major results of this study include a report on an increase in the total radiation intensity due to the high concentrations of CO_2 used. Wang et al. investigated the laminar burning velocities and flame characteristics of oxy-syngas CO_2 diluted mixtures [17]. Having CO_2 as a major component of the flue gases in oxy-syngas combustion it became relevant to study its effects on flame characteristics. Wang et al. major results include the behavior of laminar flame speed with a variation in the CO_2 content, radiation heat loss of oxy-syngas flames is determined to be much stronger than syngas-air and hydrocarbons-air due to the larger presence of CO_2 in the flame among other CO_2 related effects in the combustion.

This work looks to contribute to the existing body of knowledge by experimentally investigating the combined effects of H_2 in fuel and CO_2 diluent concentrations and firing inputs on radiation on

flame stability. This data is thought to help both industrial practitioners and combustion modeling experts in this area [28,29].

CHAPTER 3

EXPERIMENTAL APPROACH AND METHODOLOGY

3.1 Experimental Approach

A laboratory scale burner was designed and manufactured in order to withstand the high temperatures present when conducting oxy-fuel combustion and also accommodate for different burner diameters. A finite element analysis using NASTRAN 6.1 of the burner under thermal stress was performed in order to ensure structural integrity during experimentation. The final burner assembly used is presented in Fig. 3.1.

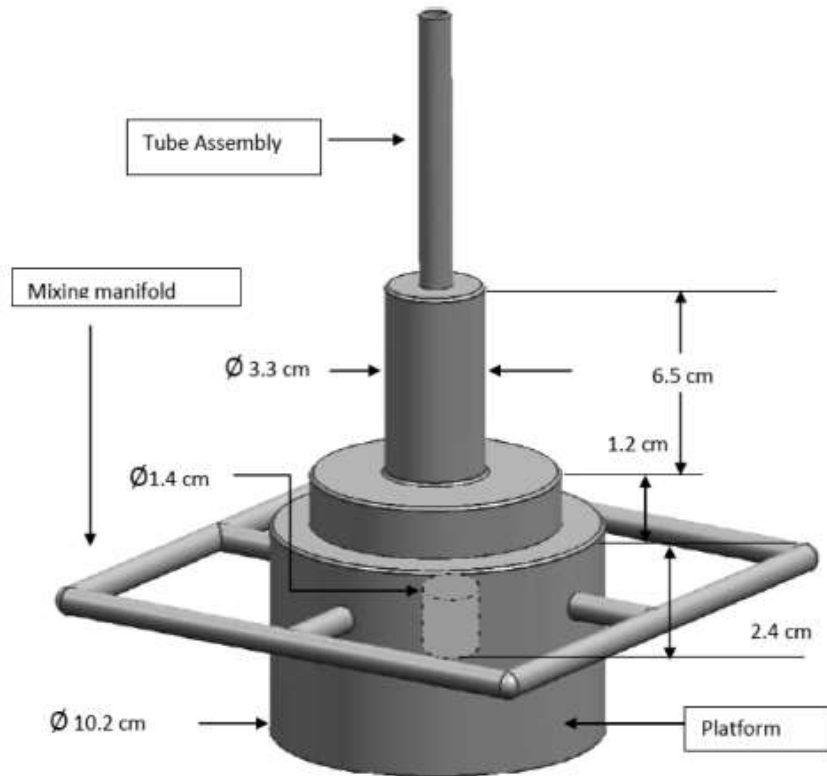


Fig. 3.1. Tubular burner assembly developed to accommodate different burner diameters.

The tubular burner consists of: a platform with four injection ports and an interchangeable burner tube assembly. The burner platform injection holes which allow for a manifold installation also provide a complete fuel/oxidant mixing at the burner base. This set up allowed for an easy change in between

burners and achieve a good premixed flame. A bank of digital volumetric flow meters (Omega FMA 1700/1800 series in Fig. 3.2) is used to measure the fuel, oxidizer and diluents flow rates. The temperature range for the flow meters goes from zero degrees Celsius to 50 degrees Celsius, maximum pressure of 500 psig, a relative humidity of 70%, and an accuracy of $\pm 1.5\%$ of the full scale.

It is important to note that for the experimentations conducted for this work, the flash back tendencies of the flame increase significantly with the addition of hydrogen to the fuel mixture. The burners utilized are therefore chosen as to be of a reasonable diameter to counter the flashback tendencies not only by means of the diluent but by means of the volumetric flow rate as well.



Fig. 3.2. Flowmeters used for experimentation

The flow meters used were selected according to the maximum volumetric flow rate that would be needed in order to be operating within the validated range. Before experimentation flow meters were calibrated using a Dry Cal DC Lite laser based calibrator shown in Fig. 3.3.



Fig. 3.3. Laser based flow meter calibrator used for experimentations

The flow meters used for the experiments are calibrated based on N_2 so a calibration is required to adjust for the actual flow of the used gas. The stream of gas entering the flow meter is split by redirecting a small sample of the gas through a capillary stainless steel sensor tube. The geometry of the primary and the capillary tubes are shaped as to have a laminar flow throughout the sensor. According to principles of fluid dynamics the flow rates through both tubes is proportional to each other.

In order to sense the flow through the sensor tube, heat flux is introduced by means of a heating coil. The heat is transferred through the sensor wall to the fluid flow. As the gas flows it carries heat from an upstream coil to a downstream coil. The resultant temperature dependent resistance differential is detected by the control unit. The measured gradient is then proportional to the instantaneous rate of flow taking place.

In order to acquire the true flow rates through the flow meters, a table of calibrated constants were used which was provided by the manufacturer. The flow of the desired gas should be adjusted so

that the value acquired through calculations is first divided by the provided constant and then shown in the calibrator. The value shown by the flow meter would become the calibrated value.

When trying to calibrate displayed flow rates into actual flow rates, one should first multiply the value times the provided constant and adjust the flow so that this value shows in the flow meter. The value displayed by the calibrator would then become the actual flow rate of the gas flowing through the flow meter.

Fig. 3.4 shows the schematic of the experimental setup and the actual set up can be seen in Fig 3.5. For the set of experiments presented in this thesis work the fuel (syngas) was assumed of being composed only of hydrogen and carbon monoxide. The oxidant used was oxygen and carbon dioxide was considered as a diluent. Research grade fuels and oxidants were delivered to the burner from pressurized tanks. Manual needle valves in conjunction with shutoff valves were used in order to moderate the flow rates and achieve the desired compositions.

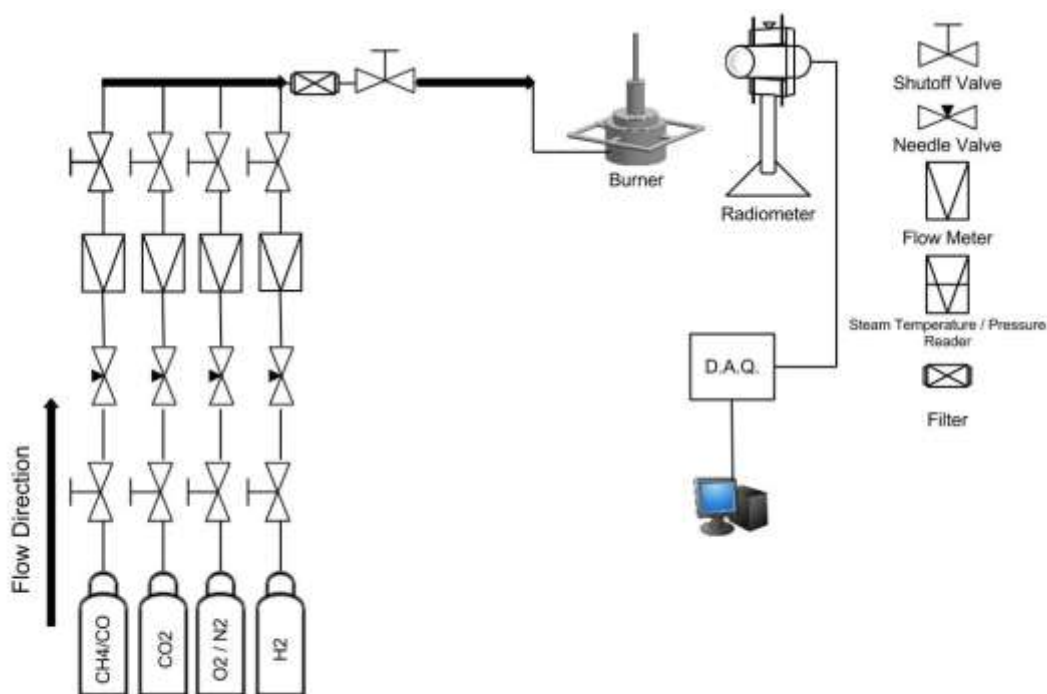


Fig. 3.4. Schematic diagram of experimental setup.

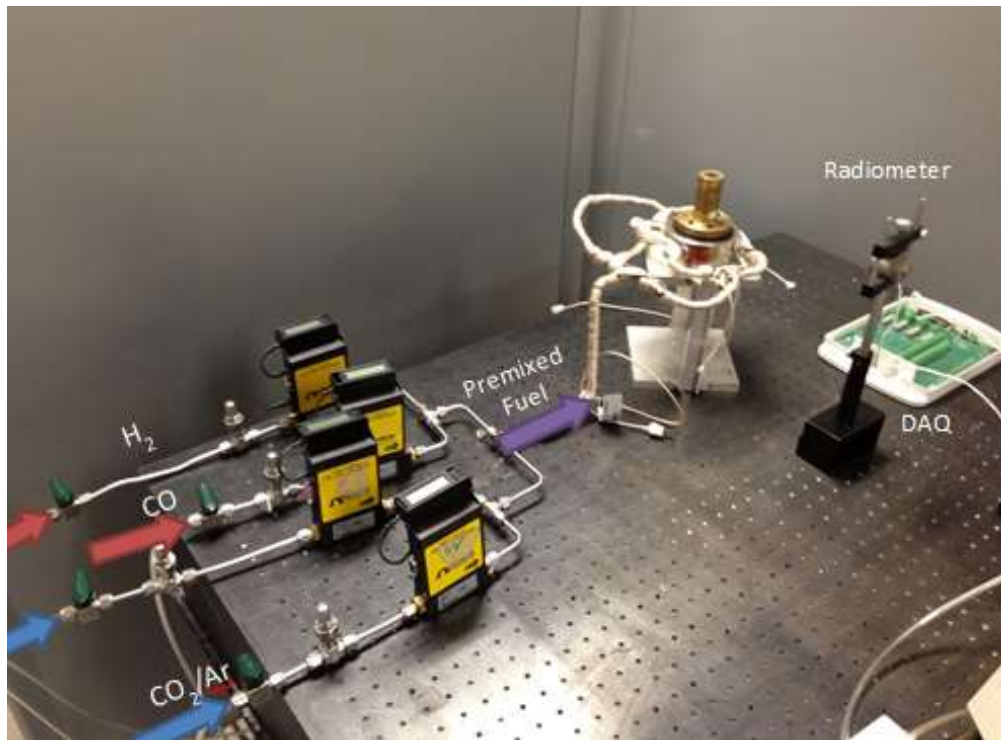


Fig. 3.5. Experimental setup

Global radiation measurements, wavelength range of .2 to 50 μm , were taken from a Mark IV non-contact temperature sensor & radiometer with a 150° view angle. The sensor is used in conjunction with a DAQ system to record the necessary readings at a rate of 1Hz. A NI SCC-68 connector block (Fig. 3.6 a) was used to record the voltage readings and a LabVIEW program was used to take the recordings. The block diagram for the labVIEW program is presented in Fig. 3.6 b. A set of 1000 voltage readings or more were recorded for each run. The recorded voltages were averaged and the final reading was taken. The voltage reading recorded would be later be manipulated using the manufacturer's provided calibration factor in order to acquire the desired measurements. The Mark IV radiometer has a sensitivity of $60 \text{ mV}/(\text{KW}/\text{m}^2)$, a time response of 2 seconds ($t^*63\%$), the max allowed mV output is 40 mV, the impedance of the sensor is 75Ω , the max body temperature is 121 degrees Celsius and the accuracy of the sensor is $\pm 3\%$. The schematic of the radiometer can be seen in Fig 3.7.



Figure 3.6 a. ANI SCC-68 connector block

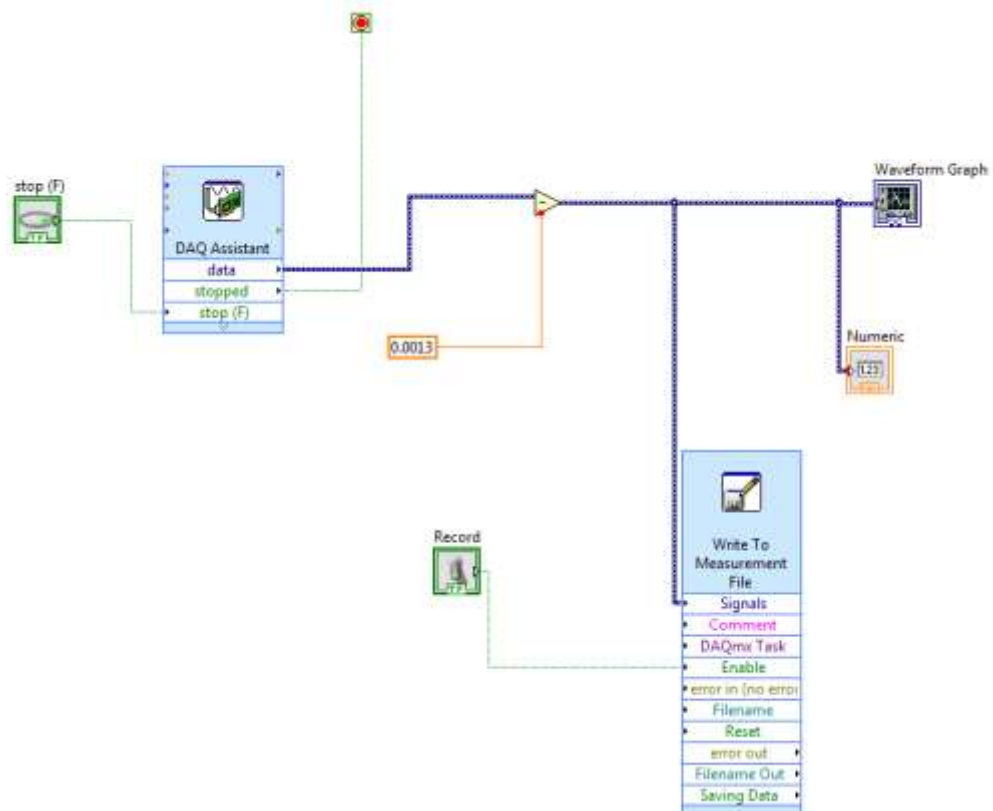


Figure 3.6 b. Block LabVIEW diagram used for voltage recordings

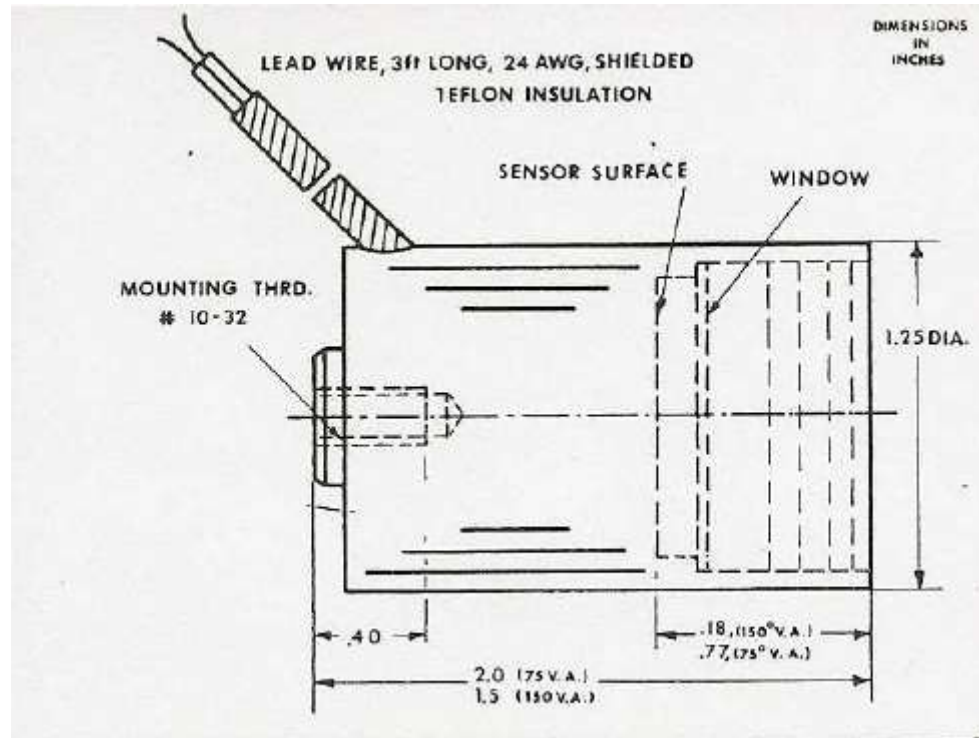


Fig. 3.7. Schematic diagram of radiometer used

For all experiments, experimental uncertainties were calculated using a Student's t-distribution with 95% confidence interval. Experimental uncertainties of present measurements are less than $\pm 1\%$ of the mean value thus error bars are not visible in the graphs presented.

3.2 Methodology

In many oxy-fuel combustion systems diluents are added into the fuel or oxidizer stream in order to reduce flame temperatures which are significantly higher for flames burning in pure oxygen. In some systems the dried exhaust stream, which is primarily CO₂, is recycled back with the oxidizer stream to help reduce temperatures. It is therefore important to characterize the amount of recirculate flue gas needed to achieve the desired flame temperatures and stability. For this paper the term recirculation ratio (RR) is defined as the mass fraction of CO₂ in the oxidizer stream.

$$RR_{CO_2} = \frac{\dot{m}_{CO_2}}{\dot{m}_{O_2} + \dot{m}_{CO_2}} \quad (1)$$

Other variables presented in this paper include the flame firing input which was calculated using the lower heating value of the fuel, LHV_{fuel} multiplied by the mass flowrate of the fuel \dot{m}_{fuel} .

For global radiation it was assumed that the flame emitted radiant heat equally in all directions. The sensor was then positioned 1.5 flame lengths away from the flame. By positioning the sensor 1.5 times the flame lengths away from the burner the entire flame is captured by the radiometer. Thus the radiative heat release factor provides a value less than 1 which expresses the amount of heat transferred by radiation from the flame. A schematic diagram of the procedures is shown in Fig 3.8.

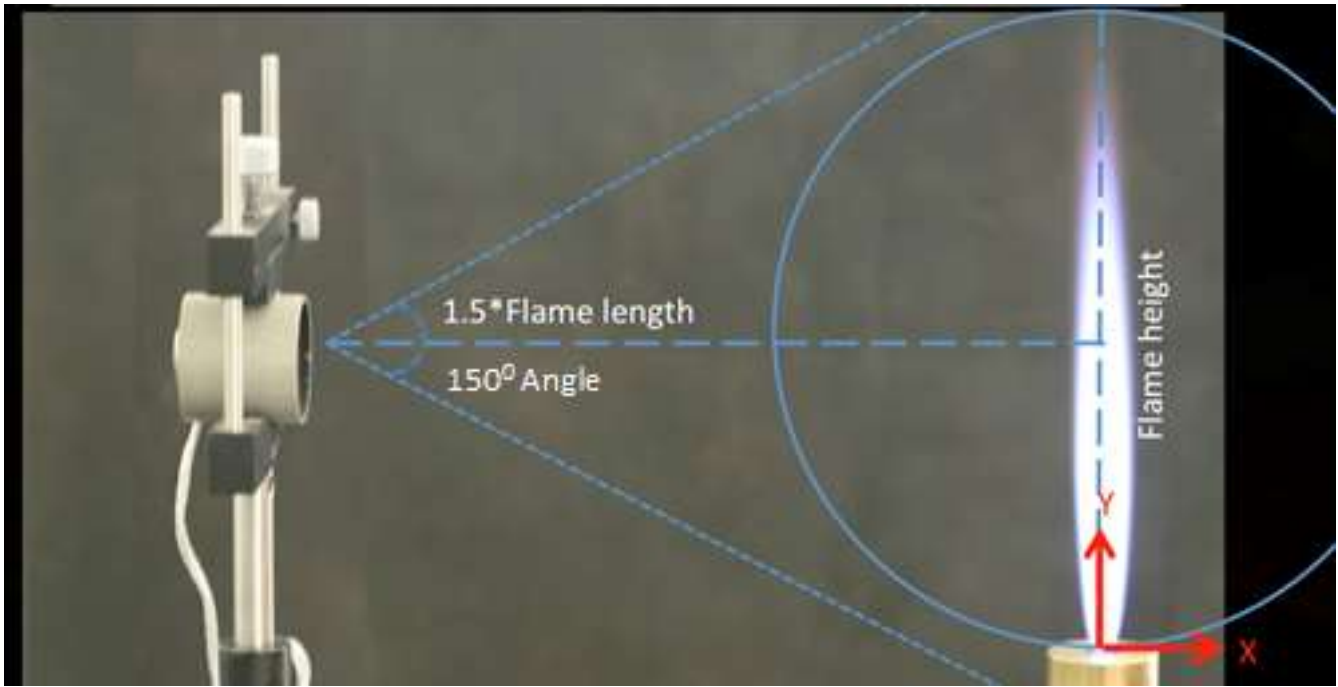


Fig. 3.8. Experimental procedure

$$F = \frac{q_{rad}}{q_{in}} = \frac{4\pi r^2 * q_{rad}}{\dot{m}_{fuel} * LHV_{fuel}} \quad (2)$$

In Eq. (2) F represents the radiative heat release factor, r represents the distance from sensor to the burner center, q_{rad} is the measured heat transfer from the flame to radiometer, \dot{m}_{fuel} is the fuel mass flowrate, and LHV_{fuel} is the lower heating value of the fuel mixture used.

For the calculations, the equivalence ratio was defined as equation 3:

$$\varphi = \frac{(O/F)_{stoic}}{(O/F)_{actual}} \quad (3)$$

In equation 3 the numerator stands for the stoichiometric oxidizer to fuel ratio and the denominator stands for the actual oxidizer to fuel ratio, both of them by mass.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Effect of RR_{CO_2} on F

For these sets of experiments the fuel was premixed with CO_2 and O_2 using a 10 mm diameter tubular burner. The mixture is composed of 10% H_2 and 90% CO at a constant equivalence ratio of 1. The flame was taken to the blow-off point which was considered when the flame was no longer anchored to the burner, Fig. 4.1.

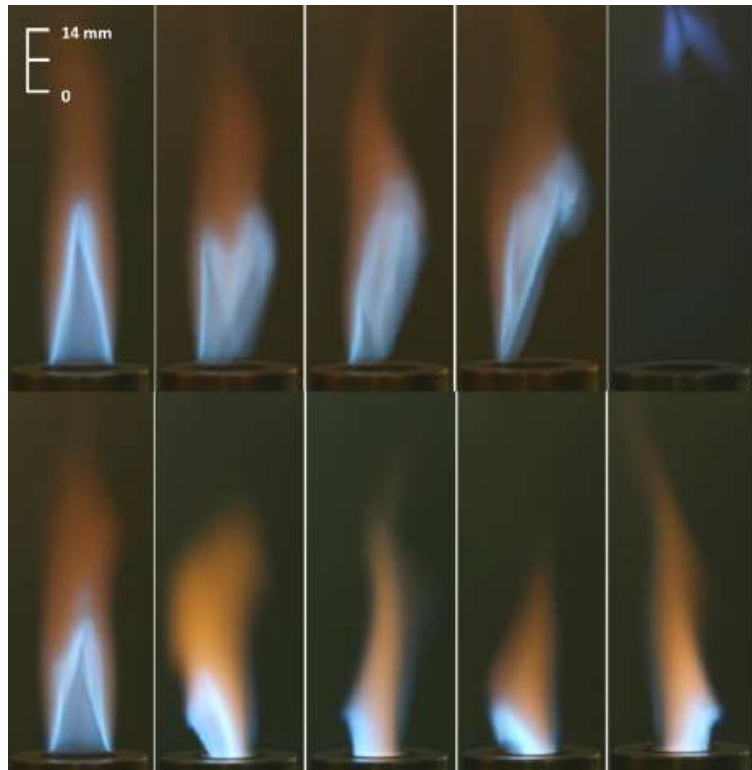


Fig. 4.1. Criterion used to determine flame flashback (bottom) and blowout (top).

In this figure we can see how the flame is initially anchored to the burner tip. As the recirculation ratio of carbon dioxide is increased the pool of O and H radicals in the reaction is reduced, thereby reducing the burning velocity of the mixture leading to a flame blowout. On the bottom picture the flashback process is shown. The flame is initially stabilized at the burner tip, as the carbon dioxide is

decreased more O and H radicals are available for the reaction to take place, this increases the temperature of the flame thereby increasing the flame speed. When the flame speed is larger than the volumetric flow rate going out of the burner the flame propagates inward into the burner tube.

For this experimentation the flame was initially on a near blow out setting. The RR_{CO_2} was then decreased until flame flashback as depicted in Fig. 4.1. The F value was then recorded at different CO_2 concentration throughout the process. The resulting data points were then plotted as shown in Fig. 4.2. Both the flashback and blow off points (FB, BO) are marked on the plot. For each F value there is a corresponding adiabatic flame temperature presented which was calculated using CHEMKIN with GRI mechanism 3.0. It was observed that the flame temperature decreased at higher RR_{CO_2} . It is well known that dilution with excess air or CO_2 decreases flame temperature [30].

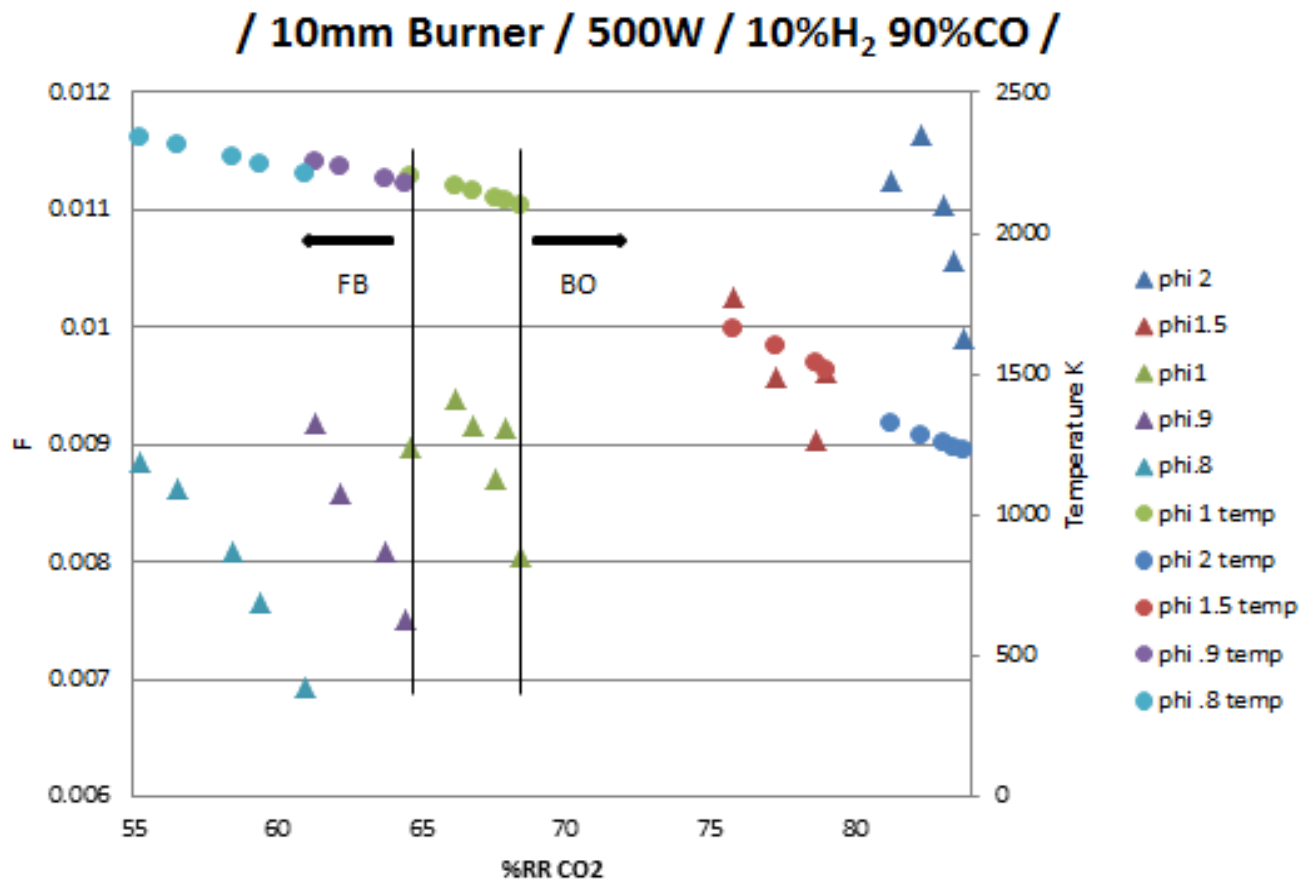


Fig. 4.2. Effect or recirculation ratio of CO₂ on F

The net radiation loss rate of a heated body radiating to its cooler surrounding is dependent on area, emissivity, and flame temperature. In Fig. 4.2 it is seen that although the adiabatic flame temperature decreases the radiative heat release factor increases for a given RR_{CO_2} . The flame lengths were recorded for each point; variations in flame length for different RR_{CO_2} can be seen in Fig. 4.3. The average calculated area assuming an axisymmetric flame shape was 0.028 mm^2 which is significantly smaller than the highest measured area and 0.003 mm^2 below the smallest measured area. Another factor influencing F measurements include flame emissivity which can also have a significant effect on the radiative heat release factor. Since CO_2 has a higher emissivity than N_2 , a major diluent in air combustion, it is feasible that since more CO_2 is present the mixture's emissivity could be significantly affected resulting in different radiative heat fraction values.

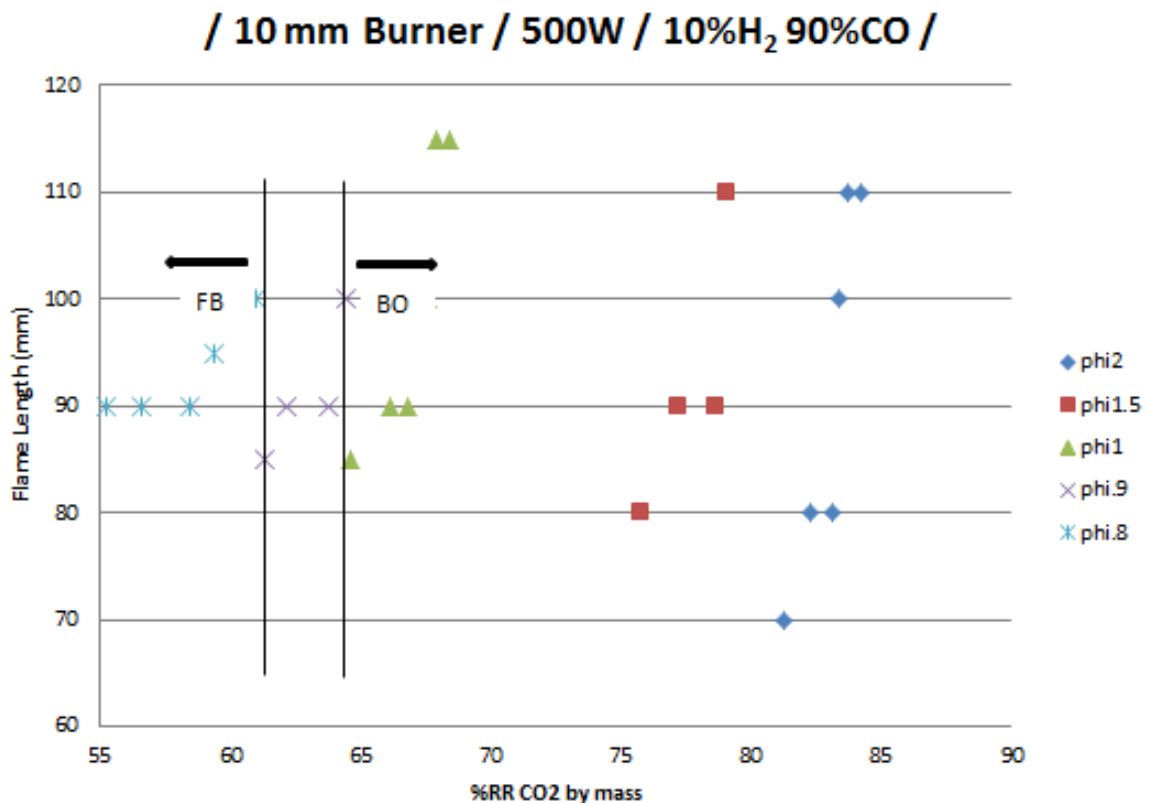


Fig. 4.3. Flame lengths measured at different equivalence ratios.

A set of mixture compositions was prepared using CHEMKIN with GRI mechanism 3.0 so that the adiabatic flame temperature was constant at different RR_{CO_2} . A good stability range was noted to occur at an adiabatic flame temperature of 2616 K. The different compositions were mainly positioned towards the lean range of the flame. Richer compositions were investigated, however; the increase in the fuel content of these mixtures promoted the occurrence of flashback due to the high concentration of hydrogen in the mixture when compared to the other reactants. The flame length of these compositions was at a steady 20 mm in height on a 10 mm burner. The radiative heat measurements were taken at the pre-determined compositions and the results are reported in Fig. 4.4. The RR_{CO_2} is plotted against F and on the secondary axis the calculated adiabatic flame temperature is shown for each on the F measurements taken. It is seen that as the RR_{CO_2} is increased the radiative heat release factor increases while the flame temperature remains constant. It is important to note that the flame length also remained constant throughout this set of experiments; this would make the possibility that the emissivity of the flame is influenced by the amount of carbon dioxide recirculated to the combustion process.

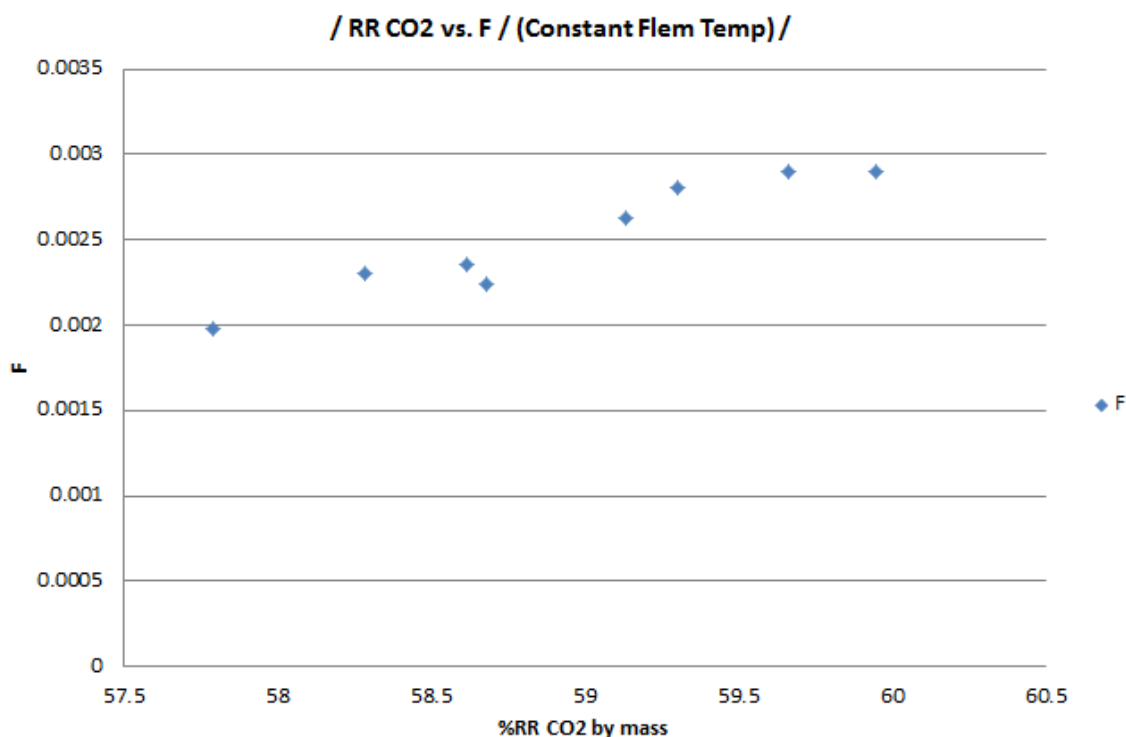


Fig. 4.4. Recirculation ratio of carbon dioxide vs. F at constant adiabatic flame temperature

Another set of experiments was conducted this time for a fuel composition consisting of 30% hydrogen and 70% carbon monoxide. The experiments were conducted on a 10 mm burner. The results can be seen in Fig. 4.5.

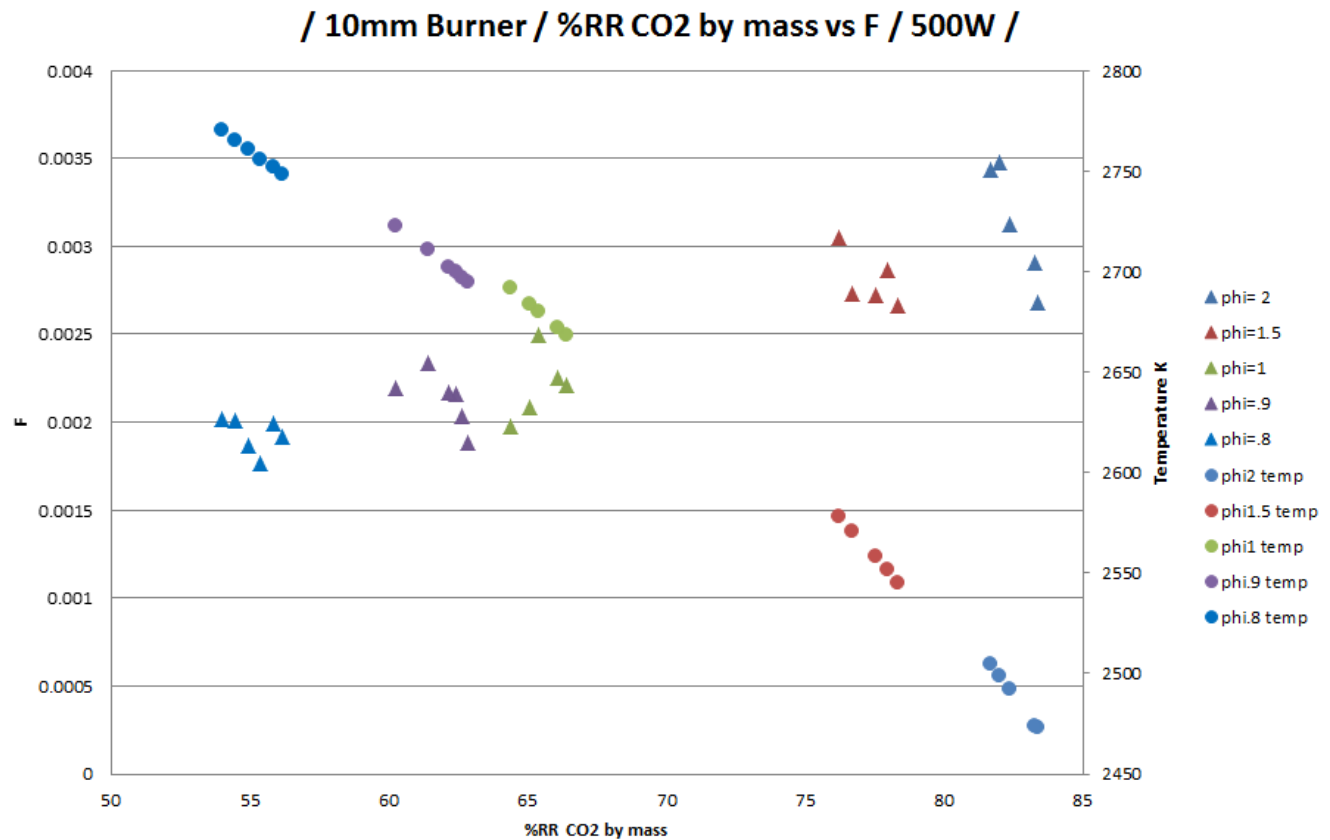


Fig. 4.5. 30%H₂, 70% CO mixture. Effect of recirculation ratio of CO₂ on F and flame temperature

In Fig. 4.5 it can be noted a decrease in intensity of the radiative heat release factor when compared to 10% H₂ in the fuel mixture. According to previous studies done with fuel mixtures containing [31], the addition of H₂ into the fuel blends prevented the formation of soot and carbon dioxide which emit strong radiation in the combustion process. A similar behavior is noted on the syngas. Also the big influence the addition of CO₂ into the syngas composition has on the adiabatic flame temperature is appreciated.

4.2 Effect of Firing Input on F

These experiments were conducted using a 10 mm tubular burner. Firing inputs of 0.5, 1 and 1.5 kW were tested and F values measured. The flame composition is 10%H₂ and 90%CO at a constant equivalence ratio of 1. The flame was first stabilized at a near blow off composition. The recirculation ratio of CO₂ was then progressively decreased until the flame experienced flashback. F values were taken at different CO₂ concentrations throughout both points. The blowout and flashback points (BO, FB) are marked on the plot. For these conditions as the RR_{CO2} was decreased for the different firing inputs, values were measured as depicted in Fig. 4.4. Measurements were taken from the flame blow off to flashback conditions as defined.

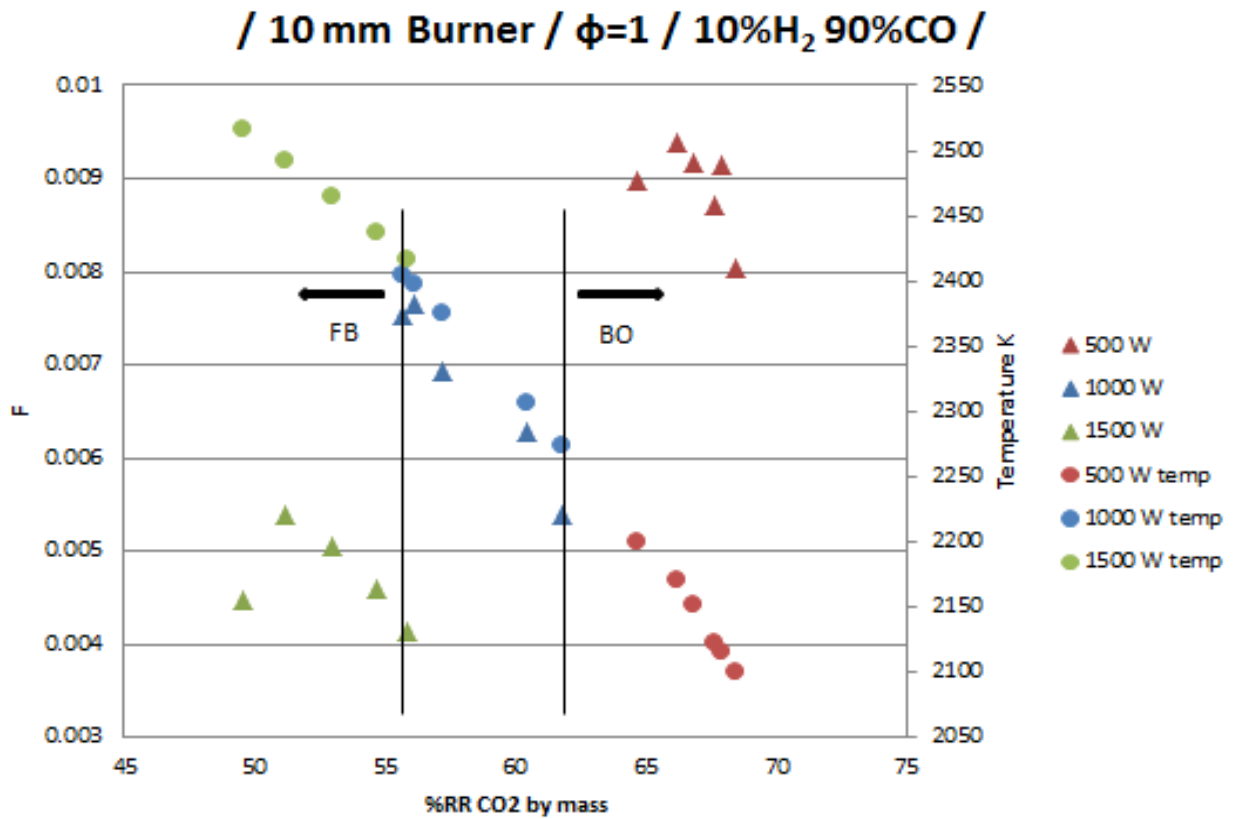


Fig. 4.6. Effect of firing input on F

When decreasing the FI from 1.5 kW to 1 kW it becomes easy to compare and observe the effect of FI where the temperatures, RR_{CO_2} and F are nearly the same for both conditions. At this point it can be seen that going to a lower firing input increases F since a higher RR_{CO_2} can be accommodated while opposite at higher firing inputs.

4.3 Effect of H₂ Concentration on F

The percentage of hydrogen content in the syngas was varied from 15 to 30% by volume for different firing inputs. For these measurements the equivalence ratio was held constant at 1. The premixed mixture was burned using a 6 mm injector. As in the previous section for each F value there is a corresponding adiabatic flame temperature calculated using CHEMKIN. For these experimental measurements argon gas was premixed with the oxidizer in order to eliminate the CO₂ radiative emission contribution and helps stabilize the flame so that flashback propensity was reduced. The results can be seen in Fig. 4.5

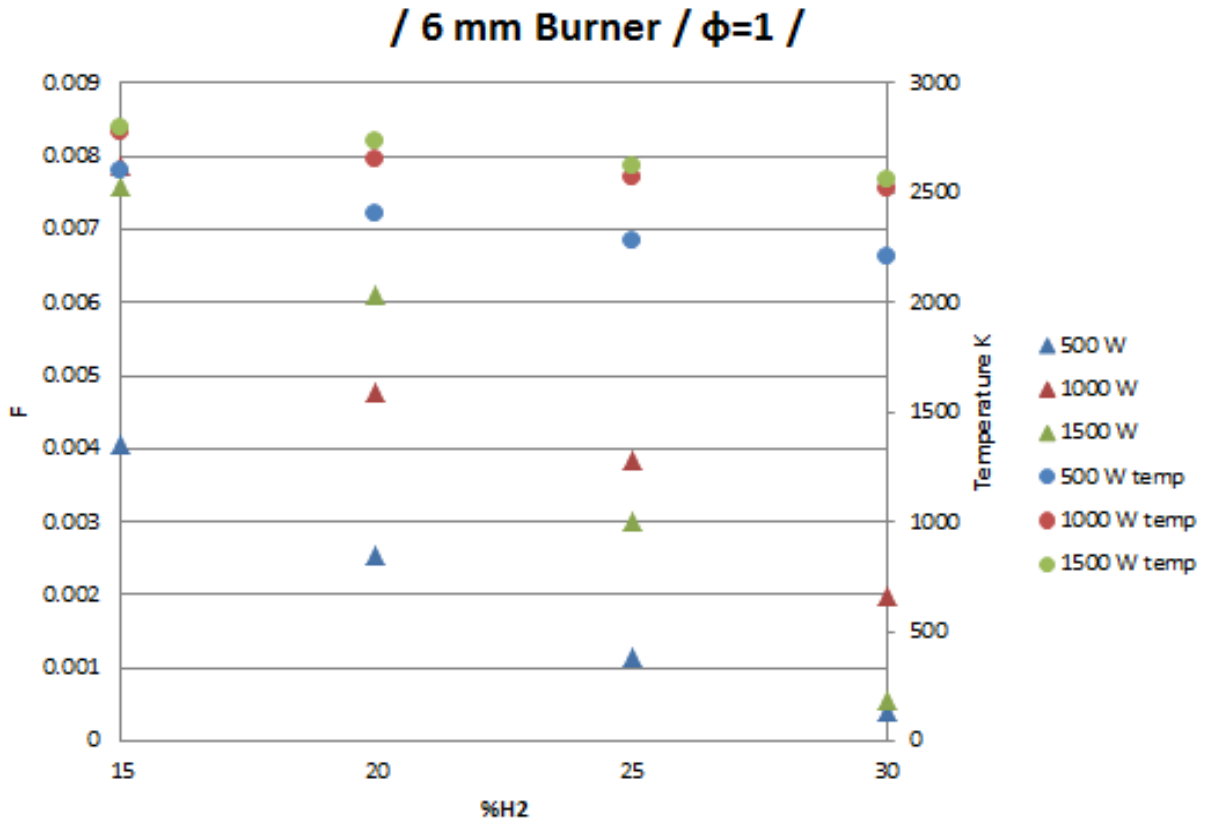


Fig. 4.7. Effect of %H₂ on radiative heat release rate.

Previous studies have been conducted where an increase in added hydrogen to a hydrocarbon fuel mixture leads to a decrease in the radiative heat release factor. This is due to the fact that hydrogen

decreases the formation of soot and carbon dioxide in the combustion process [31]. In these experimental measurements syngas combustion case a similar trend was observed. The temperature decreased even though the hydrogen content increases due to the amount of argon needed to stabilize the oxy-syngas flame at the different hydrogen contents.

CHAPTER 5

CONCLUSIONS

Motivated by the change in the radiative properties when conducting oxy-syngas combustion, this project aims to characterize the flame radiation properties of the global radiation of oxy-syngas combustion. The effects of CO_2 acting as a diluent, percentage of H_2 in the fuel and the effects of equivalence ratio on the flame's radiative heat release ratio. The results can be summarized as follows:

- Higher RR_{CO_2} increases the radiative heat release factor and decreases syngas adiabatic flame temperature.
- A broader stability range of the syngas flame was noticed on high firing inputs more than at lower ones. A similar trend was noted on leaner flames than on richer flames.
- Even when radiative heat emission from a source is strongly dependent on temperature, the radiative heat release rate increased as adiabatic flame temperature decreased. It was ruled out that the area of the flame did not fluctuate as much making it is possible that due to its high emissivity CO_2 is affecting the radiative heat emission from the flame.
- It was determined that when changing equivalence ratio at fairly constant RR_{CO_2} and T_{ad} the flame radiative heat release rate noticeably increases.
- Higher concentrations of H_2 decrease the radiative heat release ratio in a similar fashion as in previous studies performed.
- A trend was noted when having RR_{CO_2} and T_{ad} relatively constant where the decrease in the flame firing input leads to a lower radiative heat release factor.
- A plot of mixtures that generate a constant adiabatic flame temperature of 2616 K was generated.

The Radiative heat release factor increases with an increase in the RR_{CO_2} even if the flame

temperature remains constant. This supports the idea that the CO_2 present in the combustion process is responsible for a change in the emissivity.

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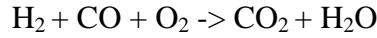
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Appendix A

Sample Calculations

Equivalence Ratio and Mixture

The balanced chemical equation is given by:



From the given formula the $(\text{O}/\text{F})_{\text{stoic}}$ can be calculated. Since it is a 1:1 relation the $(\text{O}/\text{F})_{\text{stoic}}$ for a 10% H_2 -90% CO mixture is: 1.2806. This value can be corroborated using NASA's CEA.

With the $(\text{O}/\text{F})_{\text{stoic}}$ it is possible to calculate the amount of oxidizer needed for a desired composition when a firing input is defined.

For equivalence ratio of 1:

$$1 = \frac{1.2806}{(\frac{\text{O}}{\text{F}})_{\text{actual}}}$$

Where the F is acquired from the desired firing input defined by:

$$\text{F.I.} = \dot{m}_{\text{fuel}} * \text{LHV}_{\text{fuel}}$$

For a F.I. of 500 W the \dot{m}_{fuel} needed is .301 L/min hydrogen and 2.332 L/min for carbon monoxide. From equivalence ratio equation the amount of oxidizer needed is 2.656 L/min.

Uncertainty Calculation

An uncertainty analysis was conducted using propagation of experimental uncertainty on the radiative heat release factor, F. F is given by:

$$F \pm dF = \frac{q_{\text{rad}}}{q_{\text{in}}} = \frac{4\pi r^2 * q_{\text{rad}}}{\dot{m}_{\text{fuel}} * \text{LHV}_{\text{fuel}}}$$

Where dF is given by:

$$dF = \left[\left(\frac{\partial F}{\partial q} dq \right)^2 + \left(\frac{\partial F}{\partial F_L} dF_L \right)^2 + \left(\frac{\partial F}{\partial \forall} d\forall \right)^2 \right]^{1/2}$$

Where dq , dF_L , and $dV=(B^2+R^2)^{1/2}$ (B=biased error, R=random error) for the different measured values of q_{rad} , flame length and volume flow rate respectively.

F Sample Calculation

Once the desired composition is stabilized in the burner the radiometer should be adjusted according to Fig. 3.8. The voltage reading is taken the calibration factor given by the manufacturer is used (5.28 mV/(KW/m²)) to acquire KW/m², then the value is multiplied by the surface area of a sphere to acquire the total radiation emitted. The radiative heat release factor can then be obtained through:

$$F = \frac{q_{rad}}{q_{in}}$$

Example:

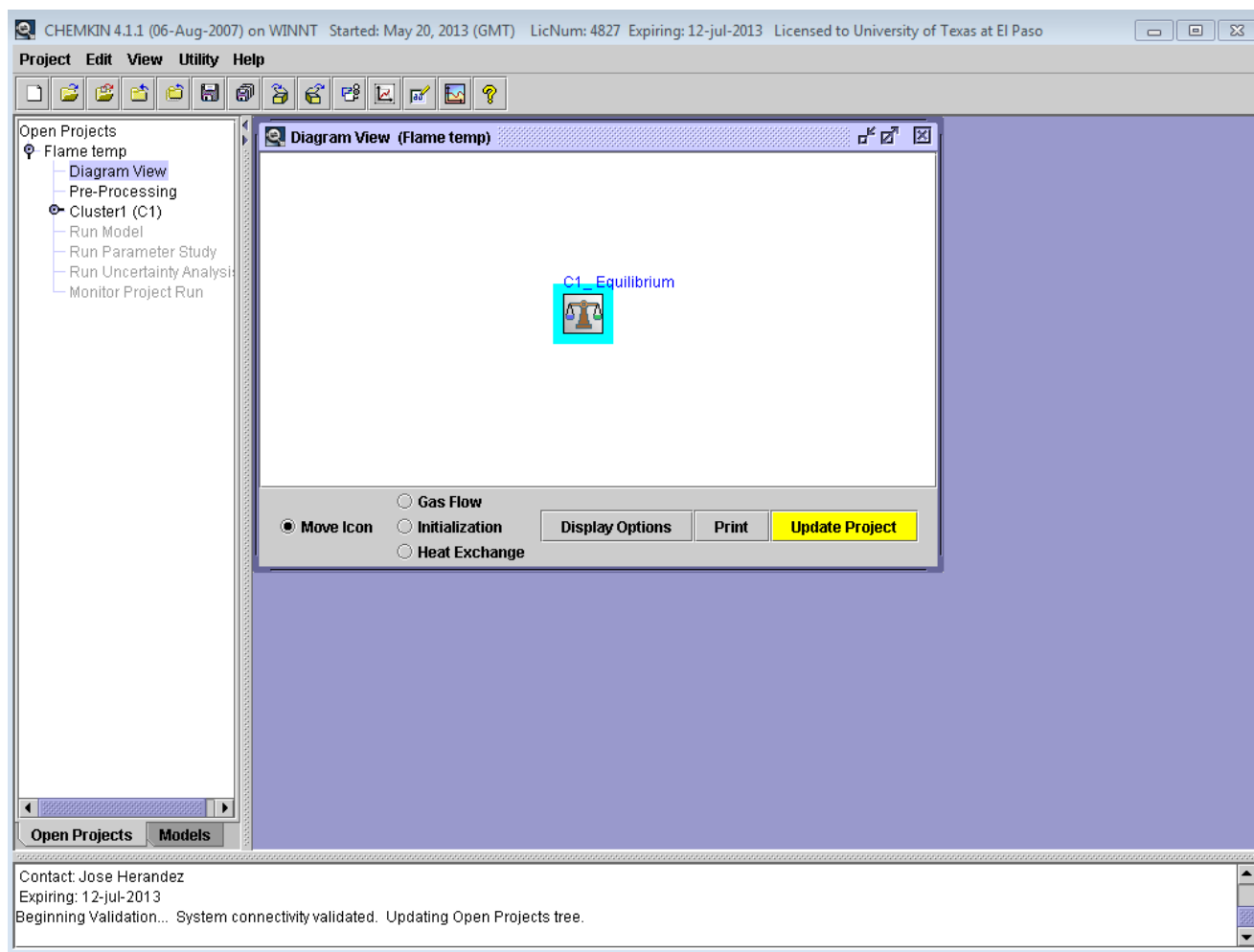
For a F.I. of 500 W the recorded flame length was 110 mm and the voltage reading acquired was .000747V or .747 mV. The value is then multiplied by the given factor to get .117 KW/m². This value multiplied by the surface area of a sphere with a 110 mm diameter gives .00446 KW or 4.464 W which is q_{rad} . The radiative heat release factor is then given by the previously mentioned formula (4.464W/500W) giving a radiative heat release factor of .00893.

Appendix B

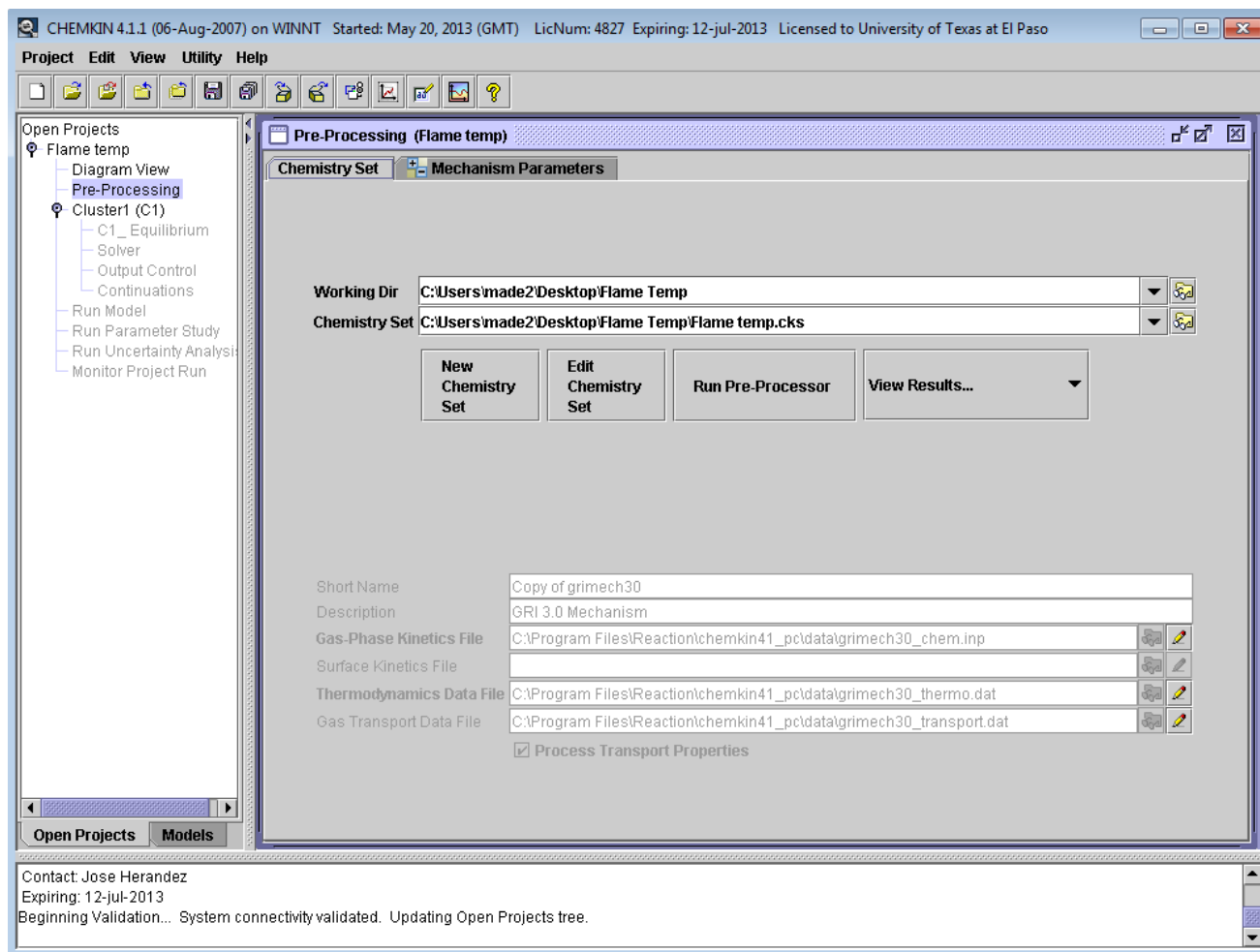
Adiabatic Flame Temperature

The following figures give the parameters needed to calculate the adiabatic flame temperature in CHEMKIN:

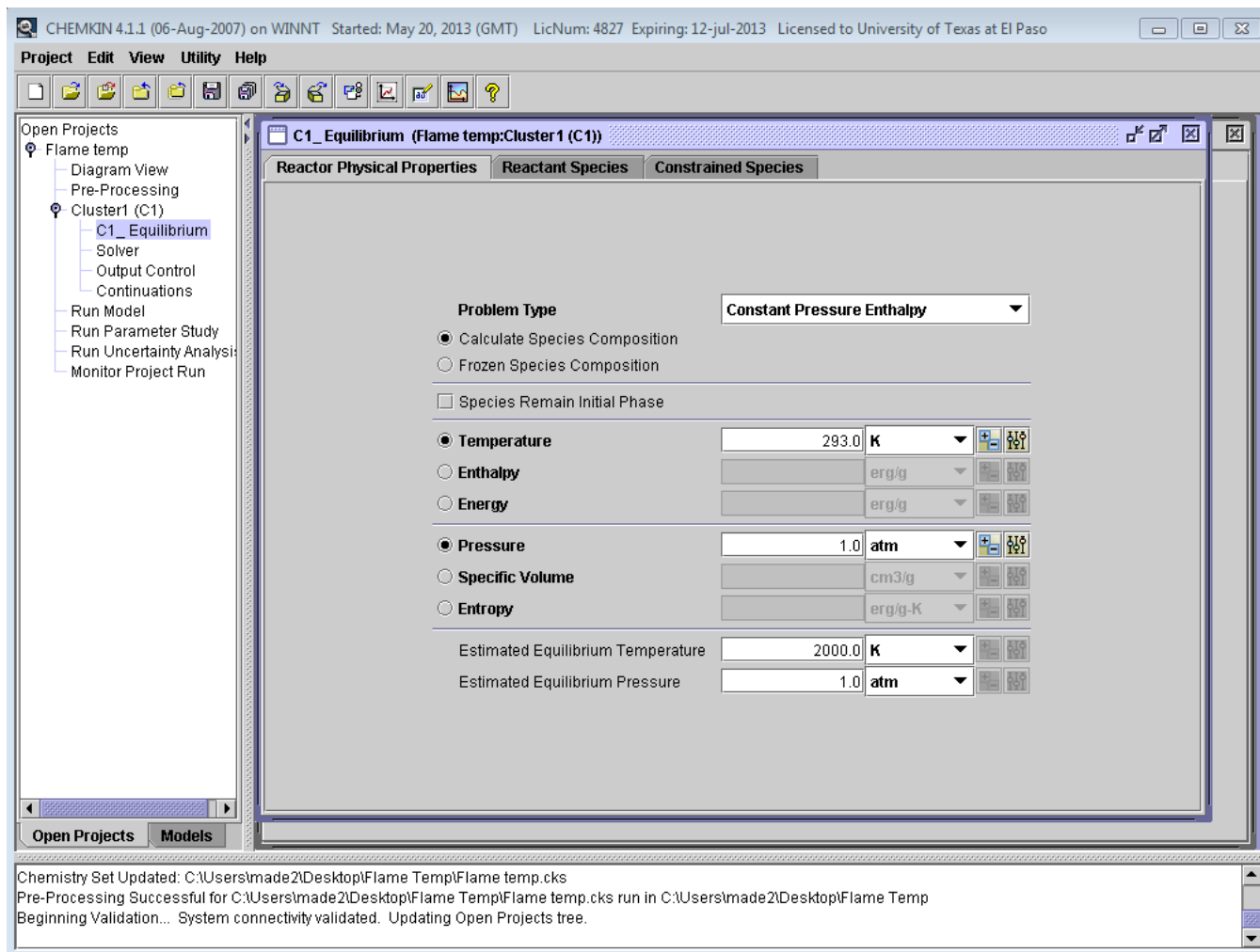
The chemical and phase equilibrium calculation model should be used.



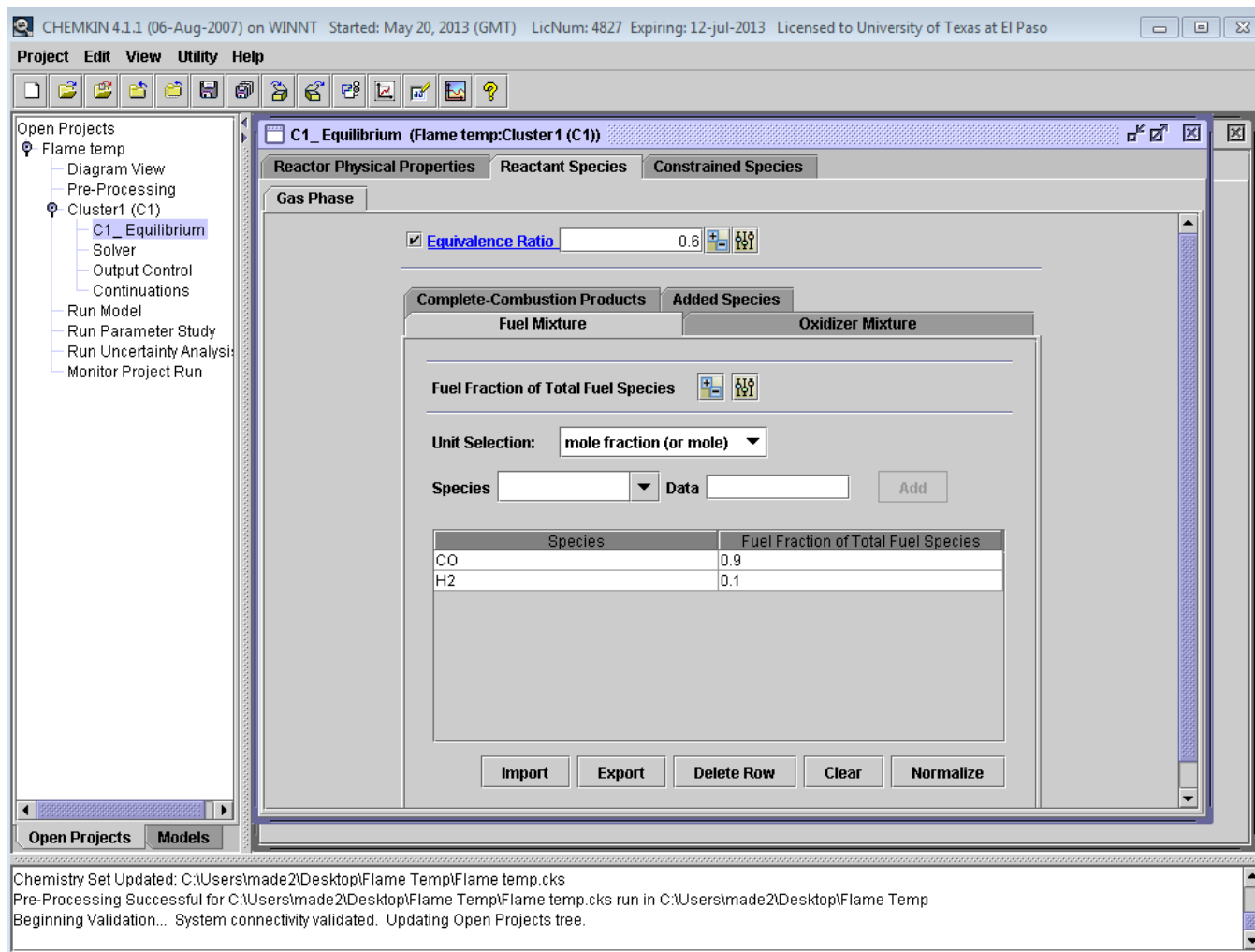
The Chemistry set used should be the one containing the GRI mechanisms 3.0



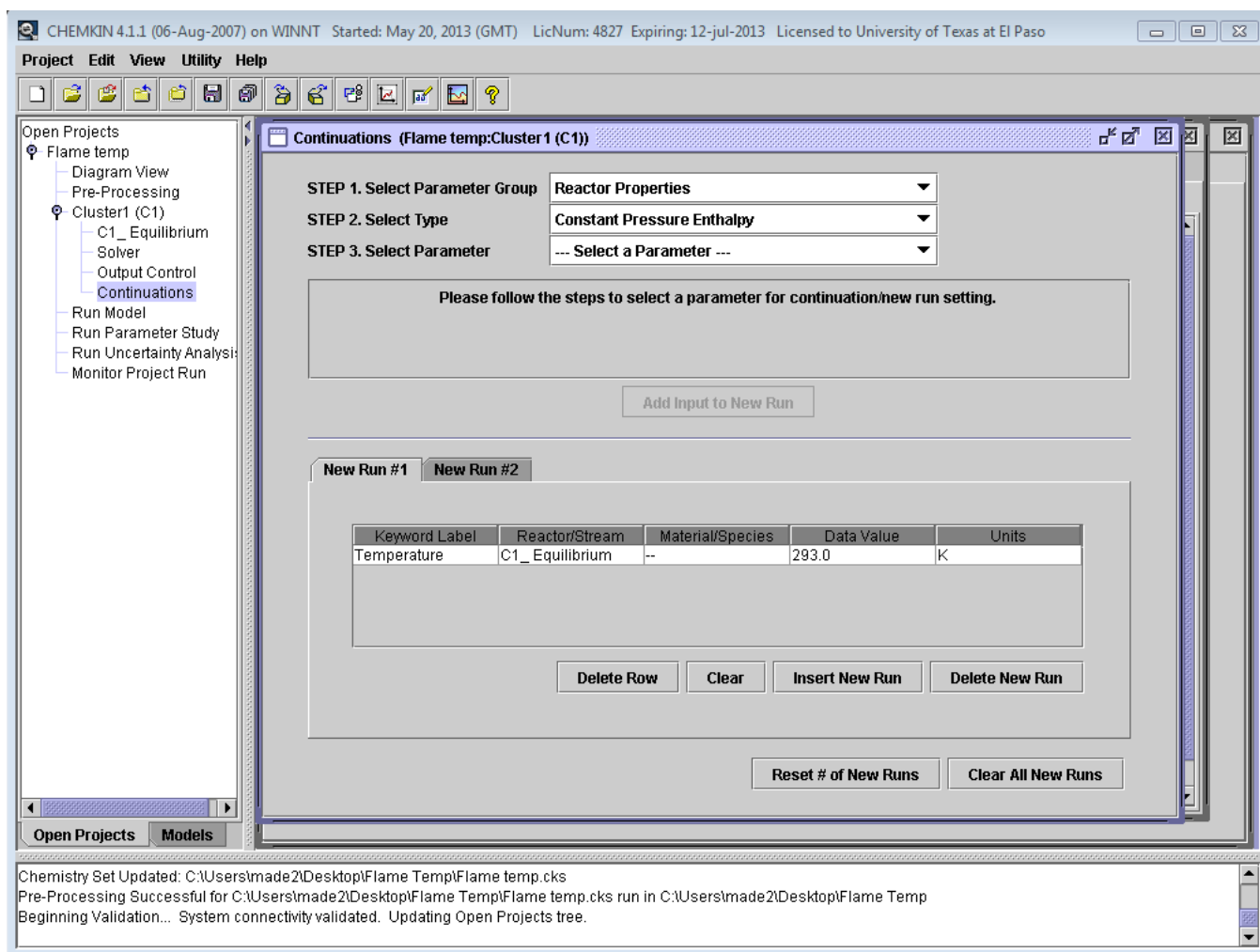
The problem type is set to constant pressure enthalpy. The gases enter at room temperature to the combustion process and an estimated equilibrium temperature of 2000K is used. Note both Equilibrium and initial pressure are constant to 1atm.



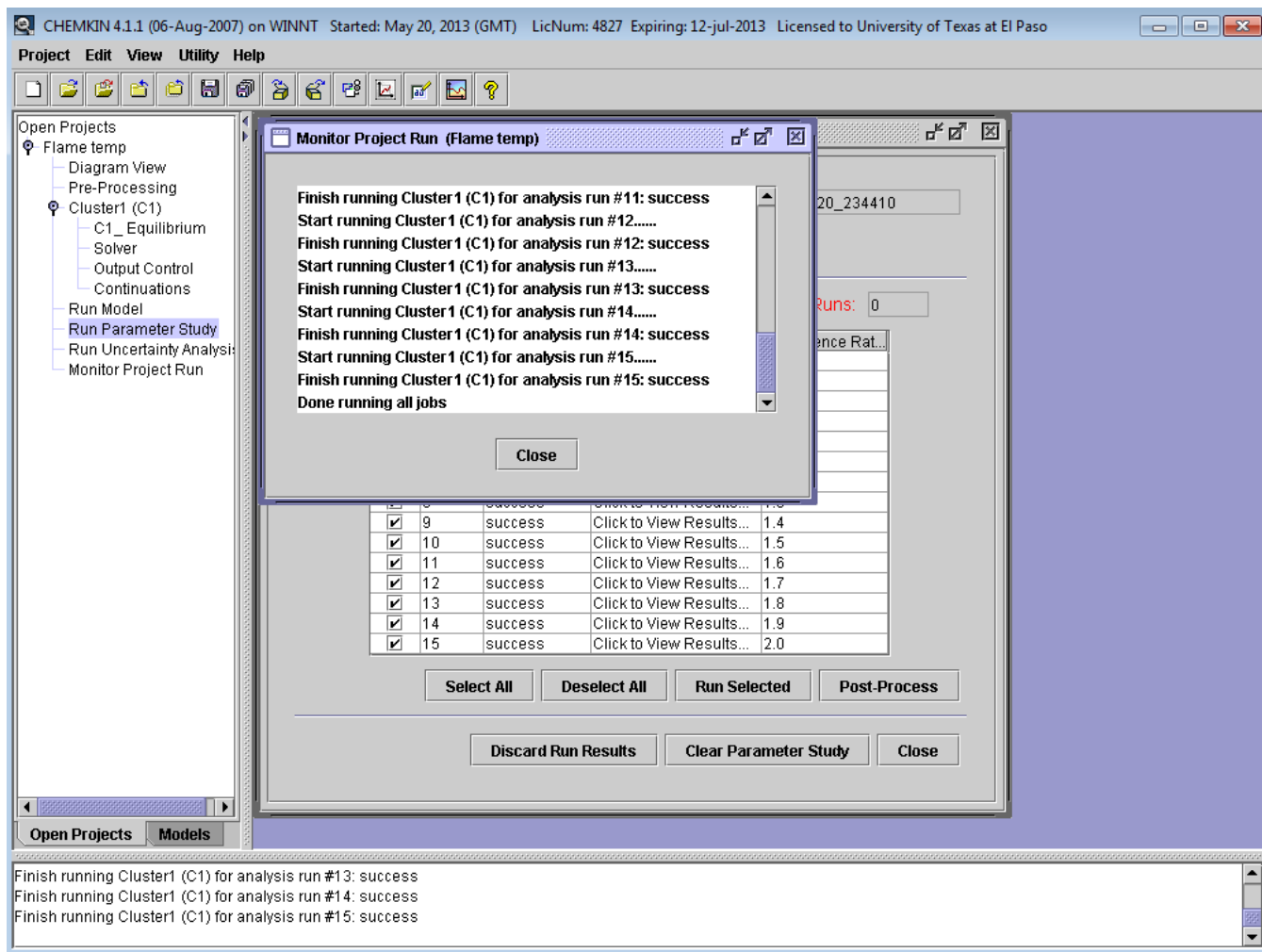
A setup parameter study should be defined according to the equivalence ratio needed. The fuel mixture, oxidizer mixture, complete combustion products and added species should be properly defined.



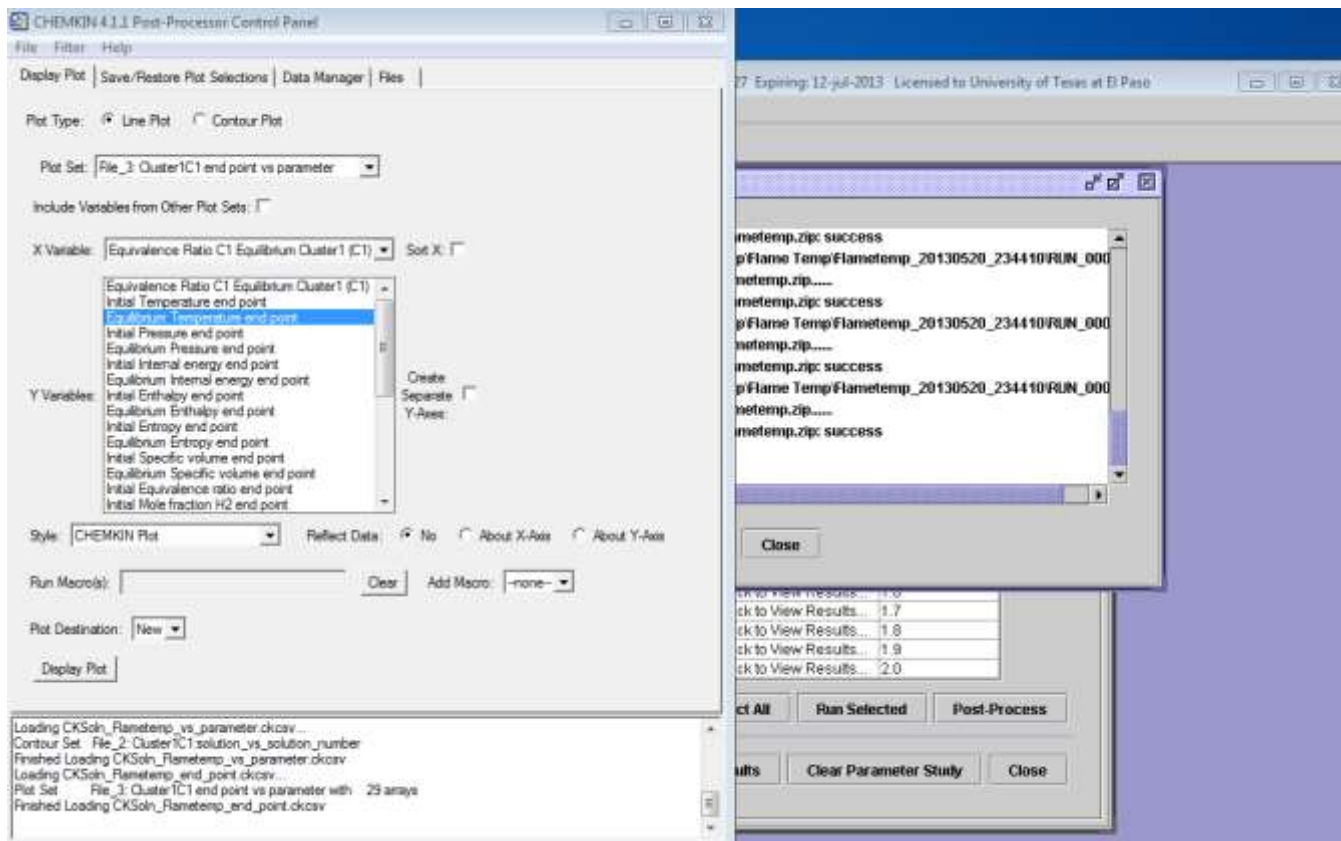
Once the C1_Equilibrium section is filled up, the number of continuations should be set. A minimum of two continuations is needed for adiabatic flame temperature calculations. The first run is set at room temperature and the second run is set at the estimated equilibrium temperature.



Once the continuations are set the parameter study can be performed. Select all and run the selected runs. Once this is done post process the solutions to generate the desired plot.

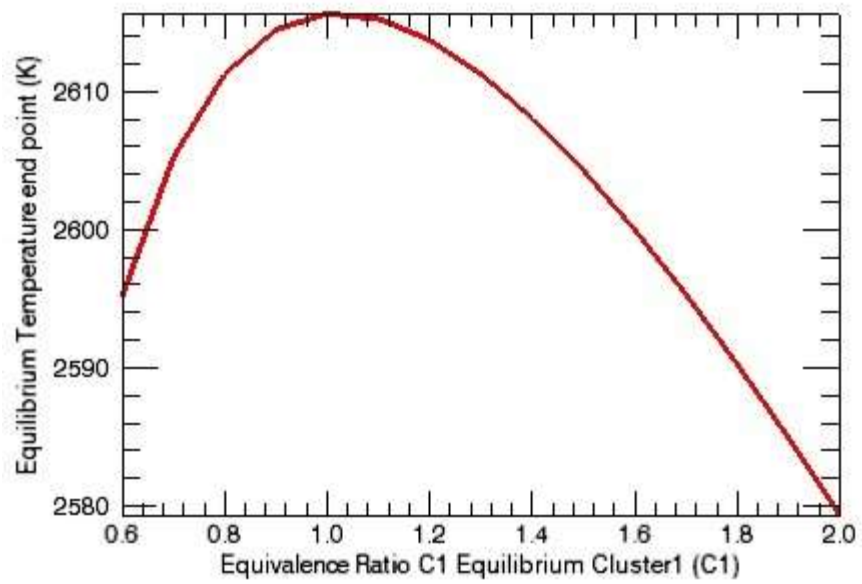


Once the post process is finished one can process the solution data to generate a plot.

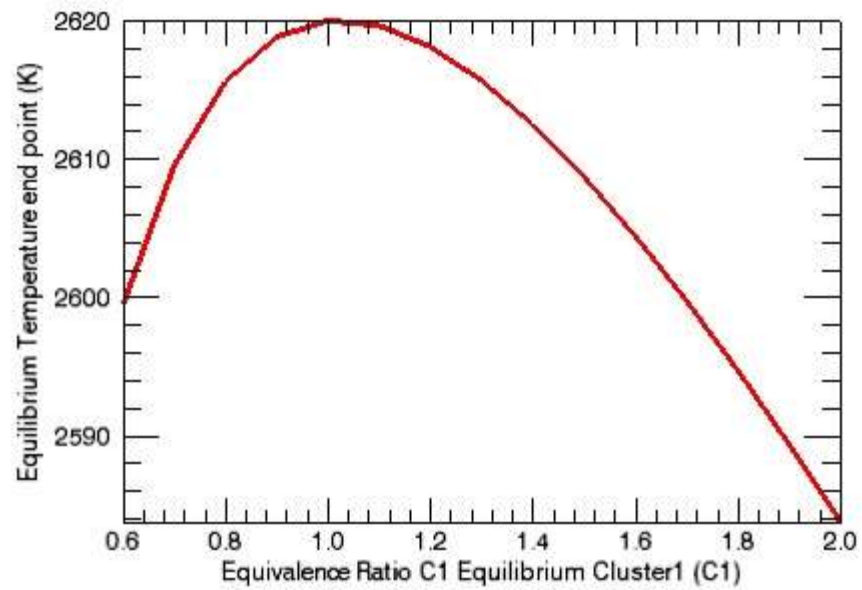


At this point when the display plot is clicked the desired plot should be generated.

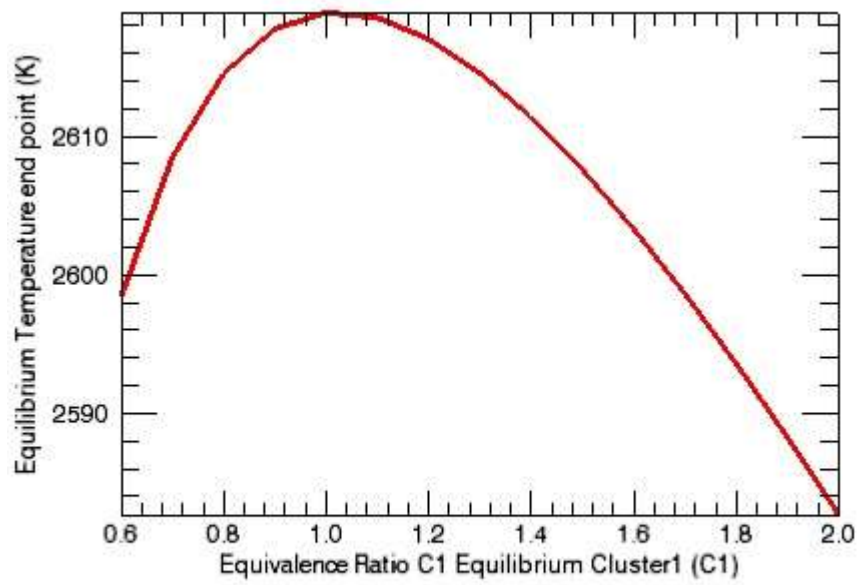
Constant Adiabatic Flame Temperature Plots



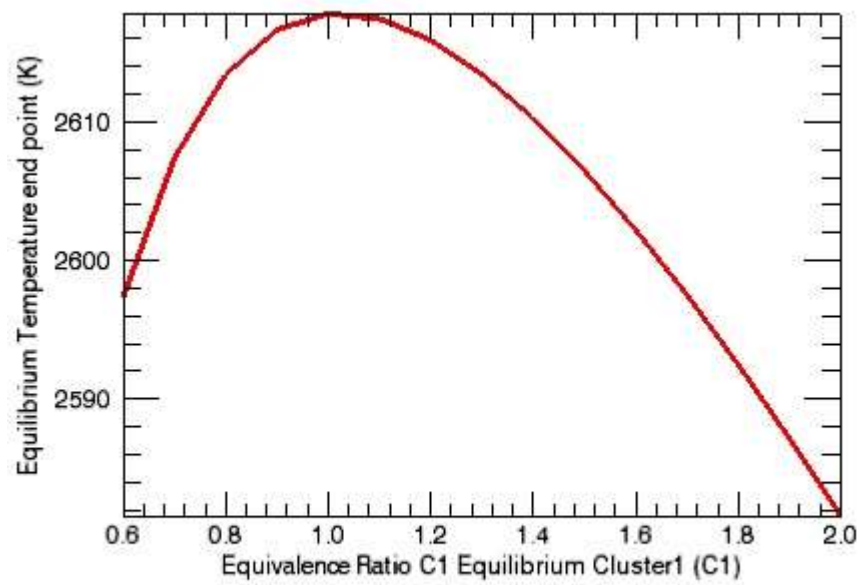
@phi=1.003, T=2616, 10%H₂-90%CO, CO₂ content=.57



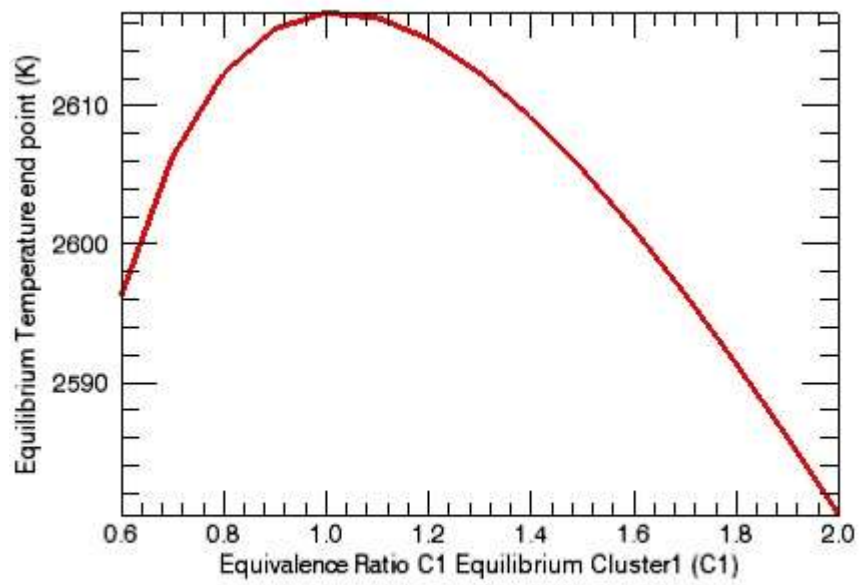
@phi=.8234, T=2616, 10%H₂-90%CO, CO₂ content .566



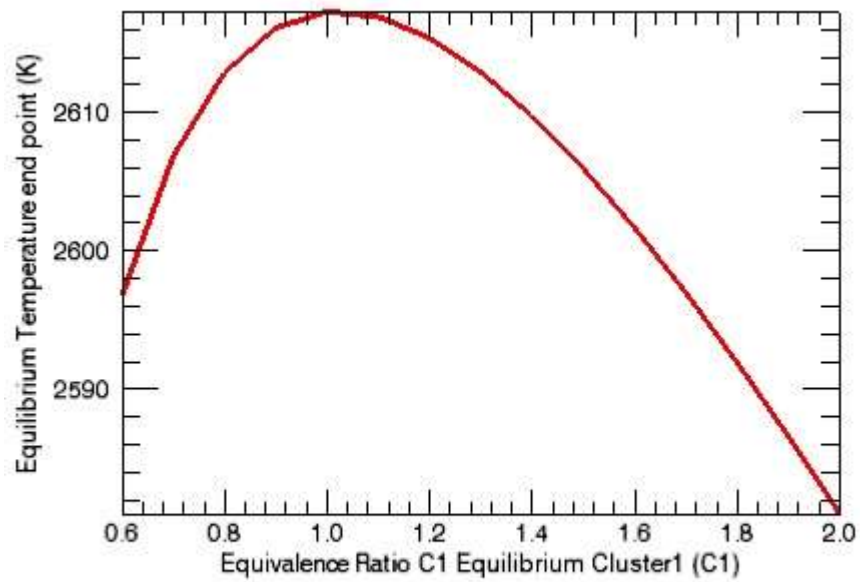
@phi=.8625, T=2616, 10%H2-90%CO, CO2 content .567



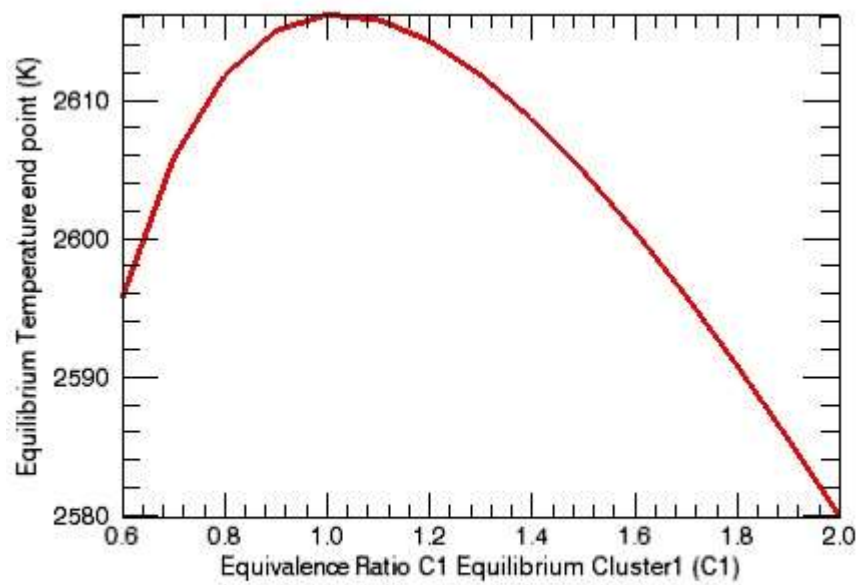
@phi=.568, T=2616, 10%H2-90%CO, CO2 content=.568



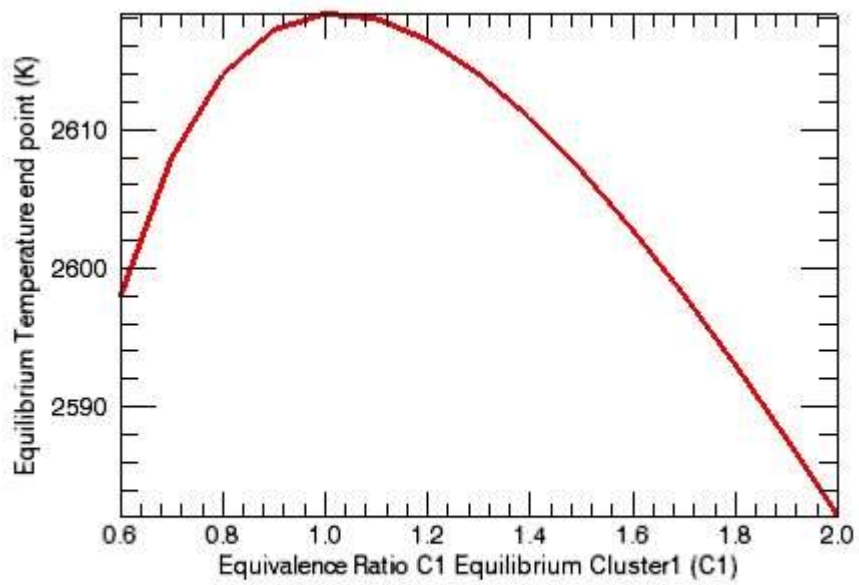
@phi=-.9797, T=2616, 10%H2-90%CO, CO2 content .569



@phi=-.9484, T=2616, 10%H2-90%CO, CO2 content .5685



@phi=.5695, T=2616, 10%H2-90%CO, CO2 content .5695



@phi=.8820, T=2616, 10%H2-90%CO, CO2 content .5675

VITA

Martin de la Torre was born in Cd. Juarez, Chihuahua, in 1987. He is the son of Martin de la Torre Rangel and Alma Rosa Gonzalez Salcido. He attended Cathedral High School and graduated in Spring 2006 and began his undergraduate studies at the University of Texas at El Paso in Fall 2006, and received a Bachelor of Science in Mechanical Engineering in May 2011. In August 2011, he began working as a research assistant at the Center for Space Exploration Technology Research (cSETR), working in the oxy-fuel combustion team under the supervision of Dr. Norman Love and Dr. Ahsan Choudhuri. All the experiments conducted to acquire the presented data were performed at the (cSETR) at the University of Texas at El Paso.

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