

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

**EXPERIMENTAL INVESTIGATION OF COMBUSTION PERFORMANCE
AND LEAN BLOWOUT LIMITS OF A COMBUSTION-AIR-HEATER**



M.Sc. THESIS

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Department of Mechanical Engineering

Heat-Fluid Programme

JUNE 2019

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**BİR YANMALI HAVA ISITICISININ YANMA PERFORMANSININ VE FAKİR
SÖNME LİMİTLERİNİN DENEYSEL OLARAK ARAŞTIRILMASI**

YÜKSEK LİSANS TEZİ

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To my family,



FOREWORD

This thesis work to complete Heat-Fluid Master Programme at Istanbul Technical University is the consequence of the effort I have given since June 2017 in a practically challenging field. I feel proud that this work, which is one of the first examples of its field in our country, will lead other researchers by offering a new vision in combustion working field.

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May 2019

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ABBREVIATIONS

CAH	: Combustion-Air-Heater
CNG	: Compressed Natural Gas
LBO	: Lean Blowout





SYMBOLS

A	: Kinetic pre-exponential factor (Chapter 2), Swirler flow area (Chapter 3)
c_p	: Heat capacity at constant pressure
c_{pk}	: Heat capacity at constant pressure of species k
d	: Diameter
D	: Heat diffusivity coefficient
D_k	: Diffusion coefficient of species k
E_a	: Activation energy
h_k	: Enthalpy of species k
H	: Enthalpy
I_b	: Blue color intensity
I_r	: Red color intensity
k	: Reaction rate constant (Section 2.1.2)
L_f	: Flame length
Le_k	: Lewis number of species k
m	: Total mass of gas in this volume
$\dot{m}_1$	: Mass flow rate of inlet 1
$\dot{m}_2$	: Mass flow rate of inlet 2
$\dot{m}_A$	: Mass flow rate of air
$\dot{m}_F$	: Mass flow rate of fuel
m_k	: Mass of species k in a given volume
$\dot{m}_O$	: Mass flow rate of oxidizer
M	: Mach number
N	: Number of species
p	: Total pressure
p_k	: Partial pressure of species k
Pr	: Prandtl number
R	: Specific gas constant
Re	: Reynolds number
Re_H	: Reynolds number based on the distance along burner axis

R_u	: Universal perfect gas constant
RR	: Rate of disappearance
s	: Stoichiometric ratio
S	: Entropy
T	: Temperature
T_0	: Reference temperature, air temperature at given altitude (Chapter 3)
T_{ad}	: Adiabatic flame temperature
T_i	: Initial temperature
T_{inlet}	: Combustion air inlet temperature
T_{outlet}	: Combustion gases temperature
T_{total}	: Total temperature
u_i	: Three dimensional velocity field
U	: Internal energy, velocity, axial mean swirler velocity (Chapters 3, 4 and 5)
U_b^*	: Dimensionless flow number to estimate blowout velocity
$\overline{U_e}$	: Dimensionless velocity at blowout
V	: Volume
w_i	: Mass fraction
W	: Mean molecular weight of a mixture
W_0/U_0	: Ratio of mean tangential and mean axial velocities at swirl cup exit
W_A	: Molecular weight of air
W_F	: Molecular weight of fuel
W_k	: Atomic weight of species k
W_O	: Molecular weight of oxidizer
x	: Stoichiometric coefficient
x_i	: Mole fraction
y	: Stoichiometric coefficient
Y_F	: Mass fraction of fuel
Y_k	: Mass fraction of species k
Y_O	: Mass fraction of oxidizer
z	: Position of the swirler inside the air jet
Z_{AB}	: Gas kinetic collision frequency
a	: Stoichiometric coefficient
β	: Coefficient of excess oxygen
δQ	: Sum of the heat transferred

$\Delta h_{f,k}^0$	: Mass enthalpy of formation of species k
ΔH_C	: Specific heat capacity of fuel
η	: Efficiency
$\eta_{\Delta T}$	: Efficiency based on temperature rise
γ	: Specific heat ratio
λ	: Heat diffusion coefficient
ν	: Kinematic viscosity
ν'_F	: Coefficient corresponding to fuel
ν'_O	: Coefficient corresponding to oxidizer
Φ	: Equivalence ratio
Φ_g	: Global equivalence ratio
ϕ/ϕ_{LBO}	: Equivalence ratio over equivalence ratio at lean blowout
ρ	: Density
ρ_k	: Density of species k
ρ_O	: Density of the oxidizer

Subscripts

<i>exp</i>	: Experimental
<i>irrev</i>	: Irreversible
<i>prod</i>	: Products
<i>reac</i>	: Reactants
<i>rev</i>	: Reversible
<i>st</i>	: Stoichiometric
<i>th</i>	: Theoretical



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EXPERIMENTAL INVESTIGATION OF COMBUSTION PERFORMANCE AND LEAN BLOWOUT LIMITS OF A COMBUSTION-AIR-HEATER

SUMMARY

In high speed air-breathing propulsion system ground tests, atmospheric flight temperature condition must be satisfied. To satisfy this condition, stored air must be heated. Such heating may accomplished by different methods. Vitiating the air by burning fuel is a low-cost and simple technic. Fuel is burned in a burner with a predetermined equivalence ratio, then the vitiated air with oxygen makeup expands through a facility nozzle. The reason for oxygen adding to the vitiated air is to replenish the oxygen amount in the air, which is consumed in combustion process. At TÜBİTAK SAGE a burner which is used as a combustion-air-heater (CAH) is established to perform ground tests.

The primary aim of present study is to carry out performance tests of the CAH and prove its ability to meet atmospheric flight temperature condition. The burner performance tests are accepted as successful, if the temperature condition is satisfied under the fuel and the oxidizer mass flow rates determined before the experiment.

The secondary aim of present study is to characterize the CAH by experimentally investigating its lean blowout limits, under ambient pressure condition. The present work focuses on the effects of oxygen enrichment of combustion air, existence of oxygen lancing and axial mean swirler velocity on lean blowout limits, respectively. Throughout present work, fuel/oxidizer equivalence ratio has been determined as lean blowout limit criterion.

Brief information about burners, oxygen-enhanced combustion and air vitiation concept is given in Chapter 1. Literature survey is also placed in this chapter. Basics of combustion theory are discussed in Chapter 2 to give background knowledge about thermochemistry and turbulent diffusion flame. Theoretical calculations for experimental study are given in Chapter 3. In Chapter 4, experimental setup is introduced. Results and comments are given in Chapter 5.

Experimental results show that the CAH used within present study is capable of providing the atmospheric flight temperature conditions for high-speed air-breathing propulsion system ground tests. It is observed that the flame becomes more stable by increasing oxygen amount in the oxidizer. It is also observed that lancing pure oxygen directly into the burner helps the flame to stabilize better.

Results also show that, combustion efficiency increases as the percentage of oxygen-enrichment in air increases: at oxygen-enrichment percentages of 1.8, 2.7 and 4.4 combustion efficiencies are 64%, 75% and 89%, respectively. When combustion takes place, heat transfer occurs between the hot combustion gases and the cold burner wall. This heat transfer prevents to obtain the steady-state gas temperature in the first 60-100 seconds of the experiment. For this reason, the CAH must be

operated for at least 60 seconds in order to obtain the steady-state gas temperature before the ground tests are being carried out.

Another important result observed in present study is that combustion efficiencies of cases with oxygen lancing are lower. The flame is attached to the center of the CAH by lanced oxygen and combustion does not take place in outer regions. Thus, some amount of fuel could not be burned. This causes low combustion efficiencies.

Burner characterization experiments show that lean blowout limits are improved (operating region broadens) while oxygen enrichment percentage is increasing. At an axial mean swirler velocity of 30 m/s, the lean blowout limit in terms of equivalence ratio is 0.48 for CNG/air flame. This value is 0.11 for CNG/oxygen-enriched-air flame of 5% oxygen enrichment.

It is also observed that as axial mean swirler velocity increases, the operating envelope of the burner gets narrowed. For CNG/air flame, lean blowout limits at $U = 20$ m/s and $U = 30$ m/s are 0.22 and 0.48, respectively. For CNG/oxygen-enriched-air flame, lean blowout limits at $U = 30$ m/s and $U = 50$ m/s are 0.11 and 0.33, respectively.

Experimental results also show that oxygen lancing strongly improves lean blowout limits. Oxygen lancing decreases the lean blowout value below 0.06, even at higher axial mean swirler velocities as 70 m/s.

While the burner characterization experiments have been conducted, gas samples have been taken at near blowout conditions to analyze the combustion gases composition. Since gas samples have been taken at near blowout conditions and the thin flame has been anchored in the central region of the burner, high percentages of unburned fuel are observed. This may appear as a problem in terms of high-speed air-breathing propulsion system ground tests. When vitiated air with a high percentage of unburned fuel enters into the test engine, it affects the performance and safety of the test engine adversely as there exists another undesirable fuel. Vitiating the test engine combustion air under very lean conditions may have undesirable results.

BİR YANMALI HAVA ISITICISININ YANMA PERFORMANSININ VE FAKİR SÖNME LİMİTLERİNİN DENEYSEL OLARAK ARAŞTIRILMASI

ÖZET

Yanma, endüstriyel proseslerde en çok kullanılan enerji kaynağıdır. Bu nedenle yanma prosesi, çalışmaya değer bir araştırma konusudur. Yanma prosesinin güvenli şekilde kontrol altında tutulabilmesi için kapalı bir hacme ihtiyaç duyulur. Yakıcılar yanmanın kontrol altında tutulması işi için tasarlanan cihazlardır ve yakıt/oksitleyici karışım stratejilerine göre ön karışım, kısmi ön karışım ve difüzyon yakıcıları olarak sınıflandırılabilirler. Difüzyon alevi olarak adlandırılan ve oksitleyici ile yakıtın yakıcıya girmeden önce karıştırılmadıkları alev tipi diğerlerine göre daha az tehlikeli ve kontrol edilebilmesi daha kolay olduğundan, birçok yanma uygulamasında difüzyon alevi görülür. Bu çalışmada kullanılan yanmalı hava ısıtıcısı da difüzyon tipi bir yakıcıdır.

Yanma prosesinde genellikle oksitleyici olarak havanın kullanıldığı görülmektedir. Ancak bazı özel yanma proseslerinin, oksitleyici içerisindeki oksijen miktarı artırılarak gerçekleştirildiği de bilinmektedir. Buna oksijen ile iyileştirilmiş yanma prosesi denebilir. Oksijen ile iyileştirilmiş yanma proseslerinin, geleneksel olanlarına göre birtakım avantajları göze çarpmaktadır. Yüksek ısı verim ve kirletici gaz emisyonunun düşüklüğü bu avantajlara örnek olarak verilebilir. Bu çalışmada, yanma havası oksijence zenginleştirilerek yanmalı hava ısıtıcısına gönderilmiştir. Ayrıca ateşlemenin ve alev sürekliliğinin gerçekleştirilemediği bazı test noktalarında, yanmalı hava ısıtıcısı içerisine doğrudan saf oksijen beslemesi yapılarak alevin stabil hale gelmesi sağlanmıştır.

Yüksek hızlı hava solumalı itki sistemlerinin yer testlerinde, atmosferik uçuş sıcaklık koşulunun sağlanması gereklidir. Bu koşulun sağlanması için önceden depolanmış basınçlı havanın ısıtılması gerekir. Havanın ısıtılmasında farklı yöntemler uygulanmaktadır. Havanın yakıt yakılarak ısıtılması, düşük maliyetli ve basit bir yöntemdir. Yakıt, önceden belirlenmiş bir denklik katsayısında bir yanma odasında yakılır. Daha sonra, yanma sırasında harcanan oksijen miktarı telafi edilerek test lülesinden genişler. Yanma sonu gazına oksijen ilavesi yapılmasının nedeni, yanma prosesi sırasında harcanan oksijen miktarını karşılayarak havadaki gerçek yüzdesine tekrar ulaştırmaktır. TÜBİTAK SAGE’de, yüksek hızlı hava solumalı itki sistemlerinin yer testlerini gerçekleştirmek üzere yanmalı hava ısıtıcısı olarak kullanılan bir yakıcı bulunmaktadır.

Bu tez çalışmasının birincil amacı, yanmalı hava ısıtıcısının yanma performans testlerini gerçekleştirmek ve yer testleri için gereken atmosferik uçuş sıcaklık koşulunu sağlayıp sağlayamadığını kanıtlamaktır. Bu sıcaklık koşulunun, testler öncesinde hesaplanan teorik yakıt ve oksitleyici debileri ile sağlanması durumunda yanma performans testleri başarılı olarak değerlendirilmektedir.

Bu tez çalışmasının ikincil amacı ise yanmalı hava ısıtıcısının fakir sönme limitlerinin deneysel olarak belirlenmesidir. Deneylerde yanmalı hava ısıtıcısı basıncı

ortam basıncına eşittir. Deneysel çalışmanın öncelikli olarak yoğunlaştığı konu; yanma havasının oksijence zenginleştirilme miktarının, yanma odasına doğrudan saf oksijen beslenmesinin ve ortalama eksenel girdap üretici hızının fakir sönme limitlerine etkileridir. Bu çalışma boyunca, yakıt/oksitleyici denklik katsayısı fakir sönme limitleri için kriter olarak kullanılmıştır.

Bu çalışmanın birinci bölümünde, yanma odaları, oksijenle iyileştirilmiş yanma ve yanmalı hava ısıtıcıları hakkında özet bilgiler verilmiştir. Birinci bölümde ayrıca literatür taraması sonuçlarına da yer verilmiştir. İkinci bölümde yanma prosesinin teorisi hakkında temel bilgiler yer almaktadır. Okuyucuya özellikle termokimya ve türbülanslı difüzyon alevi hakkında bilgiler verilmiştir. Çalışmanın üçüncü bölümünde, testler öncesinde yapılan teorik hesaplamalara yer verilmiştir. Dördüncü bölüme test düzeneğinin tanıtımı ile devam edilmiştir. Beşinci bölümde test sonuçları ve yorumlar yer almaktadır.

Bu çalışmada testlerin gerçekleştirildiği altyapı; basınçlı kuru hava sistemi, oksijen telafi hattı, saf oksijen besleme hattı, yakıt besleme hattı, ateşleme sistemi ve yanma sonu gazı numunesi toplama sisteminden meydana gelmektedir. Test altyapısı basınç, sıcaklık, kütleli debi ve gaz numunesi bileşimini ölçmeye yarayan ekipmanlar ile donatılmış durumdadır.

Yanma performans testlerinin gerçekleştirilmesinde ilk adım, belirlenen toplam debiye göre yakıt, hava ve telafi edilecek oksijen debilerinin hesaplanmasıdır. Bu debi değerleri test sıcaklık koşuluna uygun bir denklik katsayısı yardımıyla hesaplanır. Test aşamasında ilk olarak basınçlı kuru hava sistemi aracılığıyla hava debisi ayarlanır. Daha sonra sırasıyla yakıt ve telafi oksijen debileri teorik hesaplamalara uygun olacak şekilde ayarlanır. Debi ayarlamalarından sonra ateşleme sürecine geçilir. Ateşlemenin gerçekleşip gerçekleşmediği bir kamera yardımıyla kontrol odasından takip edilir. Başarılı bir ateşlemenin ardından yanmalı hava ısıtıcısı üzerinde konumlanmış ısı çiftlerinden sıcaklık verileri takip edilir ve kayıt altına alınır. Alevin kendiliğinden sönmesi veya yanmalı hava ısıtıcısı duvarında yapısal dayanımı etkileyecek düzeyde yüksek sıcaklık değerleri görülmesi gibi olumsuz herhangi bir durum ile karşılaşılması takdirde ateşlemeden 120 saniye sonra test sonlandırılır.

Yanmalı hava ısıtıcısının fakir sönme limitlerini belirlemek için gerçekleştirilen testlerde ateşleme sürecine kadar olan test prosedürü, yanma performans testleri için yukarıda anlatıldığı gibidir. Ateşlemenin gerçekleşmesinden sonra yakıt debisi yavaş yavaş azaltılarak fakir sönme limitine ulaşılmaya çalışılır. Yakıt debisini azaltma işleminde dikkat edilmesi gereken nokta, bir sonraki azaltmaya kadar debi değerinin stabil hale gelmesinin beklenmesi gerektiğidir. Fakir sönme limitine ulaşıldığında, denklik katsayısının hesaplanması için yakıt, oksijen ve hava debileri kayıt altına alınarak test sonlandırılır.

Bu çalışma kapsamında gerçekleştirilen testler, kullanılan yanmalı hava ısıtıcısının yüksek hızlı hava solumalı itki sistemlerinin yer testleri için gereken atmosferik uçuş sıcaklık koşulunu sağladığını göstermektedir. Testler sırasında, oksitleyici (yanma havası) içindeki oksijen miktarı arttıkça alevin daha stabil hale geldiği gözlemlenmiştir. Buna ek olarak yanma odasına saf oksijen beslenmesinin, alevin sabitlenmesinde olumlu rol oynadığı görülmüştür.

Test sonuçları ayrıca, yanma havasındaki oksijen miktarının artması ile yanma veriminin de arttığını göstermektedir. Örneğin; yanma havasının yüzde olarak 1.8, 2.7 ve 4.4 kadar oksijence zenginleştirilmesi sonucu, yanma verimleri sırasıyla %64,

%74 ve %89 olmaktadır. Yanma prosesi meydana geldiğinde sıcak yanma sonu gazları ile soğuk yanma odası duvarı arasında ısı geçişi olmaktadır. Bu ısı geçişi olayı, yanma sonu gazlarının test başlangıcından 60-100 saniye sonrasına kadar sabit bir sıcaklıkta bulunmasına engel olmaktadır. Bu nedenle, yüksek hızlı hava solumalı itki sistemlerinin yer testleri yapılırken sabit hava sıcaklığını elde edebilmek için yanmalı hava ısıtıcısının testten en az 60 saniye önce çalıştırılması gerekmektedir.

Bu çalışma sonucu gözlemlenen bir diğer önemli sonuç ise yanmalı hava ısıtıcısına doğrudan saf oksijen beslenmesinin yanma verimini düşürdüğüdür. Saf oksijen beslemesi ile alev yanma odası merkezine sabitlenmekte ve çevre bölgelerde yanma gerçekleşmemektedir. Bunun sonucu olarak, yanma odasına gönderilen yakıtın bir kısmı yanmadan yanmalı hava ısıtıcısını terk etmektedir. Bu durum ise yanma verimini düşürmektedir.

Yanmalı hava ısıtıcısı karakterizasyon testleri, yanma havasının oksijence zenginleştirilme miktarı arttıkça fakir sönme limitlerinin iyileştiğini, dolayısıyla yanmalı hava ısıtıcısı çalışma zarfının genişlediğini göstermektedir. Ortalama eksenel girdap üretici hızının 30 m/s olduğu durumda, CNG/hava alevinin fakir sönme limiti denklik katsayısı değeri 0.48'dir. Aynı hızda CNG/oksijence %5 zengin hava alevinde bu değer 0.11'e kadar inmektedir.

Karakterizasyon testleri ayrıca, ortalama eksenel girdap üretici hızının artması ile yanmalı hava ısıtıcısı çalışma zarfının daraldığını göstermektedir. CNG/hava alevi için 20 m/s ve 30 m/s ortalama eksenel girdap üretici hızlarında fakir sönme limitleri denklik katsayısı değerleri sırasıyla 0.22 ve 0.48'dir. CNG/oksijence %5 zengin hava alevi için ise 30 m/s ve 50 m/s ortalama eksenel girdap üretici hızlarında fakir sönme limitleri denklik katsayısı değerleri sırasıyla 0.11 ve 0.33'tür.

Karakterizasyon testleri sonucunda, yanma odasına doğrudan saf oksijen beslenmesinin fakir sönme limitlerini oldukça iyileştirdiği görülmüştür. 70 m/s gibi yüksek bir ortalama eksenel girdap üretici hızında, yanma odasına saf oksijen beslenmesi ile fakir sönme limiti denklik katsayısı 0.06 değerinin altına indirilebilmektedir.

Yanmalı hava ısıtıcısı karakterizasyon testleri gerçekleştirilirken, bazı test noktalarında alevin sönmesine yakın koşullarda yanma sonu gazı bileşimini analiz etmek için gaz numuneleri toplanmıştır. Gaz numuneleri toplanırken alev sönmeye yakın ve yanma odası merkezinde sabitlenmiş halde olduğu için yüksek miktarlarda yanmamış yakıt rastlanmıştır. Yanma sonu gazlarında yanmamış yakıtın bulunması yüksek hızlı hava solumalı itki sistemleri yer testlerinde sorun teşkil etmektedir. Test motoru için sağlanan sıcak hava içerisinde yanmamış yakıtın bulunması, test motorunun performansını ve yer testlerinin güvenliğini olumsuz yönde etkiler. Bu nedenle yanmalı hava ısıtıcısının yakıtça çok fakir koşullarda çalıştırılmaması gerekmektedir.

Yanma proseslerinde karşılaşılan en büyük sorun alev stabilizasyonudur. Birçok durumda çakılı, stabil bir alevle karşılaşmak, salınımlı ve stabil olmayan bir alev gözlemlemeye göre oldukça zordur. Bu zorluğun üstesinden gelmek için yakıcı geometrisinde değişiklikler yapılması gerekmektedir.



1. INTRODUCTION

Combustion is the oldest technology of mankind; it has been used for more than one million years. At present, about 90% of our worldwide energy support is provided by combustion; therefore it is really worthwhile studying this process [1]. Combustion is the leading phenomena in industrial processes such as metal and ceramic industries, heat-treatment etc.

Combustion can be defined as a self-sustaining rapid exothermic reaction that liberates substantial energy as heat and flames as combustion reactions with the ability to propagate through a suitable medium [2,3]. A flame is the reaction zone between fuel and oxidizer and is often only a millimeter or so thick. There is fuel and oxidizer at low temperature side and are combustion products at high temperature side of the flame [3]. In Figure 1.1, two types of flame (premixed and diffusion) produced by a Bunsen burner are shown.

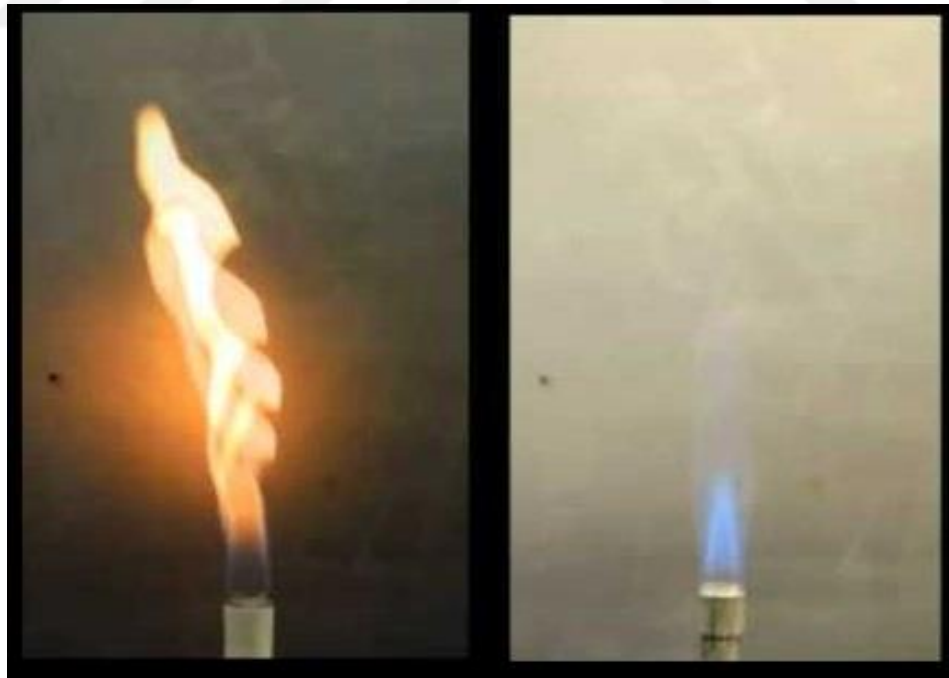


Figure 1.1: Premixed (on the right) and diffusion (on the left) flames produced by a Bunsen burner.

Generally, oxygen is used as oxidizer. In practice, combustion reactions proceed to completion with the fuel as the limiting reagent (with the excess air) [3].

In order to use combustion in industry, flame must be enclosed by a body which is called burner.

A burner should satisfy the basic requirements as follows [4]:

- High combustion efficiency,
- Reliable and smooth ignition,
- Wide stability limits,
- Low pressure loss,
- Low emission of smoke,
- Freedom from pressure pulsations and other manifestations of combustion-induced instability,
- Size and shape compatible with geometric envelope,
- Maintainability and durability.

1.1. Classification of Burners

By using burners, the combustion reaction can be controlled safely. Burners are designed as diffusion, premixed and partial premixed burners according to their operating principle. If fuel and oxidizer do not mix before entering to burner, this is a diffusion burner. On the other hand, in a premixed burner fuel and oxidizer do mix before entering to burner. A partial premixed burner mixes a part of the combustion air, with the remainder provided later. With respect to major considerations that affect burner design, burners are classified with five categories as shown in Table 1.1 [3]:

Table 1.1: Classification of burners.

Fuel State	Flame Shape	Fuel-Oxidizer Mixing Strategy	Firing Orientation	Emissions
Gas	Round	Premixed	Up-fired	Reduces combustion-related emissions
Liquid	Flat	Diffusion	Down-fired	Has no special features for reducing combustion-related emissions
Solid		Partial premixed	Side-fired	

Gas burners are mainly premixed or turbulent jet diffusion burners. Premixed burners generally are used where the required heat liberation is relatively small and a high intensity flame is required. The following characteristics are specific for premixed flames [5]:

- Small in volume relative to heat release rate,
- High combustion efficiency,
- Non-luminous and low radiant heat transfer efficiency,
- Noisy.

In Figure 1.2, an example of a premixed gas burner is shown.

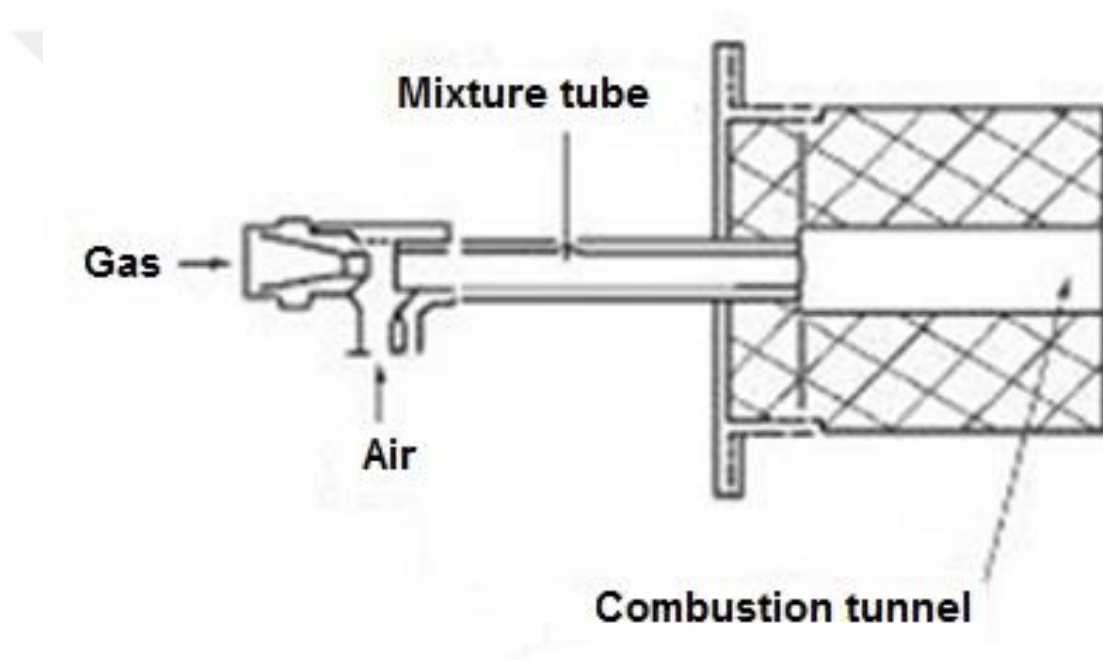


Figure 1.2: Premixed burner [5].

Due to safety issues and size limitations of premixed burners, the great majority of industrial burners are turbulent jet diffusion burners. In addition to these, diffusion flame is easier to control compared to premixed flame.

The combustion air is supplied separately and mixes with the fuel jet within the burner. In the turbulent jet flame, the fuel is generally supplied via a central jet and the combustion air is supplied coaxially surrounding the fuel jet [5]. In Figure 1.3, principle of turbulent jet diffusion flame is schematically shown.

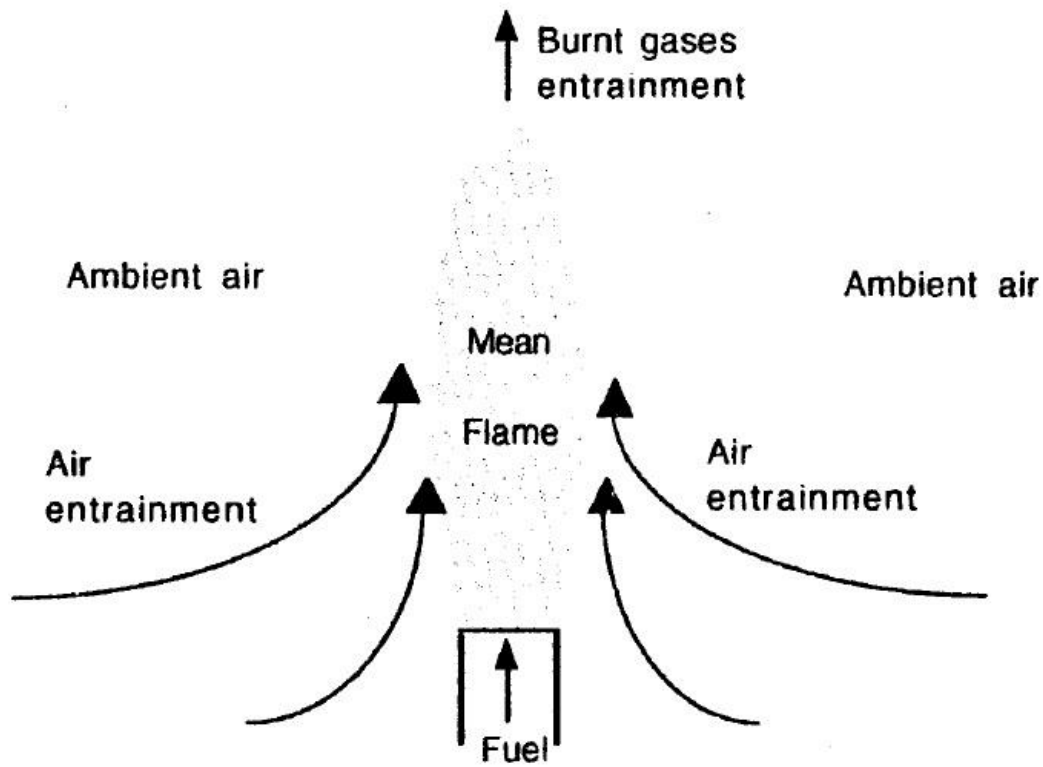


Figure 1.3: Diffusion flame [6].

In a partial premixed burner, a part of the combustion air is mixed with fuel, the remainder is provided separately. In Figure 1.4, principle of partial premixed flame is schematically shown.

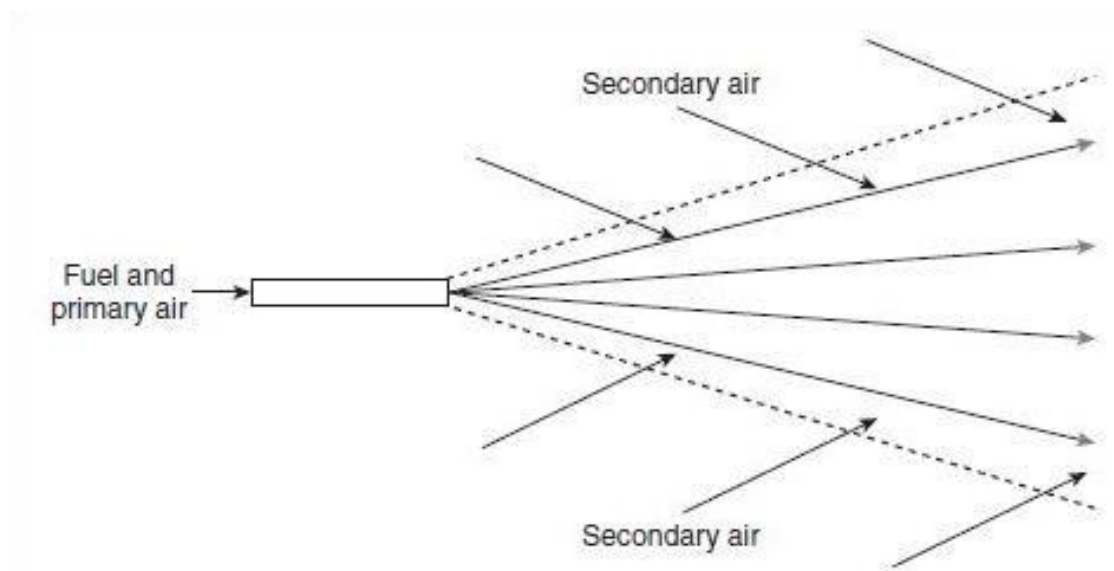


Figure 1.4: Partial premixed flame [5].

Based on their principle of operation, burners can also be classified as swirl types or direct/parallel flow types. A swirl burner uses a set of guiding vanes to give a swirling motion to the combustion air. This creates a recirculation zone, which helps igniting the fuel as well as sustaining the flame. The recirculation also helps accelerating the process of mixing of fuel and combustion air [7]. In Figure 1.5, an example of swirl burner is shown.

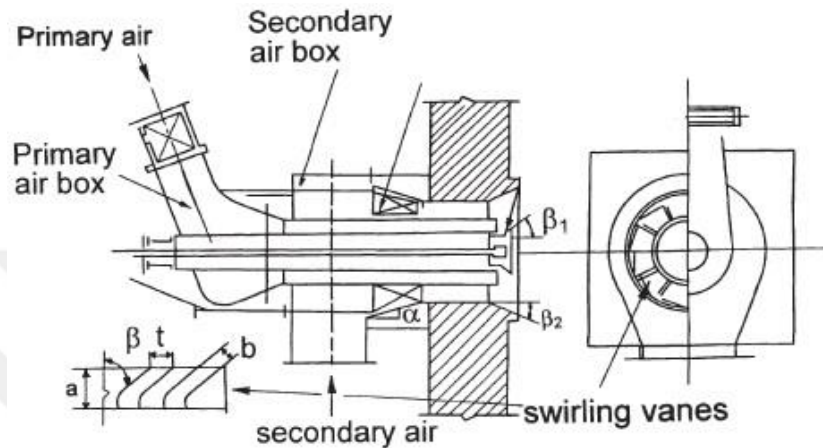


Figure 1.5: An example of swirl burner [7].

Direct flow burners do not add any swirl to the flow. Here the fuel and air flows are parallel to each other.

1.2. Oxygen-Enhanced Combustion

Historically, air/fuel combustion has been the conventional technology used in nearly all industrial heating processes. In many cases, combustion processes can be enhanced by using an oxidant that contains a higher proportion of oxygen than that in air. This is known as oxygen-enhanced combustion. Oxygen-enhanced combustion systems are becoming more common in a variety of industries. When traditional air/fuel combustion systems have been modified for oxygen-enhanced combustion, many benefits have been demonstrated. Typical improvements include increased thermal efficiency, increased processing rates, reduced flue gas volumes, and reduced pollutant emissions. One example of oxygen-enhanced combustion is using an oxidant consisting of air, blended with pure oxygen [8].

Oxygen has been commonly used to enhance combustion processes in four primary ways [8]:

- Adding oxygen into the incoming combustion air stream,
- Injecting oxygen into an air/fuel flame,
- Replacing the combustion air with high purity oxygen,
- Separately providing combustion air and oxygen to the burner.

The methods listed above can be combined for special applications.

In Figure 1.6 an air/fuel process where the air is enriched with oxygen is shown. This is low-level oxygen enrichment which is defined as the first way of oxygen-enhanced combustion [8]. Due to increasing oxidizer level, this method enhances the performance of many burners.

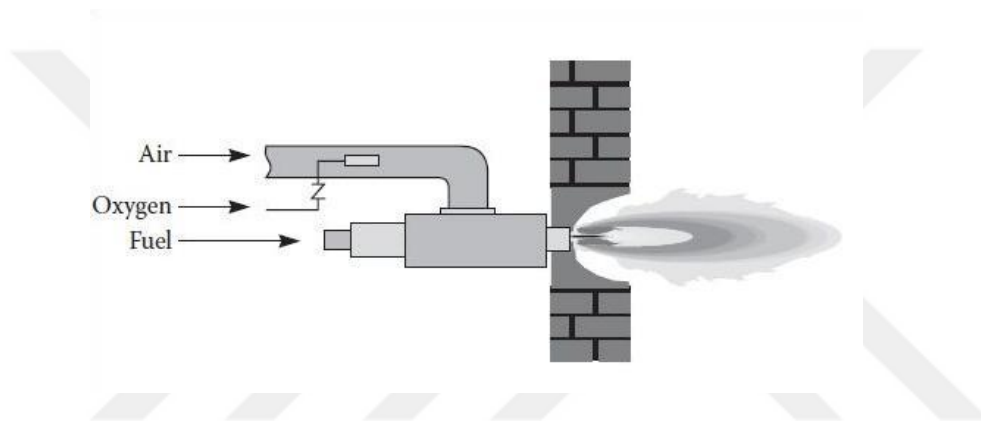


Figure 1.6: An oxygen-enriched-air/fuel process [8].

Another way of oxygen-enhanced combustion is oxygen lancing which is to lance the high-purity oxygen into the burner. Figure 1.7 shows enriching an air/fuel process with oxygen. Depending on the injection location, the flame shape may be lengthened by staging the combustion reactions [8].

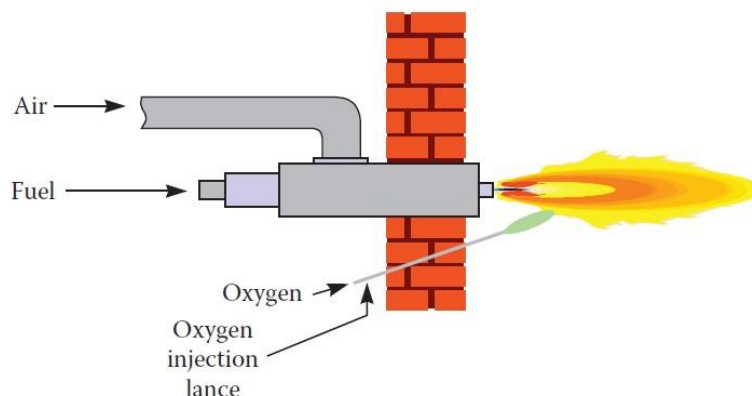


Figure 1.7: Lancing high-purity oxygen into the burner [8].

1.3. The Use of Burners for True-Temperature Propulsion Wind Tunnels

In ground tests of high-speed air-breathing propulsion systems, stored high-pressure air must be heated significantly, before expansion through a facility nozzle, to simulate supersonic flight conditions. Such heating may be accomplished in various ways: combustion-air-heaters (CAHs), heat storage devices and electric arc heaters.

CAHs heat air directly with a fuel-oxidizer reaction. Fuel is burned in the air stream, often in a jet engine style burner. Exhaust gases are used for testing after the consumed oxygen is replenished. Main advantages of CAHs are the low-cost, and their simplicity of operation and maintenance. Disadvantages include the effects of CAH combustion products on air-breathing engine combustion and the change of air properties [9].

Heat storage devices are heat exchangers of high thermal mass that are gradually heated to operating temperature and during a test run give up stored thermal energy to air passing through them. Commonly, large vessels filled with ceramic or metal pebbles are used. The main challenge in designing heat storage device is obtaining a constant output temperature for the required run time and range of test conditions [9].

Electric arc heaters heat air through the release of energy produced by an electric arc between two electrodes. Arc heaters are capable of producing very high air temperatures. Due to extremely high temperatures produced by the arc, NO_x and other undesired contaminants are formed. As with any electric heater the high power requirements of arc heaters make them very expensive to operate [9].

Considering the advantages and disadvantages of three air heating methods mentioned above, it seems logical to use a CAH in a ground test facility of high-speed air-breathing propulsion systems.

In heating the air, combustion in a CAH depletes part of the available oxygen. In order to conduct combustion experiments, the oxygen content of the flow must be restored to the proper percentage (0.21 mole fraction of oxygen in flow) [9].

The principal problem associated with CAHs, is that the resulting air, after combustion heating and oxygen replenishment, contains higher mass fractions of water vapor and carbon dioxide than normal air. Fortunately, this has proved to be only a minor problem in air-breathing engine testing [10].

Some examples of high-speed air-breathing propulsion systems ground test facilities with CAH are Aerodynamic and Propulsion Test Unit at Arnold Engineering Development Center in Tennessee (the United-States), Institute of Space Propulsion in Stuttgart (Germany), TNO Prins Maurits Laboratory in Rijswijk (the Netherlands), ONERA Modane-Avrieux in France, Technion – Israel Institute of Technology in Haifa (Israel), Korea Aerospace Research Institute in Daejeon (Republic of Korea), United Technologies Research Center in Connecticut (the United-States), JAXA – Kakuda Space Center in Miyagi (Japan) and Beijing Institute of Technology in Beijing (China).

Within present study, a swirl type burner, whose side cross-section is shown in Figure 1.8, is used as a combustion-air-heater (CAH). The burner consists of a combination of the two oxygen-enhanced combustion method mentioned in Section 1.2.

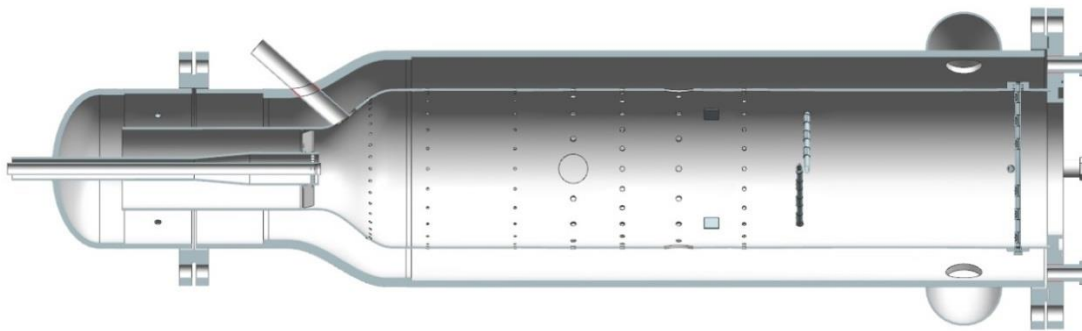


Figure 1.8: Side cross-section of the combustion-air-heater (CAH).

1.4. Objective and Scope of the Thesis

In ground tests of high-speed air-breathing propulsion systems, atmospheric flight temperature condition should be satisfied. This temperature is function of altitude and Mach number. At TÜBİTAK SAGE a burner which is used as a CAH (Figure 1.8) is established to perform ground tests. The primary aim of present thesis is to carry out combustion performance tests of the CAH and prove its ability to meet that atmospheric flight temperature condition. Combustion tests are accepted as successful, if the temperature condition is satisfied under the fuel and the oxidizer mass flow rates determined before the experiment.

Blowout limits play an essential role on characterizing a burner. The secondary aim of present thesis is to characterize the CAH by experimentally investigating its lean blowout limits, under ambient pressure condition. This work focuses on the effects of oxygen enrichment of combustion air, existence of pilot oxygen (oxygen lancing) and axial mean swirler velocity on lean blowout limits, respectively. Throughout present work, fuel/oxidizer equivalence ratio has been determined as lean blowout limit criterion.

In first chapter of present study, brief information about burners, oxygen-enhanced combustion and air vitiation concept is given. Literature survey of present work is also placed in this chapter.

In second chapter; basics of combustion theory are discussed to give background knowledge about thermochemistry and turbulent diffusion flame.

In third chapter theoretical calculations for the experimental study are given.

The experimental setup and the values to be measured are discussed in forth chapter. The experimental matrix and the results are given in fifth chapter. Lean blowout limits obtained are also discussed in fifth chapter.

1.5. Literature Review

1.5.1. True-temperature air-breathing propulsion system test facilities with combustion-air-heater

Stallings and Burt have examined test capabilities of the Aerodynamic and Propulsion Test Unit with a vitiated air heater which has been operated at Mach numbers from 2.2 to 3.5 at simulated altitudes ranging from 5000 to 70000 feet. In this facility, they have made around 150 runs of test. Their tests demonstrated that with a vitiated air heater, successful testing of a developmental ramjet engine configuration over a wide range of simulated flight conditions is operational in this facility [11].

Schulte et al. have performed experimental studies for ramjet combustion chamber performance analysis. The facility they used for their experiments is a true-temperature air-breathing propulsion system test facility with CAH, which is schematically shown in Figure 1.9. This CAH burns hydrogen with oxygen to heat

air. Oxygen is replenished to keep the oxygen amount constant at 21% of the total airflow [12].

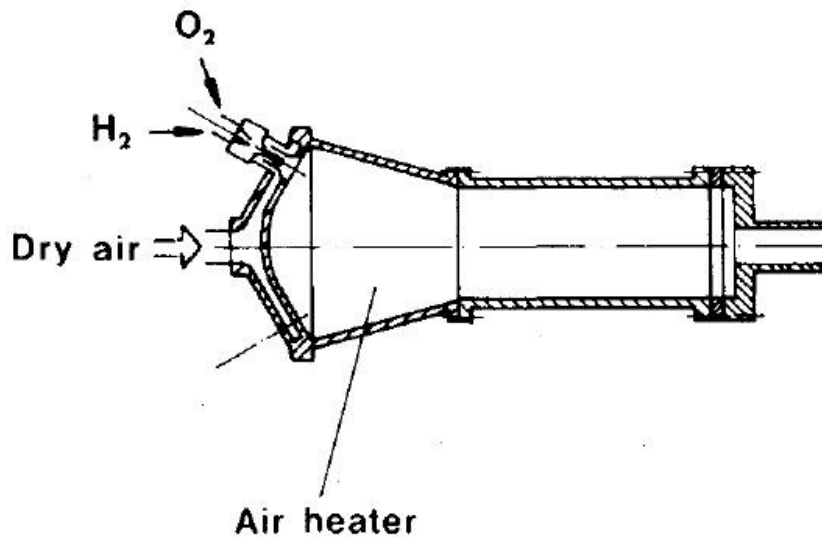


Figure 1.9: The schematic of the CAH [12].

Elands et al. have conducted experimental studies in a connected-pipe test facility for comparing experimental combustion results with theoretical estimates. In the test facility, the air is heated by burning methane in a CAH. Oxygen is added to keep its amount constant in this heated air to that of ambient air [13].

Ben-Yakar et al. have experimentally investigated a ramjet combustion chamber performance in a connected-pipe test facility with a CAH. In this test facility, methane is burned in the CAH with oxygen makeup for heating air. The air heated in the CAH is then collected in a plenum as shown in Figure 1.10 [14].

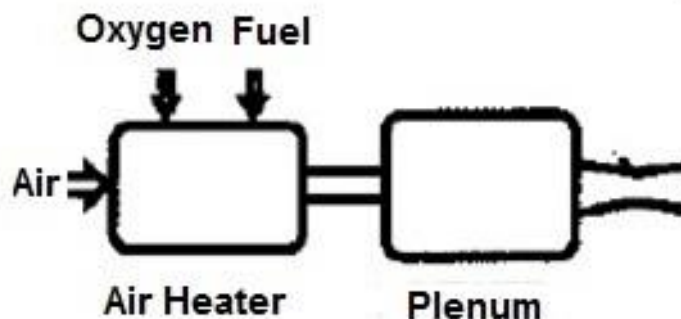


Figure 1.10: The schematic of the CAH and the plenum [14].

Kang et al. have experimentally investigated a supersonic-combustion air-breathing engine in a blowdown wind tunnel test facility with a CAH. This facility generates high-pressure high-temperature airstream by adding hydrogen combustion gas to the high-pressure air inflow. To compensate for the combusted air, gaseous oxygen is supplied to the stream [15]. A very similar test facility has also been used by Donohue for his supersonic-combustion ramjet engine experiments [16].

Wang et al. have conducted experiments to obtain combustion parameters of a supersonic-combustion air-breathing engine in a blowdown wind tunnel test facility with a methane-burning CAH with oxygen makeup [17].

1.5.2. Lean blowout

Due to being an important parameter to characterize a burner, lean blowout limit concept attracts many attention of researchers.

Parker argues that the first useful estimates for the lean limit of methane/air mixtures were reported by Davy in his efforts to prevent explosions of methane gas in coal mines. According to these estimates, limits of inflammability are between 6.2% and 6.7% of methane/air ratio [18]. This represents an equivalence ratio range for methane between 0.68 and 0.74. In his further investigations, Parker has complicated the concept of the lower limit of inflammability by examining mixtures of oxygen and nitrogen rather than using the standard ratio of these molecules in air. His findings are shown in Figure 1.11, with a minimum at 5.77% methane using a 25% oxygen mixture [18]. These results show that the limits of lean combustion depend not simply on an equivalence ratio, but on the oxidizer and the diluent composition. For example, if the 5.77% methane is considered relative to a stoichiometric mixture of methane and normal air, the equivalence ratio would be 0.61, but if the stoichiometry is taken relative to the slightly oxygen-enriched mixture reported, the equivalence ratio at the lean limit is 0.47 [18].

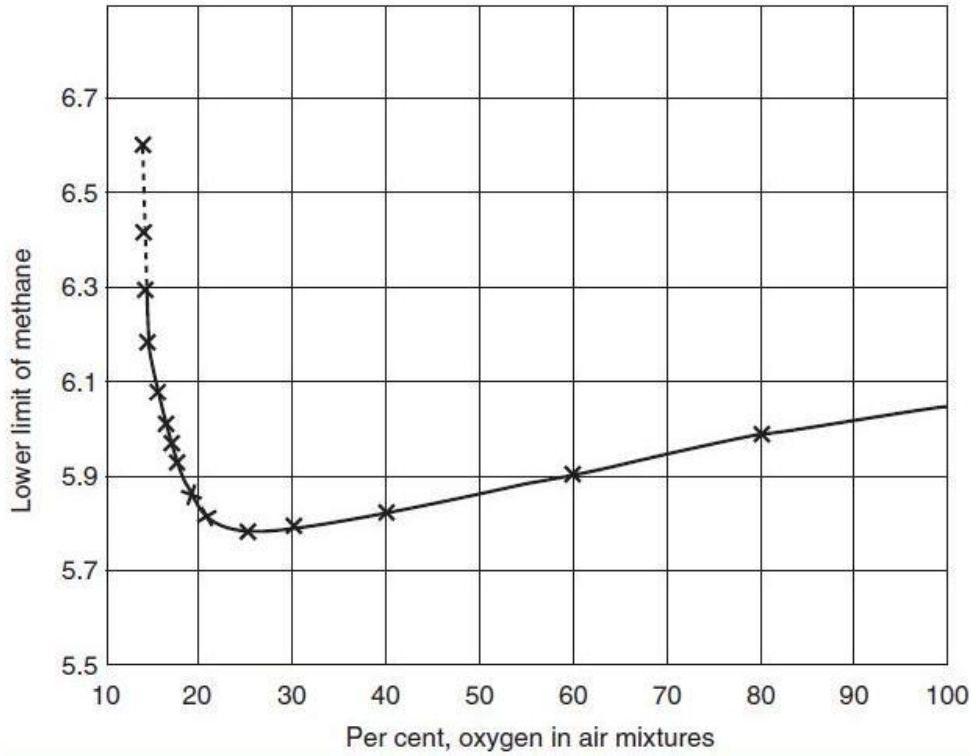


Figure 1.11: Inflammability limits of methane in mixtures of oxygen with nitrogen [18].

Kalghatgi has made a systematic experimental study for the blowout stability of jet diffusion flames in still air using fuel gases such as methane, propane, ethylene, acetylene, commercial butanes and hydrogen. He has derived a universal empirical formula (Equation 1.1) that describes the blowout stability limit of gaseous jet diffusion flames in still air. He has established validity of this formula over a wide range of parameters that affect the blowout limit [19]. In his formula, $\overline{U}_e$ is the nondimensional velocity at blowout and R_H is the Reynolds number based on the distance along burner axis at which mean fuel concentration falls to stoichiometric level.

$$\overline{U}_e = 0.017 R_H (1 - 0.0000035 R_H) \quad (1.1)$$

Karbasi and Wierzbza have studied the flame stability limits of confined jet diffusion flames flowing into a co-axial oxidizing stream experimentally and analytically. They have used methane, hydrogen and their mixtures as fuel. They have observed that the blowout limits of a jet diffusion flame decrease with an increase in the stream velocity. The rate of decrease depends on whether the flame is lifted or attached before blowout. The blowout limits of lifted flames deteriorated very

significantly with a small increase in the co-flowing stream velocity, while for attached flames they were less sensitive to this increase [20]. Figure 1.12 shows stability limits of methane jet diffusion flame as a function of the co-flowing stream velocity.

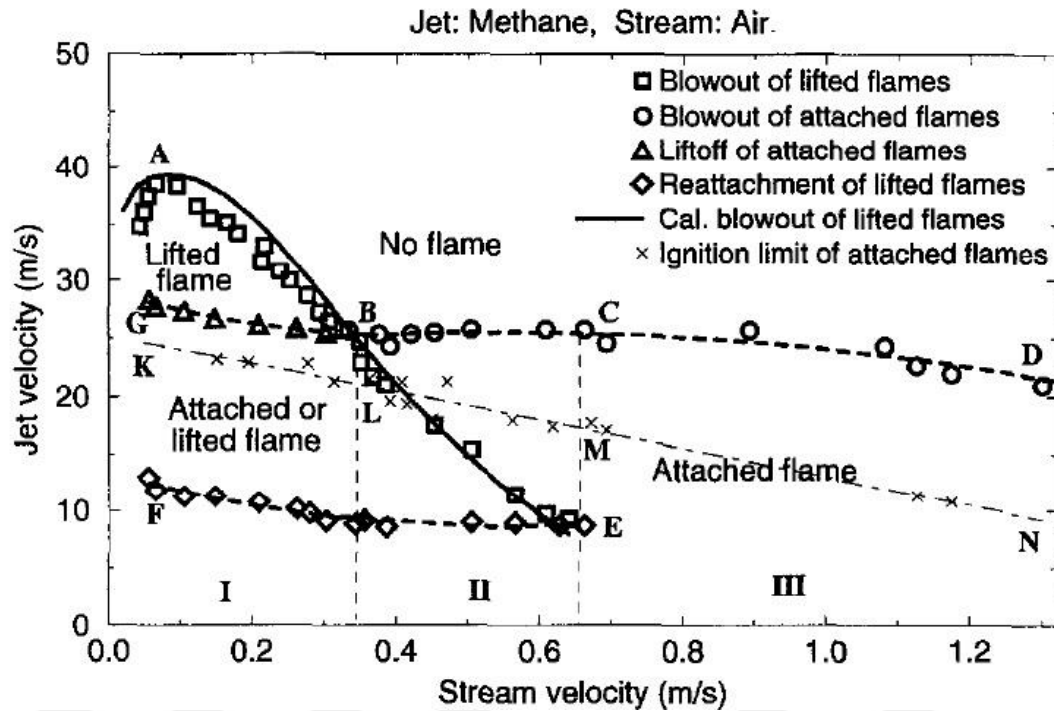


Figure 1.12: Stability limits of methane jet diffusion flame as a function of the co-flowing stream velocity [20].

Habib et al. have studied to check the stability of the oxy-fuel combustion diffusion flame and the minimum percentages of oxygen in the oxidizer mixture required to get a stable oxy-fuel flame without a blowout. The test facility is shown in Figure 1.13. In their study, the burner has been fed with methane as fuel and a mixture of carbon dioxide and oxygen as oxidizer. Large operating range of parameters including equivalence ratio and percentages of oxygen/carbon dioxide in the oxidizer mixture has been considered. They have recorded the temperature of the exhaust gases and its concentrations to characterize the flames in detail. They have observed that the flame blowout limit is significantly affected as shown in Figure 1.14. They have also confirmed experimentally that the operation below 21% of oxygen is impossible because of flame blowout [21].

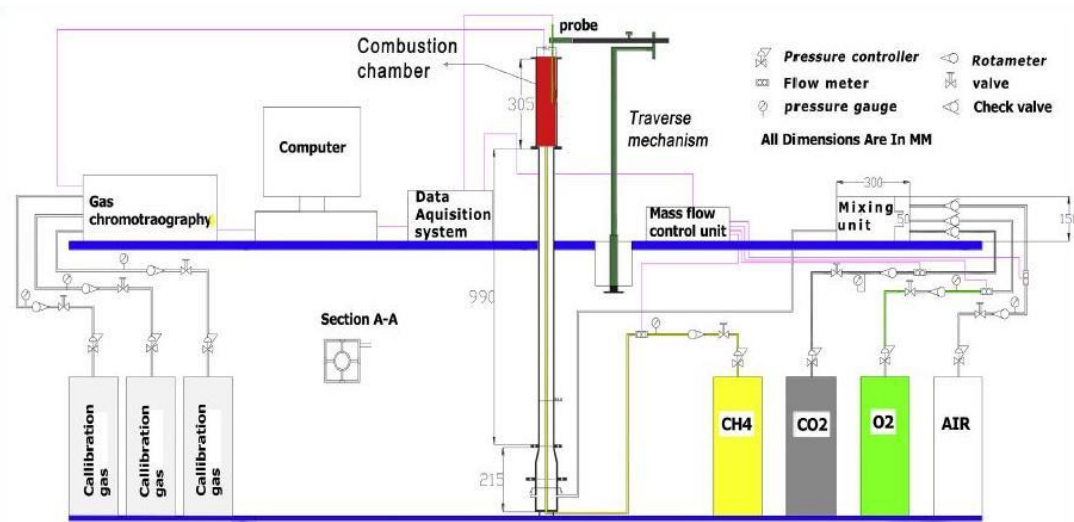


Figure 1.13: Schematic of the test rig facility [21].

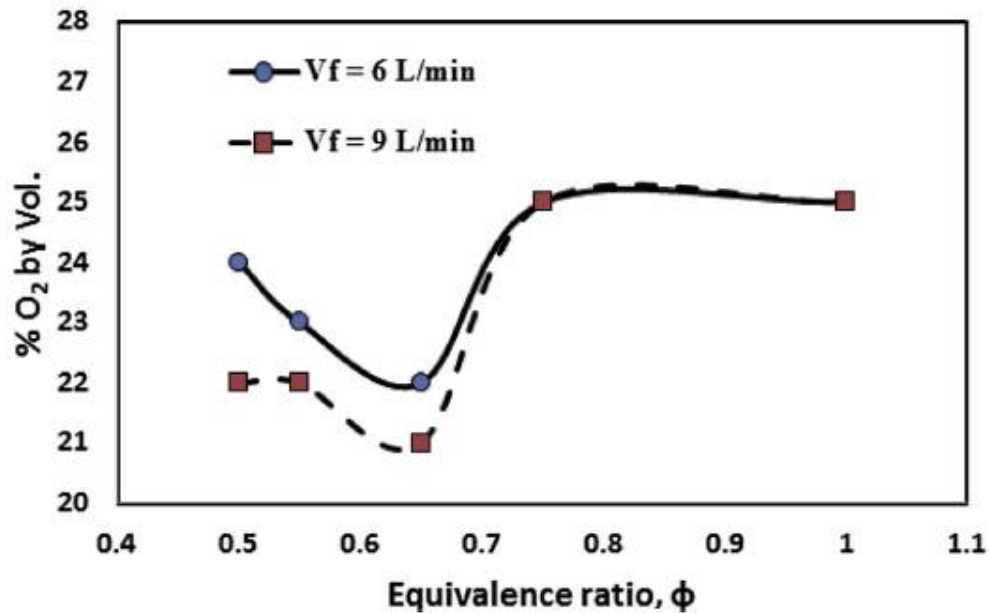


Figure 1.14: Percentage of oxygen in the oxidizer mixture at which the flame blows out at different equivalence ratios and fuel volume flow rates [21].

Choi et al. have experimentally investigated the fundamental properties of inverse non-premixed pure oxygen/methane co-flow flames in a model burner (NTP). Their experimental setup is shown in Figure 1.15. They have observed two distinct flame stability behaviors: stable, attached flame and oscillating, near-blowout flame at fuel-rich and fuel-lean conditions, respectively. These flames are shown in Figure 1.16. They have also stated that oxygen enrichment extends the stability limits of the flame [22]. They have extended their study to measure the ignition and combustion stability limits and observed that stability of gaseous methane/oxygen coaxial jet flames is

greatest at fuel-rich condition as shown in Figure 1.17. They have also stated that ignition limits are restricted compared with steady combustion stability limits [23].

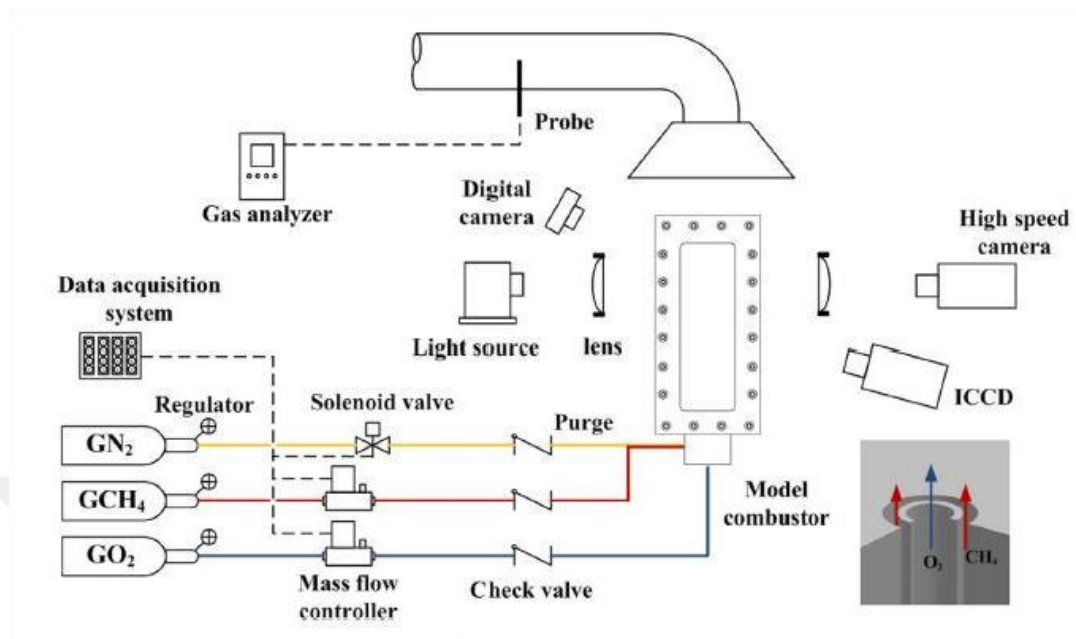


Figure 1.15: Schematic of experimental apparatus [22].

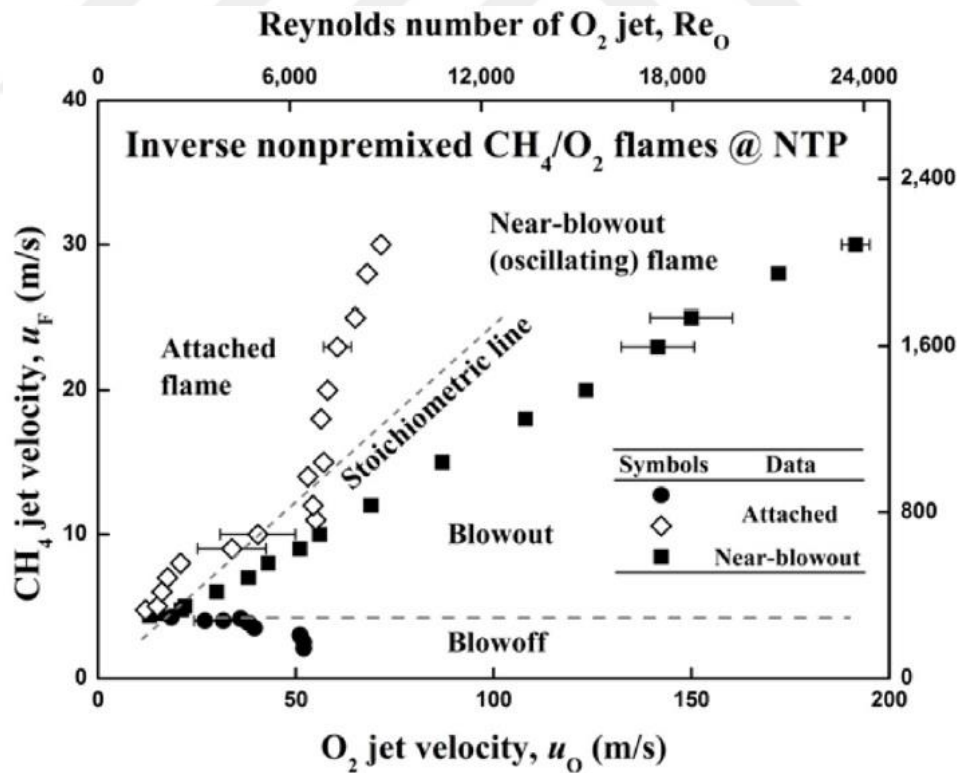


Figure 1.16: Combustion stability limits for non-premixed methane/oxygen flames [22].

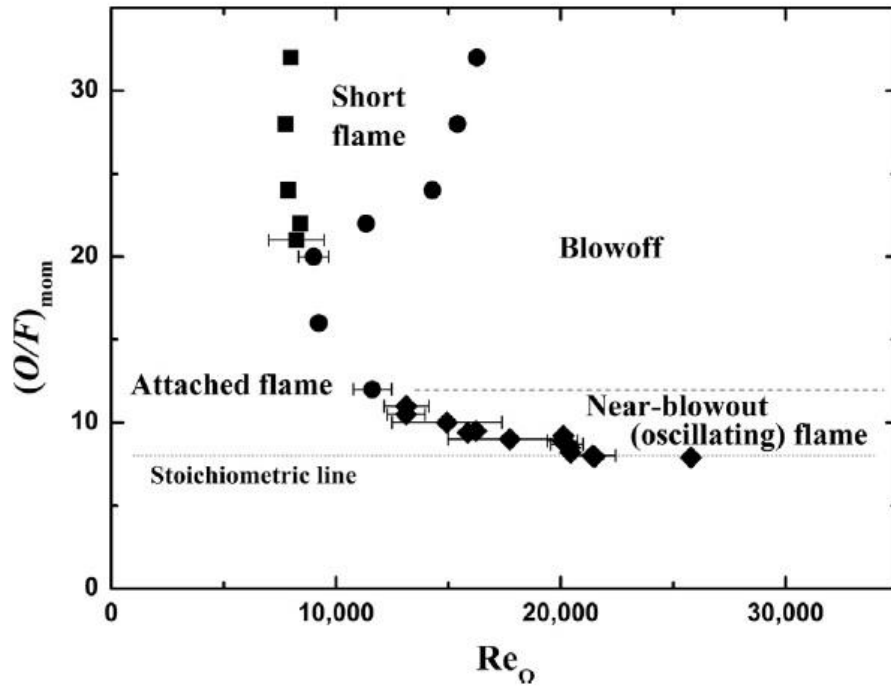


Figure 1.17: Combustion stability regimes for non-premixed methane/oxygen flames [23].

Xiao and Huang have conducted an experiment for studying the lean blowout limits of a single dome rectangular model burner with swirl cup using liquid fuel and gaseous methane fuel which is schematically shown in Figure 1.18. They have claimed that the lean blowout limits increase with the swirl intensity as shown in Figure 1.19. Here, W_0/U_0 is the ratio of mean tangential and mean axial velocities at swirl cup exit [24].

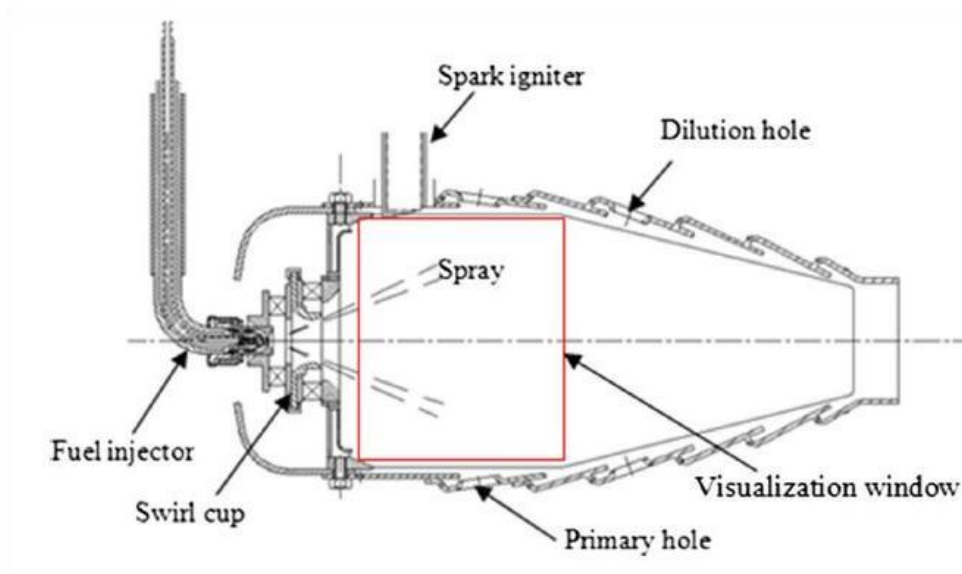


Figure 1.18: Schematic of single dome rectangular model burner [24].

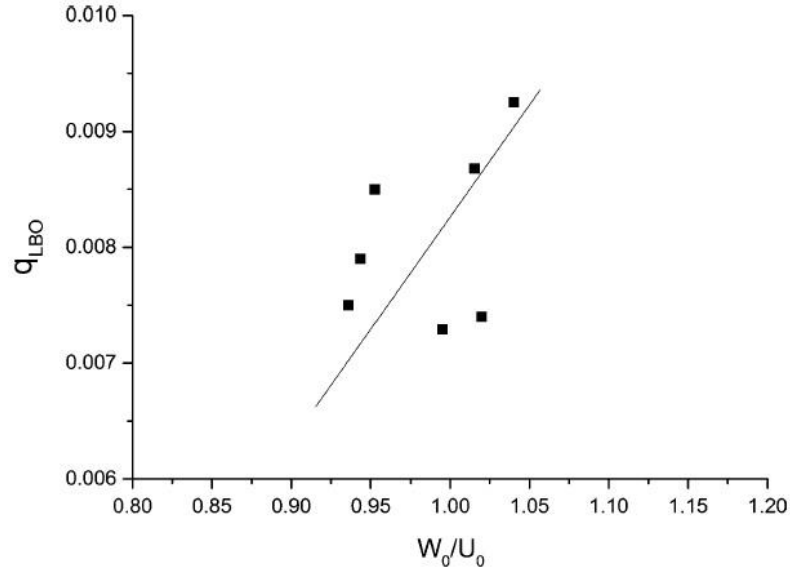


Figure 1.19: Relationship between lean blowout limits and ratio of W_0/U_0 with using methane [24].

Palacios et al. have experimentally studied the effect on the blowout velocity of a subsonic jet of adding air to methane and propane fuel jets, respectively. They have expected higher jet velocities before blowout occurs, as the addition of air aids fuel/air mixing. However, excess air might induce earlier lean flame extinction and blowout. They have concluded that it is difficult to generalize the conditions for jet flame blowout, which are unique for each fuel. They employed a dimensionless flow number (U_b^*) to estimate blowout velocity. Blowout velocities of methane/air and propane/air flames are given in Figure 1.20 [25].

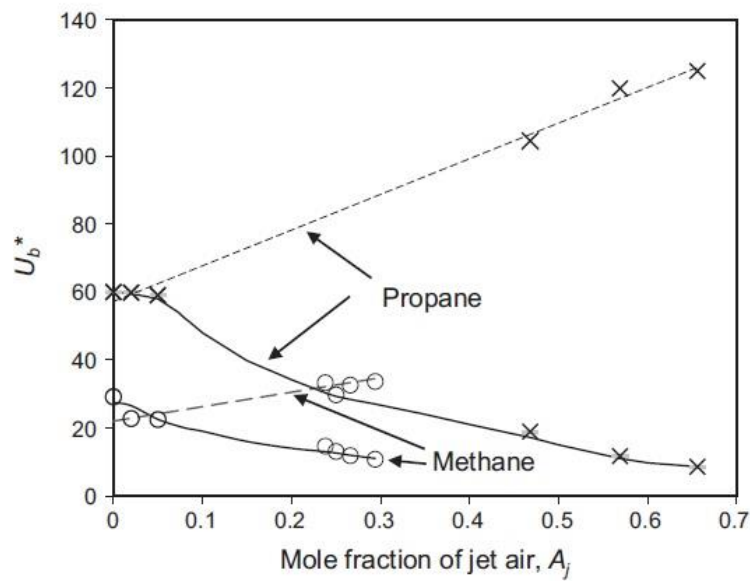


Figure 1.20: Blowout U_b^* velocities for methane/air and propane/air flames [25].

Abubakar et al. have studied blowout characteristics of oxy-fuel/air combustion of propane in a non-premixed, swirl-stabilized burner. Experimental setup they have used is shown schematically in Figure 1.21. They have investigated the effect of equivalence ratio, oxidizer mixtures and swirl numbers on the flame. They have observed flame transitions from attached flame to lifted flame and subsequent no flame with air oxidizer. However, the flame transits directly from attached flame to no flame in oxy-fuel oxidizer. This is because the critical velocity required for attached flame to lifted flame transition in oxy-fuel flame could not be achieved before flame blowout. They have also observed that oxy-fuel flame is more stable under a swirling flow as given in Figure 1.22 [26].

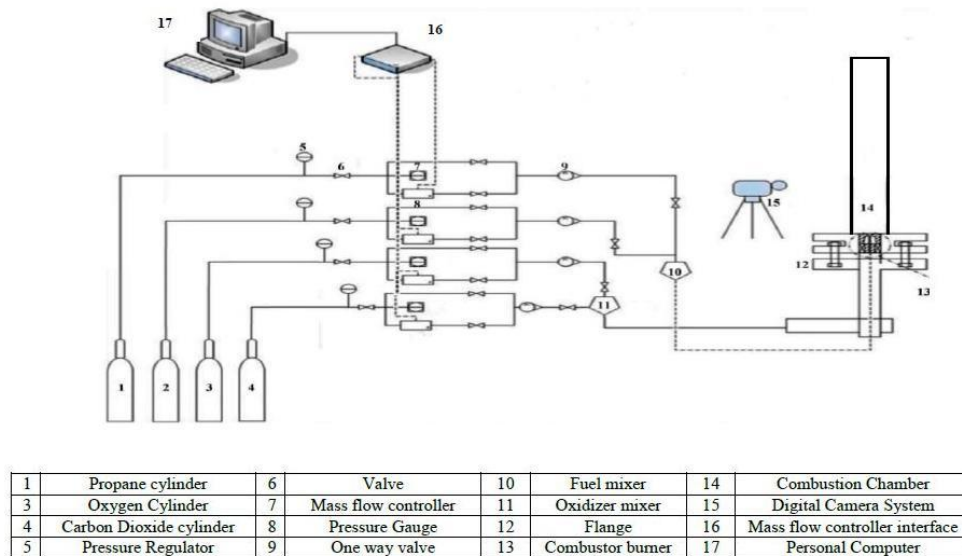


Figure 1.21: Schematic of the experimental setup [26].

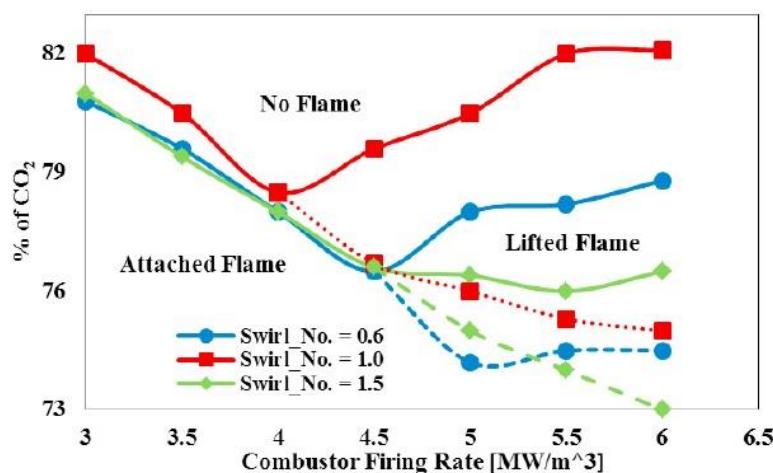


Figure 1.22: Effect of swirl number on blowout (dashed lines: attached-lifted flame transition) [26].

Swirl Number [-]	Φ_{LBO} [-] (Axial fuel injection)	Φ_{LBO} [-] (Tangential fuel injection)
0.285	0.485	-
0.29	-	0.66
0.31	0.498	0.58
0.335	0.492	0.53

Miles has conducted a well-stirred-reactor investigation to determine the effect of partial air vitiation on propane/air blowout rates. He has used a central-feed zirconia

spherical reactor with a diameter of 7.6 cm to observe blowout limits. His results show that the observed blowout limit decreases by a factor of about 2.6 for each 10% increase in air vitiation [28].

Yuasa has experimentally investigated the stability of swirling-methane-jet diffusion flames in swirling air streams, using a double-swirl burner. The primary variable studied has been swirl intensity of the air stream. He has observed that at higher swirl intensities of the air stream, the flame stability increased noticeably because of the formation of a recirculation zone near the injector exit. Without air swirl, blowout has been observed in the air streams above 1.5 m/s. On the other hand, with air swirl, the methane flame anchors in the high velocity air streams up to about 10 m/s [29].

Feikema et al. have measured the blowout limits of swirl-stabilized, non-premixed flames. They have observed that if overall lean conditions are desired, some amount of swirl is required to achieve a stable flame. However, excessive swirl also can destabilize a lean flame, so an optimum amount of swirl exists [30]. In another study, they have compared the blowout limits of maximum coaxial air velocities achievable with and without swirl. They have concluded that with swirl, overall lean flames can be stabilized for a wide range of conditions as shown in Figure 1.25. They believe that swirl enhances the stability of overall lean flames since swirl creates a local region having a reduced velocity and a reduced local strain rate [31].

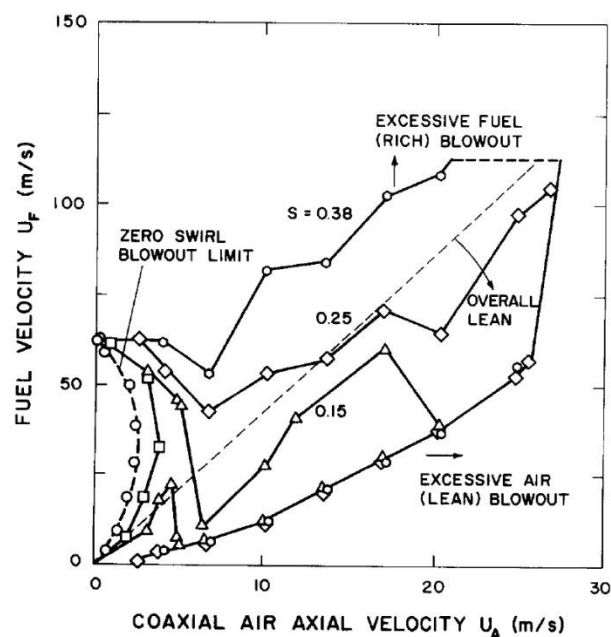


Figure 1.25: Flame blowout limits for zero swirl compared with blowout limits with swirl [31].

Santhosh and Basu have performed an experimental work (experimental setup is shown in Figure 1.26) to observe flame topology in a non-premixed swirling flame as the geometric swirl number is varied from a magnitude of zero till flame blowout. According to them, flame stabilization locations play an important role in determining the blowout limits. They have stated that when the swirl intensity is very high (i.e. a swirl number value of around 10), the flame blows out due to excessive straining. The flame regime map they obtained is given in Figure 1.27. Their investigation shows that any change in global flame structure causes oscillatory heat release that can couple with dynamic pressure and velocity fluctuations leading to unsteady combustion. In this light, understanding mechanisms of flame stabilization is essential to tackle the problem of thermo-acoustic instability [32].

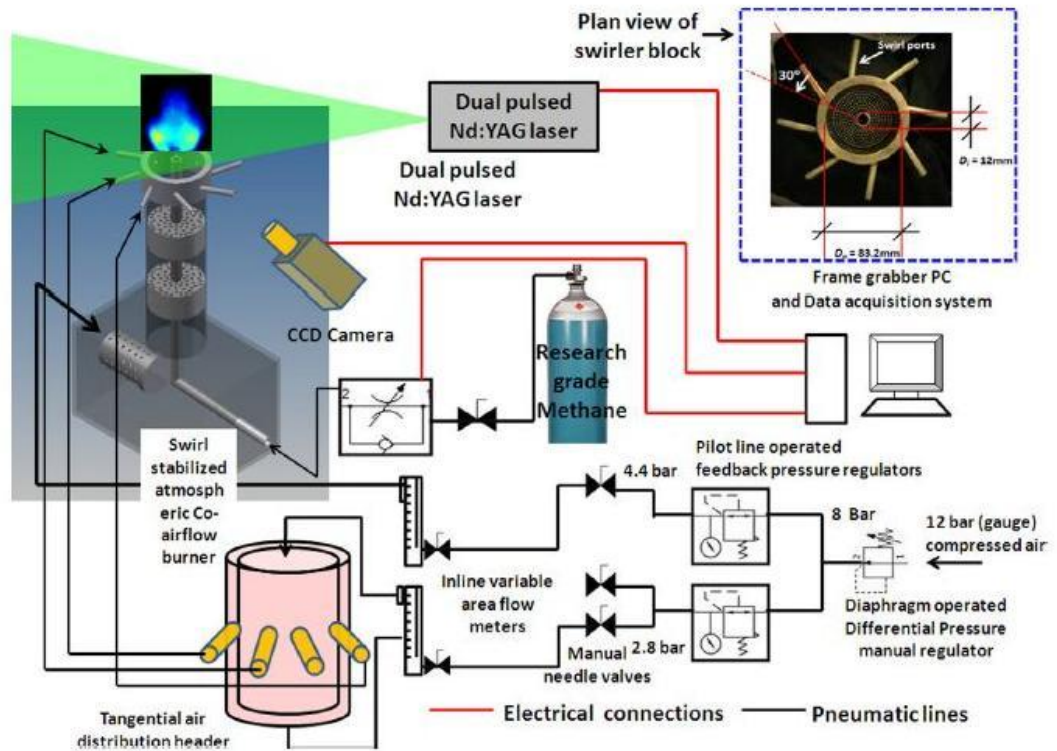


Figure 1.26: Schematic of experimental setup [32].

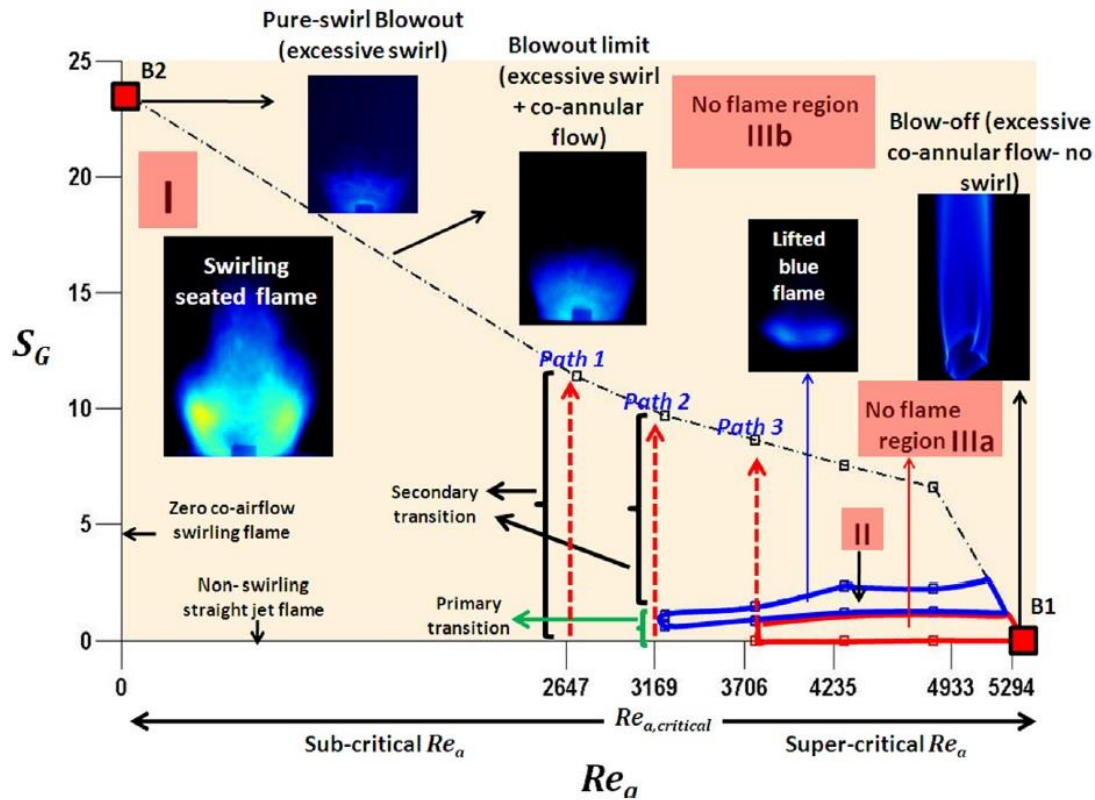


Figure 1.27: Flame regime map [32].

Yoon et al. have conducted experiments with a model gas turbine burner to examine the combustion instability and flame structure. In their study swirling methane/air flame has been investigated with an overall equivalence ratio of 1.2 to lean blowout limit and dump plane velocity of 30-70 m/s. They have observed that at an unstable condition, flame root size varies a lot compared to stable condition which is because of air and fuel mixture flow rate changes due to burner pressure modulation. After this structural change, local extinction and re-ignition occur and it can generate a feedback loop for combustion instability. This analysis suggests that pressure fluctuation of combustion causes deformation of flame structure and variation of flame has a strong effect on combustion instability [33].

Chen et al. have studied the flame stability and heat transfer characteristics of methane/air mixtures in catalytic micro-combustors numerically. They have obtained that the wall thermal conductivity greatly affects blowout. They have also obtained that the presence of homogeneous chemistry extends blowout limits, especially for inlet velocities above 6 m/s and the flame stability increases with the increase of equivalence ratio towards the stoichiometric point [34].

Kypraiou et al. have experimentally investigated the effect of forced oscillations on the behavior of non-premixed swirling methane flames close to the lean blowout limits using a lab-scale burner which is schematically shown in Figure 1.28. They have used two fuel injection configurations characterized by variation of equivalence ratio. The main aim of the work is to understand the effect of forcing amplitude on the flame structure and lean blowout limits. Results show that the acoustic forcing reduces the stability of the flame and changes the operability limits. Both axial and radial fuel injection systems show a gradual decrease in the flame size at the blowout condition [35].

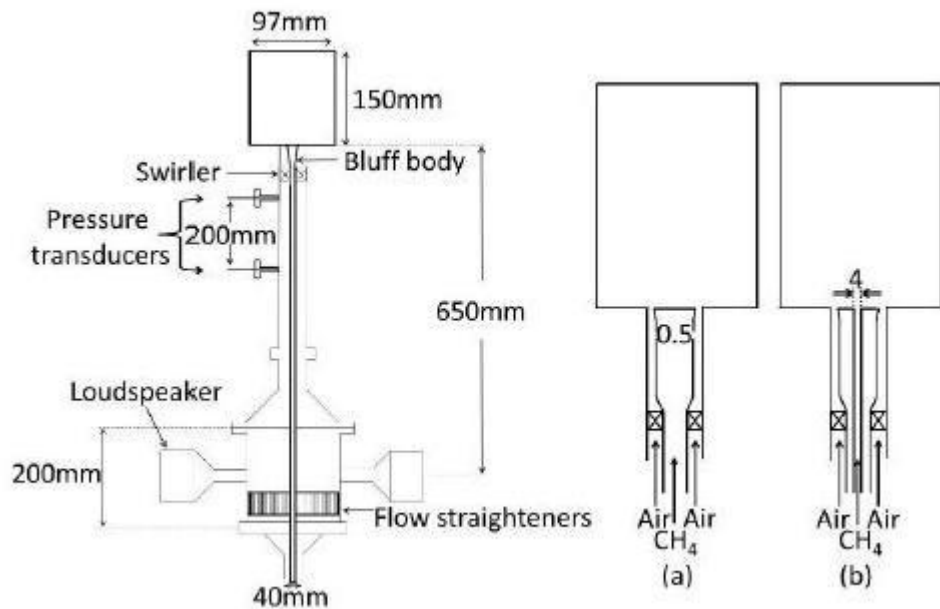


Figure 1.28: Schematic of the burner used for the blowout study of forced (a) non-premixed radial and (b) non-premixed axial flames [35].

Li et al. have conducted experiments for controlling lean blowout limits of a swirl-stabilized propane-fueled burner. Their experimental procedure has been based on reaching lean blowout by decreasing the propane flow rate gradually while the air flow rate is held constant [36].

Yi and Gutmark have experimentally made a real-time lean blowout equivalence ratio prediction for gas turbine burners. They have approached lean blowout by stepwise, small reductions in the fuel flow rate, whereas the air flow rate is kept constant. According to their experiments, after each decrement of the fuel flow rate, it usually takes 20 seconds for obtaining a constant temperature value [37].

Stouffer et al. have presented details of lean blowout characteristics of a swirl-stabilized burner. They have indicated that to approach lean blowout in a controllable and repeatable manner, test conditions such as air and fuel flow rates should carefully controlled. They have stated that a sufficiently slow fuel ramp rate is important allow the wall temperatures to respond to reductions in the fuel flow rate. Excessively fast reductions in the fuel flow rate will tend to bias the lean blowout event to lower equivalence ratios because of higher wall temperatures [38].

Chaudhari et al. have proposed a lean blowout prediction strategy based solely on the flame color. They have used methane as fuel. They have started with stoichiometric air-fuel mixture, and then equivalence ratio has been gradually reduced in steps of 0.02 keeping the air flow rate constant until lean blowout occurred. Their experiments have shown that as the flame approaches lean blowout, its color changes from reddish to blue. This is graphically given in Figure 1.29. Here; ϕ/ϕ_{LBO} is the equivalence ratio over equivalence ratio at lean blowout, $\sum I_r$ and $\sum I_b$ are red and blue color intensities, respectively [39].

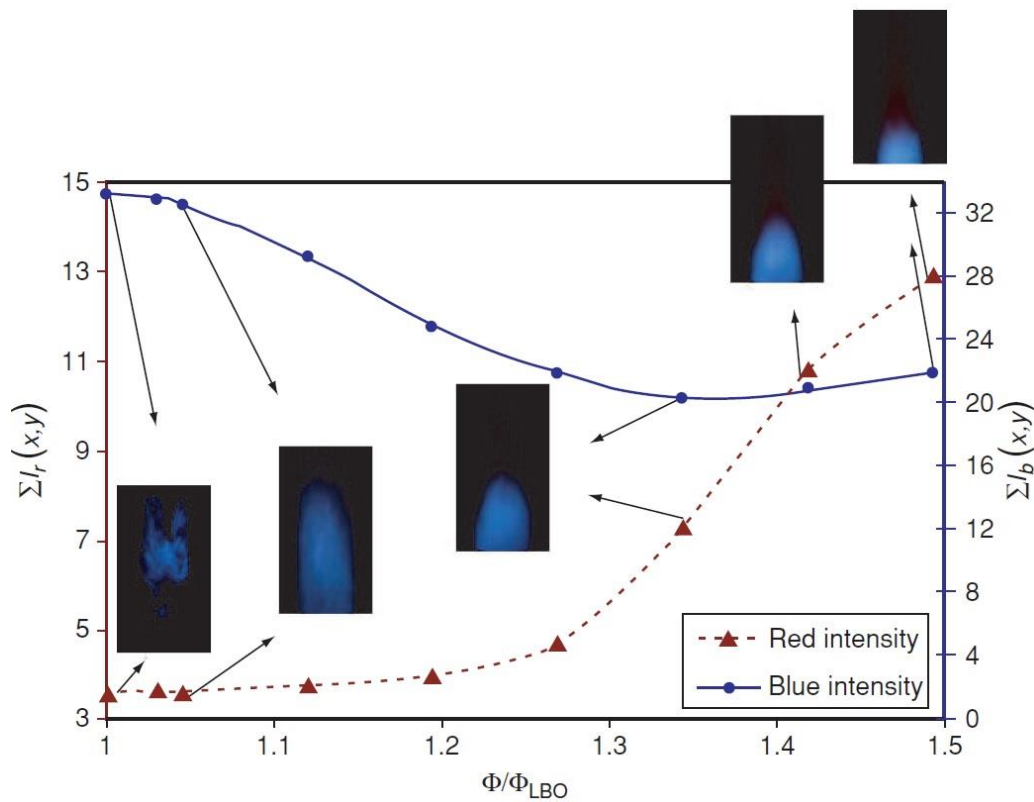


Figure 1.29: Variation of red color intensity and blue color intensity with ϕ/ϕ_{LBO} [39].

2. COMBUSTION CONCEPT

In this chapter, some basic information about combustion, chemical thermodynamics and diffusion flame has been given to the reader.

2.1. Combustion Theory

Combustion involves multiple species reacting through multiple chemical reactions. Species are characterized through their mass fractions Y_k for $k = 1$ to N where N is the number of species in the reacting mixture [6]. The mass fractions Y_k are defined by Equation (2.1):

$$Y_k = \frac{m_k}{m} \quad (2.1)$$

where m_k is the mass of species k in a given volume and m is the total mass of gas in this volume. The primitive variables for a three dimensional compressible reacting flow are; the density $\rho = m/V$, the three dimensional velocity field u_i , one variable for energy and the mass fractions Y_k of N reacting species.

For a mixture of N perfect gases total pressure is the sum of partial pressures as given with Equation (2.2):

$$p = \sum_{k=1}^N p_k \quad (2.2)$$

The sum of partial pressures can be defined by Equation (2.3):

$$p_k = \rho_k \frac{R_u}{W_k} T \quad (2.3)$$

where T is the temperature, $R_u = 8.314 \text{ J/(mole)K}$ is the universal perfect gas constant, $\rho_k = \rho Y_k$ and W_k are respectively the density and the atomic weight of species k . The density ρ of the multi-species gas is defined by Equation (2.4):

$$\rho = \sum_{k=1}^N \rho_k \quad (2.4)$$

The state equation, which relates state variables such as pressure, temperature and density, can be defined by Equation (2.5):

$$p = \rho \frac{R_u}{W} T \quad (2.5)$$

where W is the mean molecular weight of the mixture given by Equation (2.6):

$$\frac{1}{W} = \sum_{k=1}^N \frac{Y_k}{W_k} \quad (2.6)$$

A reference enthalpy h_k can be defined by means of reference temperature T_0 as given with Equation (2.7):

$$h_k = \int_{T_0}^T c_{pk} dT + \Delta h_{f,k}^0 \quad (2.7)$$

where c_{pk} is the heat capacity at constant pressure of species k and $\Delta h_{f,k}^0$ is the mass enthalpy of formation. For methane that value is (-)4675 kJ/kg [6]. The heat capacity at constant pressure of the mixture is defined by Equation (2.8):

$$c_p = \sum_{k=1}^N c_{pk} Y_k \quad (2.8)$$

The diffusion coefficient of species k in the rest of the mixture is called D_k . The D_k coefficients are often characterized in terms of Lewis number defined by Equation (2.9):

$$Le_k = \frac{\lambda}{\rho c_p D_k} = \frac{D}{D_k} \quad (2.9)$$

where $D = \lambda / \rho c_p$ is the heat diffusivity coefficient. Here λ is the heat diffusion coefficient. The Lewis number compares the diffusion speeds of heat and species k .

The Prandtl number, Pr , can be defined by Equation (2.10) which compares momentum and heat transport:

$$Pr = \frac{\nu}{D} \quad (2.10)$$

In Equation (2.10), ν is the kinematic viscosity which is also called momentum diffusivity in mass transfer.

2.1.1. Stoichiometry and equivalence ratio

Even though multiple radicals may be involved in a flame, certain species are more important to characterize the combustion regime. The fuel and the oxidizer mass fractions are significant quantities and their ratio is commonly used to characterize the flame. Burners are classified as premixed and non-premixed as depicted in Figure 2.1 [6].

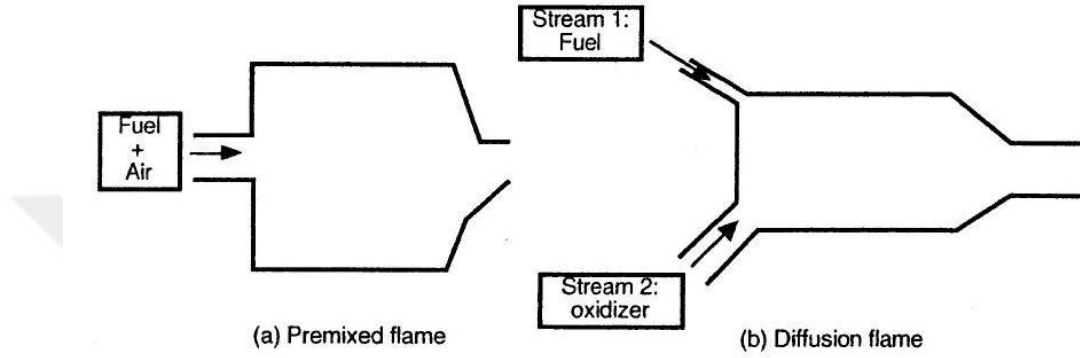


Figure 2.1: Classification of burners [6].

In a premixed burner as shown in Figure 2.1a, fuel and oxidizer are mixed before they enter the combustion chamber. The mass fractions of fuel and oxidizer correspond to stoichiometric conditions as given with Equation (2.11):

$$\left(\frac{Y_O}{Y_F}\right)_{st} = \frac{v'_O W_O}{v'_F W_F} = s \quad (2.11)$$

where v'_O and v'_F are the coefficients corresponding to fuel and oxidizer, respectively. This ratio is called the stoichiometric ratio. The equivalence ratio of a given mixture (Φ) is defined by Equation (2.12):

$$\Phi = s \frac{Y_F}{Y_O} \quad (2.12)$$

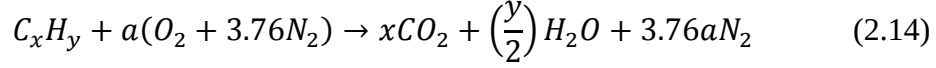
The equivalence ratio can also be written by Equation (2.13):

$$\Phi = s \frac{\dot{m}_F}{\dot{m}_O} \quad (2.13)$$

where $\dot{m}_F$ and $\dot{m}_O$ are mass flow rates of fuel and oxidizer, respectively.

For $\Phi > 1$, rich combustion is obtained, while lean combustion is seen when $\Phi < 1$. The stoichiometric oxidizer-fuel ratio is determined by writing simple atom balances,

assuming that the fuel reacts to form an ideal set of products [40]. For example, a hydrocarbon fuel given by C_xH_y , the stoichiometric relation can be expressed by Equation (2.14):



The stoichiometric coefficient, a , can be defined by Equation (2.15):

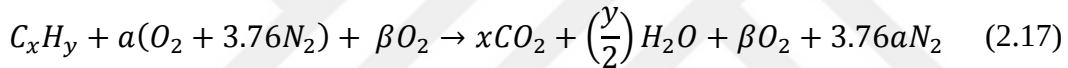
$$a = x + y/4 \quad (2.15)$$

The stoichiometric air-fuel ratio can be found as given with Equation (2.16):

$$\left(\frac{\dot{m}_A}{\dot{m}_F}\right)_{st} = 4.76a \frac{W_A}{W_F} \quad (2.16)$$

where $\dot{m}_A$ is the mass flow rate of air and W_A is the molecular weight of air.

For oxygen-enhanced combustion cases, Equation (2.14) can be rewritten as shown in Equation (2.17):



where β is the coefficient of excess oxygen.

For a diffusion flame, fuel and oxidizer are introduced separately into the combustion chamber through two or more inlets where flow rates and mass fractions are controlled separately. For the burner which is seen in Figure 2.1b, equivalence ratio is primarily defined as Equation (2.12). This ratio characterizes the local structure of flames formed when the fuel and oxidizer streams interact. As this ratio does not represent the overall behavior of the burner, a global equivalence ratio must be defined by Equation (2.18) [6]:

$$\Phi_g = s \frac{\dot{m}_F}{\dot{m}_O} \quad (2.18)$$

where $\dot{m}_F$ and $\dot{m}_O$ are mass flow rates of fuel in the first stream and oxidizer in the second stream, respectively.

The correlation between Φ and Φ_g can be defined by Equation (2.19):

$$\Phi_g = \Phi \frac{\dot{m}_1}{\dot{m}_2} \quad (2.19)$$

where $\dot{m}_1$ and $\dot{m}_2$ are the total flow rates entering inlets 1 and 2, respectively. For non-premixed burners, Φ and Φ_g may differ significantly.

Non-premixed flames include more complex chemistry than premixed ones, because the equivalence ratio covers the whole range from 0 to ∞ . Rich combustion occurs on the fuel side, lean combustion on the air side. Because of the safety considerations, non-premixed flames are mostly used in burners. Unless very sophisticated techniques are used, non-premixed flames show a yellow luminescence, caused by glowing soot particles formed by fuel-rich chemical reactions in the rich domains of non-premixed flames [1].

2.1.2. Chemical kinetics

Ignition and flame extinction are related to chemical processes. The study of the elementary reactions and their rates, chemical kinetics, is a specialized field of physical chemistry. In the past few decades, much progress has been made in combustion because chemists have been able to define the detailed chemical pathways leading from reactants to products, and to measure or calculate their associated rates [40].

Flames will propagate through only those chemical mixtures that are capable of reacting quickly enough to be considered explosive. Indeed, the expression explosive essentially specifies very rapid reaction. From the standpoint of combustion, the interest in chemical kinetic phenomena has generally focused on the conditions under which chemical systems undergo explosive reaction [41].

Including combustion, all chemical reactions take place at a definite rate and depend on the conditions of the system. The most important of these conditions are the concentration of the reactants, the temperature, radiation effects, and the presence of a catalyst or inhibitor [41].

According to Arrhenius, only molecules that possess energy greater than a certain amount E_a (activation energy), will react. Arrhenius' postulate may be written by Equation (2.20):

$$RR = Z_{AB} \exp\left(-\frac{E_a}{RT}\right) \quad (2.20)$$

where RR is the rate of disappearance, Z_{AB} is the gas kinetic collision frequency and $\exp(-\frac{E_a}{RT})$ is the Boltzmann factor. Kinetic theory shows that the Boltzmann factor gives the fraction of all collisions that have energy greater than E_a . Generally; the Arrhenius form of the reaction rate constant (k), which depends only on temperature, is defined by Equation (2.21):

$$k = A \exp(-\frac{E_a}{RT}) \quad (2.21)$$

where A is defined as the kinetic pre-exponential factor.

The activation energy E_a , corresponds to an energy barrier to be overcome during the reaction. This phenomenon is graphically shown in Figure 2.2 [1].

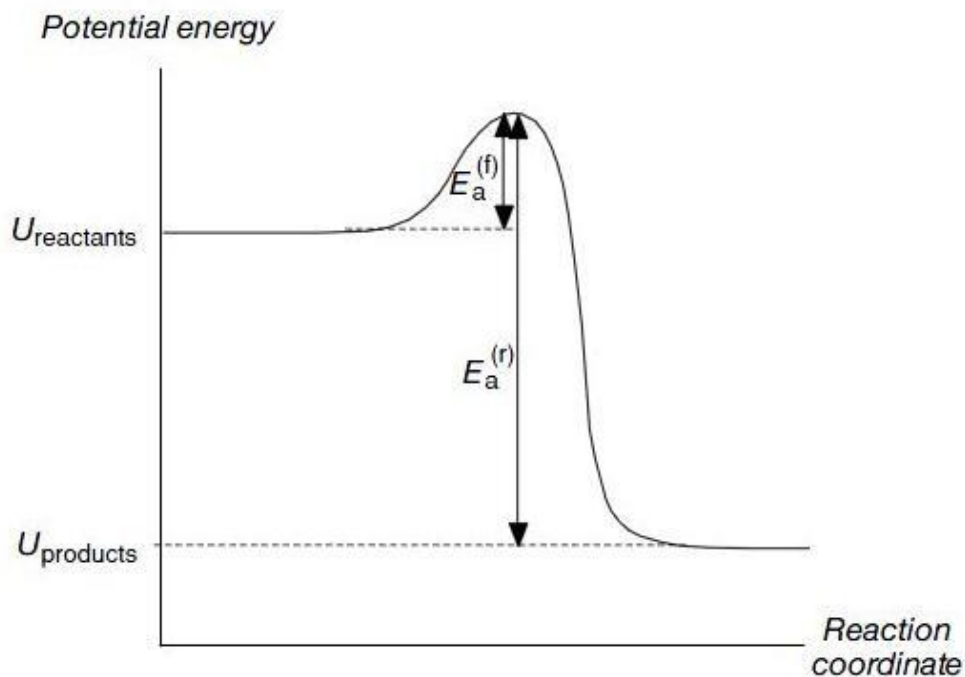


Figure 2.2: Energy diagram for a chemical reaction [1].

2.1.3. Chemical thermodynamics

2.1.3.1. First and second laws of thermodynamics

According to first law of thermodynamics as given with Equation (2.22):

$$dU = \delta Q - pdV \quad (2.22)$$

In Equation (2.22), U indicates the internal energy and δQ is the sum of heat transferred.

Chemical processes usually take place at constant pressure. It is convenient to define enthalpy H , by Equation (2.23):

$$dH = dU + pdV + VdP \quad (2.23)$$

Introducing Equation (2.22) into Equation (2.23) leads to Equation (2.24):

$$dH = \delta Q + VdP \quad (2.24)$$

For constant pressure, $dP = 0$. Then Equation (2.24) reduces to Equation (2.25):

$$dH = \delta Q \quad (2.25)$$

Second law of thermodynamics defines state variable entropy S as given with Equation (2.26):

$$dS = \frac{\delta Q_{rev}}{T}; dS > \frac{\delta Q_{irrev}}{T} \quad (2.26)$$

Here the index “rev” denotes a reversible and “irrev” an irreversible process, respectively.

Introducing Equation (2.26) into Equation (2.22) and referring to the principle of le Chatelier, which indicates that when a settled system is disturbed, it will adjust to diminish the change that has been made to it, the equilibrium condition is obtained by Equation (2.27):

$$dU + pdV - TdS \leq 0 \quad (2.27)$$

2.1.3.2. Adiabatic flame temperature

If a fuel-air mixture burns adiabatically at constant pressure, the absolute enthalpy of the reactants at the initial state ($T = T_i$) equals the absolute enthalpy of the products at the final state ($T = T_{ad}$) as given with Equation (2.28):

$$H_{reac}(T_i, P) = H_{prod}(T_{ad}, P) \quad (2.28)$$

In this statement T_{ad} is called adiabatic flame temperature. In Figure 2.3 constant pressure adiabatic flame temperature is illustrated.

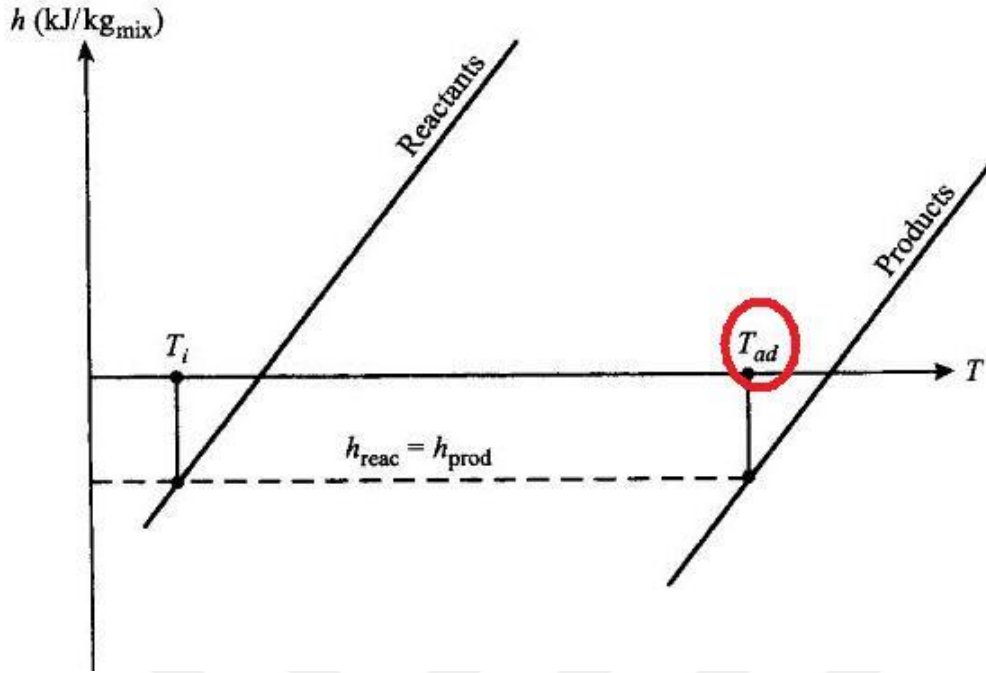


Figure 2.3: Constant pressure adiabatic flame temperature [40].

If an adiabatic steady-state process is presumed; the energy balance can be written by Equation (2.29):

$$T_{ad} = \frac{\Delta H_C}{C_p \left(1 + \frac{\dot{m}_O}{\dot{m}_F}\right)} + T_i \quad (2.29)$$

where ΔH_C is the specific heat capacity of fuel.

For methane/air flame, adiabatic flame temperature is approximately 2222 K [1].

2.2. Diffusion Flames

Diffusion flames constitute a specific class of combustion problems where fuel and oxidizer are not mixed before they enter the combustion chamber. For these flames, mixing must bring reactants into the reaction zone fast enough for combustion precede. Figure 2.4 represents the prototype of the diffusion flame configuration. Fuel and oxidizer diffuse towards the reaction zone where they burn and generate heat. Temperature is maximum in this zone and diffuse away from the flame front towards the fuel and oxidizer streams [6].

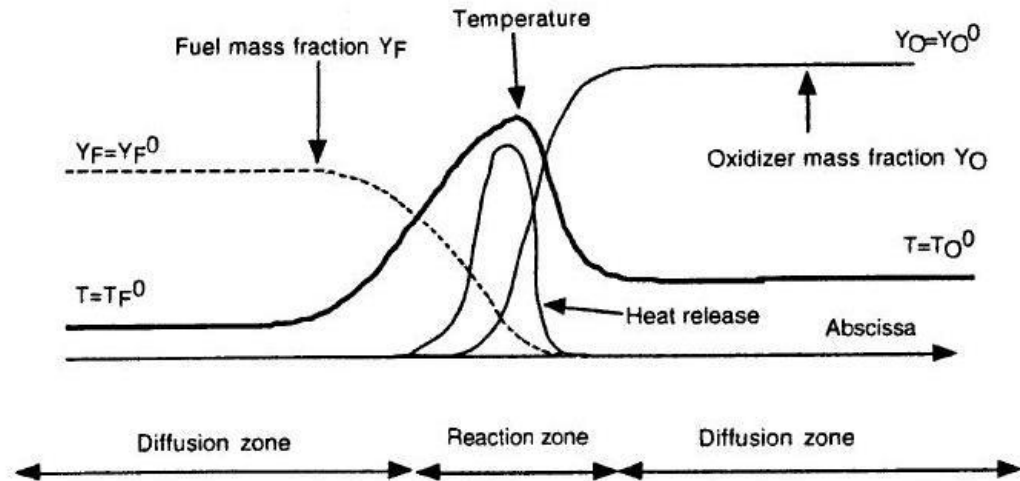


Figure 2.4: The prototype of the diffusion flame configuration [6].

By analyzing Figure 2.4, the following considerations are obtained:

- On each side of the flame, too lean and too rich gas regions exist. Reaction zone is limited, which chemical reactions occur. Homogeneous mixing is obtained under stoichiometric condition.
- Due to being unable to propagate, a diffusion flame does not exhibit a reference speed. The reaction zone does not move significantly relatively to the flow field. Hence, diffusion flames are sensitive to turbulence.
- Diffusion flames are useful for industrial applications. The equivalence ratio is simply adjustable. As they do not propagate nor flashback, diffusion flames are safer to operate.

In diffusion flames; the fuel may be in the form of a gaseous fuel jet or a condensed medium, and the oxidizer may be a flowing gas stream or the quiescent atmosphere [41].

Hottel and Hawthorne have measured species distribution in a concentric laminar hydrogen-air diffusion flame. Figure 2.5 schematically shows a radial distribution of species they obtained [42].

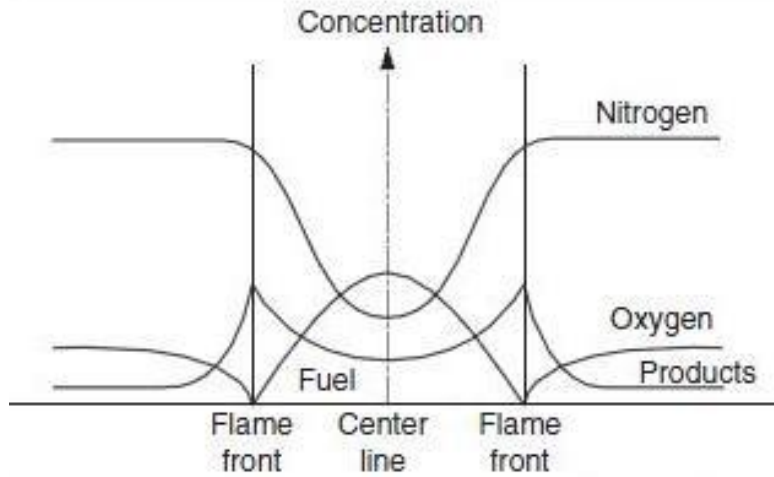


Figure 2.5: Radial distribution of species in a concentric laminar hydrogen-air diffusion flame [41].

Smyth et al. have made detailed measurements of temperature and species distribution in a methane-fueled burner. Their results are shown in Figure 2.6 [43].

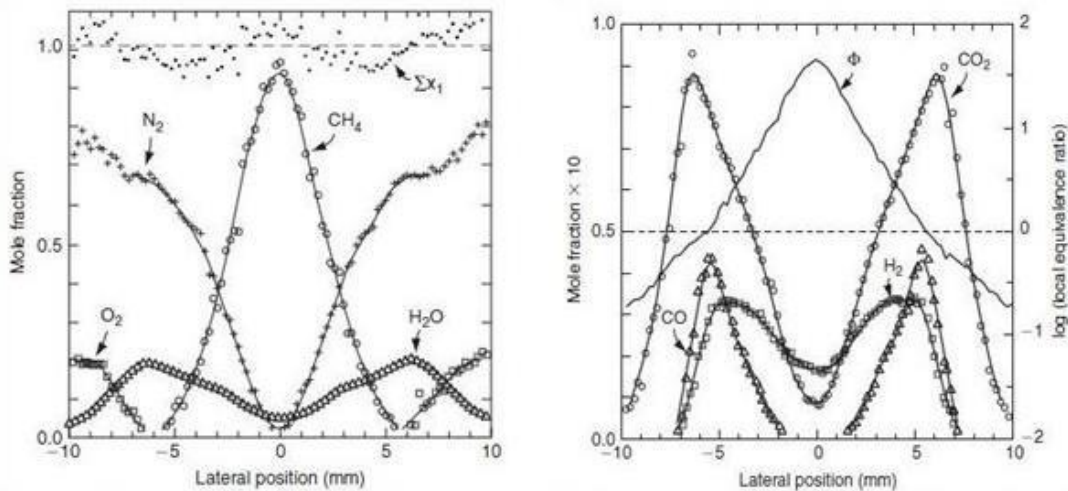


Figure 2.6: Species distribution in a methane-fueled burner [43].

Figure 2.6 shows that the fuel and oxidizer diffuse toward each other under stoichiometric condition.

2.2.1. Turbulent diffusion flames

The flow regime is turbulent in most practical combustion systems. Combustion in aircraft or internal combustion engines, rockets, industrial burners can be given as example for turbulent combustion. Turbulence and combustion are very complex

phenomena to analyze, even when they do not interact with each other. Schematic drawing of a momentary picture of a turbulent non-premixed jet flame is shown in Figure 2.7.

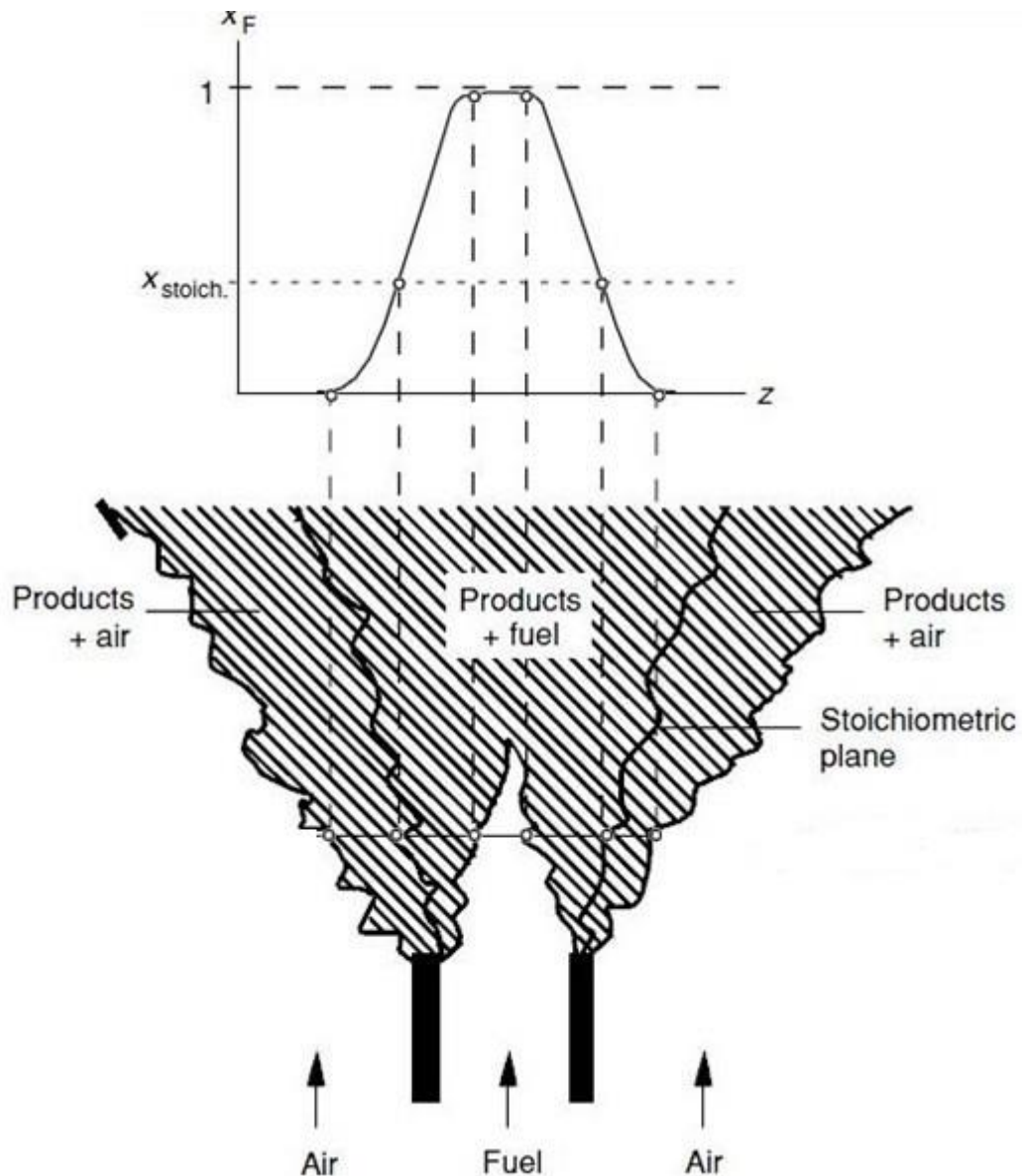


Figure 2.7: A momentary picture of a turbulent non-premixed jet flame [1].

When a flame interacts with a turbulent flow, turbulence is modified by combustion because of the strong flow accelerations through the flame front induced by heat release, and because of the large changes in kinematic viscosity associated with temperature changes. This mechanism may generate turbulence, called “flame-generated turbulence”. On the other hand, turbulence alters the flame structure, may enhance chemical reaction but also, in extreme cases, completely inhibit it, leading to flame quenching [6].

In Figure 2.8, a fuel jet is schematically illustrated, which is injected into the ambient air.

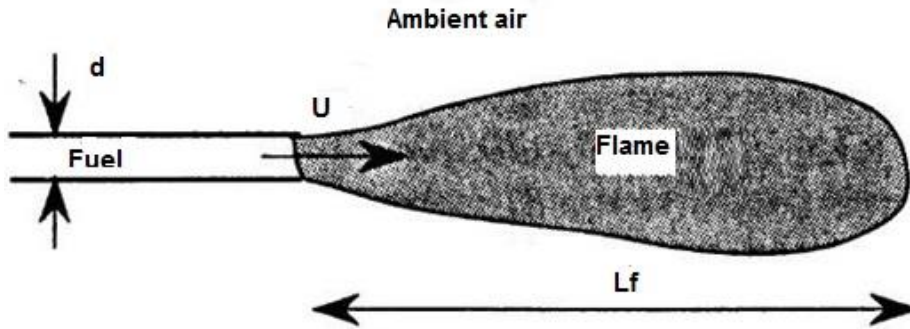


Figure 2.8: A fuel jet injected into ambient air [6].

The flame length L_f can be measured by means of Reynolds number which is defined by Equation (2.30):

$$Re = \frac{U d}{\nu} \quad (2.30)$$

where U , d and ν are the initial velocity, the diameter and the kinematic viscosity of the fuel jet stream, respectively [44]. In Figure 2.9, flame length L_f as function of Reynolds number is shown.

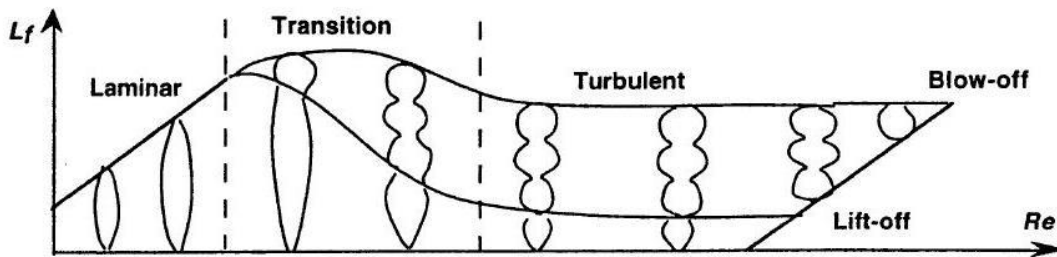


Figure 2.9: Flame length as function of Reynolds number [6].

The flame length increases linearly at first with increasing Reynolds number [44]. For a sufficiently high Reynolds number (around 1350-1650), the flow becomes turbulent and the flame length decreases before reaching a constant value independent on the Reynolds number. The transition point between laminar and turbulent region of the flame moves closer to the injector tip. For sufficiently high injection velocities, the flame is lifted from the burner (lifted flame) and then may be extinguished by blow-off [44].

2.2.2. Swirl-stabilized diffusion flames

Flames in practical burners must first be ignited. After this first ignition, the incoming reactants must be continuously mixed and ignited by the hot gases present in the chamber, for combustion to continue. This process, called flame stabilization, is a central design criterion for combustion chambers. Insufficient stabilization can result in a burner which cannot operate safely or oscillates dangerously [6].

For large powers and inlet flow speeds, creating a recirculation zone behind a sudden expansion may not be sufficient to ensure flame stabilization while minimizing pressure losses. For such cases, swirl offers another stabilization mechanism used in multiple industrial turbulent non-premixed flames [6].

Swirl corresponds to a rotating movement of the incoming reactants and is produced upstream of the combustion chamber by vanes or lateral injection. Swirling the flow creates a low-speed region on the combustion chamber axis as seen in Figure 2.10 [6].

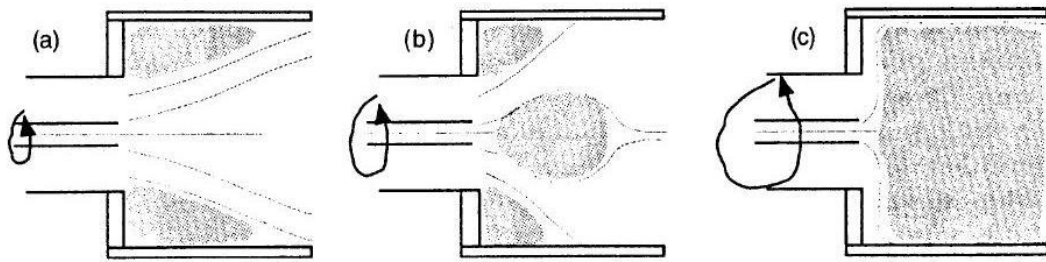


Figure 2.10: Non-reacting swirled flows in a combustion chamber. Cases (a) to (c) correspond to increasing swirl intensities [6].

El-Mahallawy et al. have investigated the effect of swirl and the swirl position on the stability of turbulent free diffusion flames. They have used a vertical burner. They have used four swirlers which swirler vanes placed at 0° , 30° , 45° and 60° . The position of the swirler inside the air jet (z : the distance between swirler surface and burner rim) has been varied between $z = 0$ mm and $z = 7$ mm [45]. Blow-off velocities for different swirlers are shown in Figure 2.11 against the equivalence ratio.

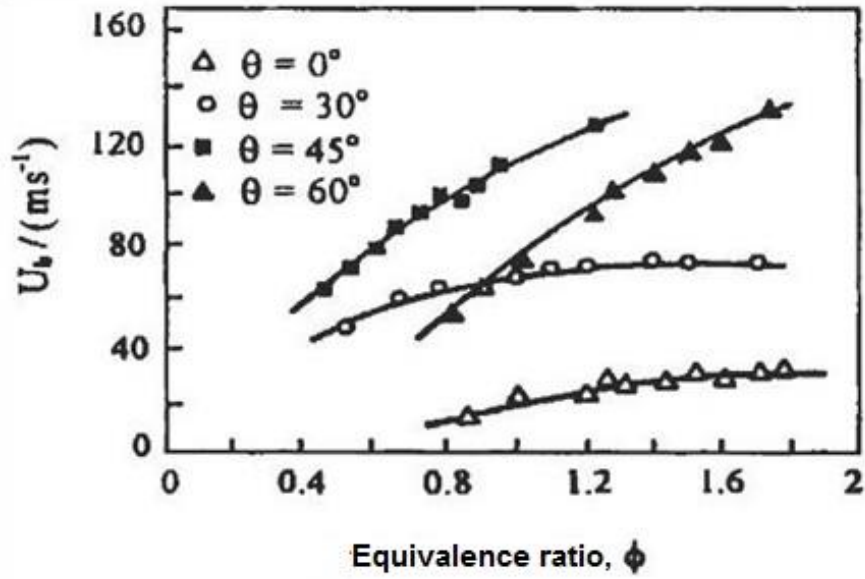


Figure 2.11: Blow-off velocities for different swirlers against the equivalence ratio [45].

As seen in Figure 2.11, swirling the air jet increases blow-off velocities. For high degrees of swirl, 60° , there is a decrease in blow-off velocities. In Figure 2.12 and Figure 2.13, effect of the degree of swirl on the blow-off velocity for different equivalence ratios is graphically shown at $z = 0$ mm and $z = 7$ mm, respectively.

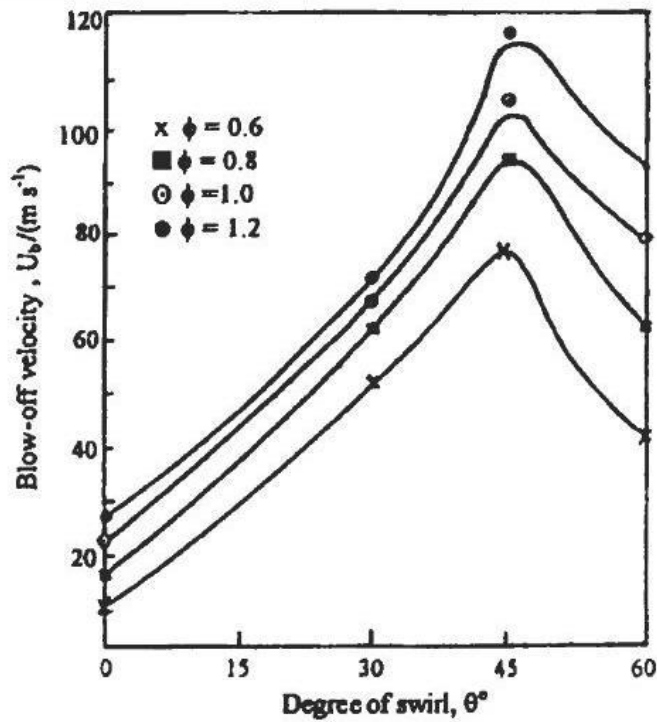


Figure 2.12: Effect of the degree of swirl on the blow-off velocity at $z = 0$ mm [45].

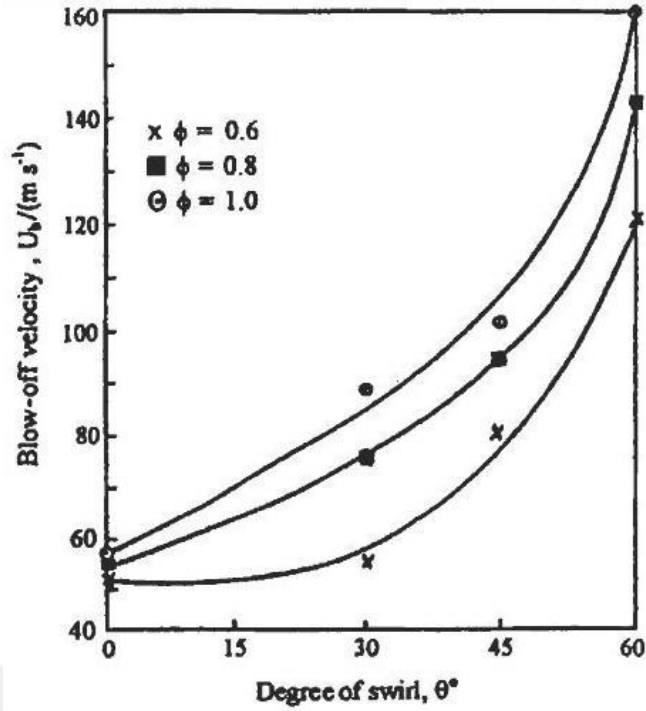


Figure 2.13: Effect of the degree of swirl on the blow-off velocity at $z = 7$ mm [45].

By examining these graphics, it is obtained that the flame stabilization improves with increasing equivalence ratio. It is also obtained that swirler position has a significant effect on blow-off velocity. When the swirler surfaces were lowered inside the air jet, flame stability improves and the blow-off velocities increase. Another consideration may be made as there is an optimum degree of swirl. Figure 2.12 shows that 45° of swirl is the optimum value when $z = 0$ mm. However, Figure 2.13 shows that when $z = 7$ mm, maximum blow-off velocity is reached with 60° of swirl.



3. THEORETICAL CALCULATIONS FOR EXPERIMENTAL STUDY

In present study, experimental results for combustion performance experiments are evaluated with combustion efficiency and combustion gases temperature. For burner characterization experiments, equivalence ratio and axial mean swirler velocity are evaluation parameters.

In this chapter, theoretical calculations for experimental evaluation parameters are presented.

3.1. Temperature Calculation

In present experimental study, the operating envelope given in Figure 3.1 has been investigated. Test points have been chosen and marked with red according to desired flight conditions such as altitude and Mach number.

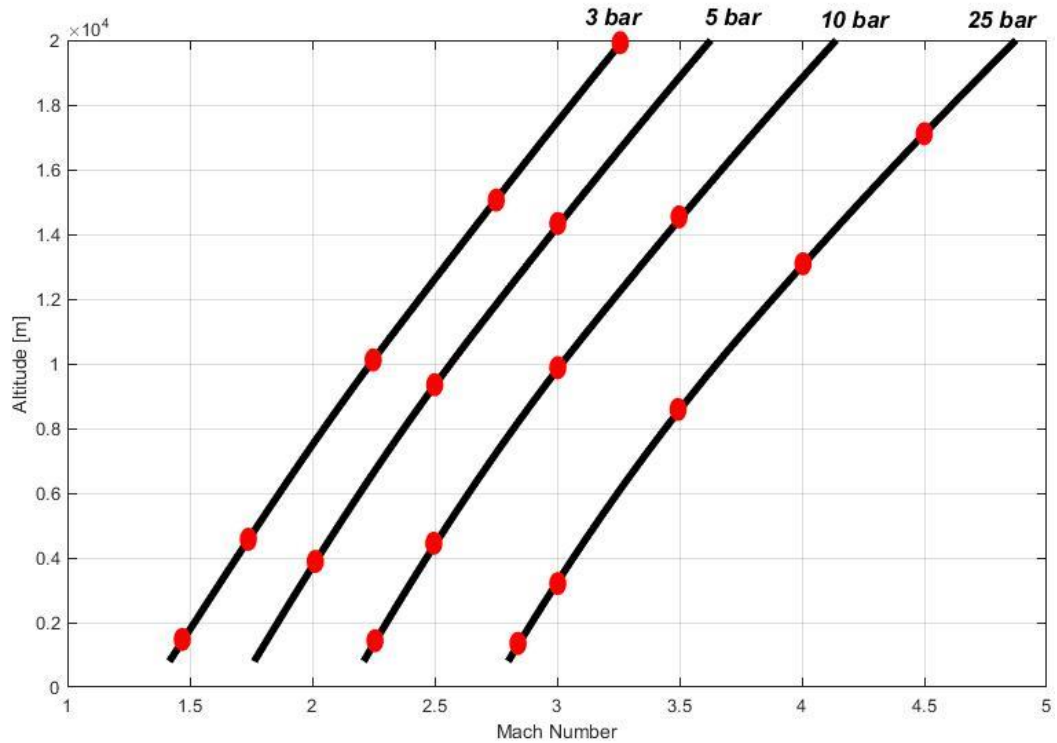


Figure 3.1: Desired flight altitude and Mach number conditions for ground testing.

Total temperatures for desired experimental test points are calculated with Equation (3.1):

$$T_{total} = T_0 \left(1 + \frac{\gamma - 1}{2} M^2\right) \quad (3.1)$$

where T_0 is the air temperature at given altitude, γ is the specific heat ratio and M is the given Mach number.

By using Equation (3.1), temperature values of desired flight conditions given with Figure 3.1 can be filled as shown in Figure 3.2.

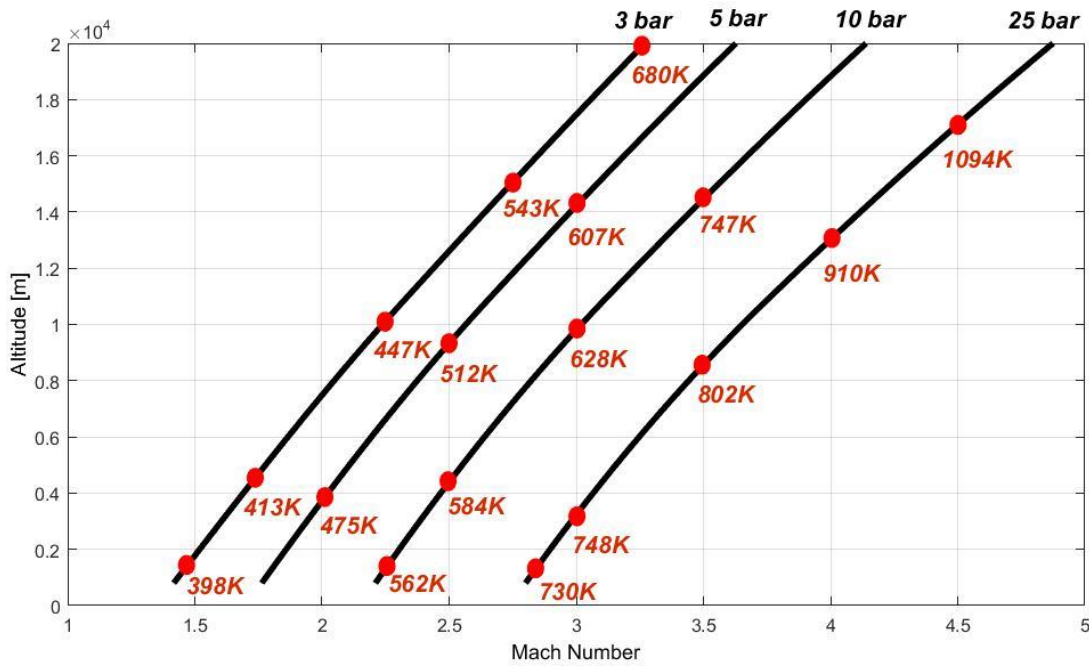


Figure 3.2: Desired test points with their total temperature values.

Temperature values given with Figure 3.2 are target adiabatic flame temperature values to achieve for combustion performance experiments by burning fuel in CAH.

NASA CEA is a simple and user-friendly aero-thermochemical equilibrium code to calculate fuel and oxidizer mass flow rates that will provide temperature values given with Figure 3.2. NASA CEA equilibrium code has been used in present study for mass flow rates and adiabatic flame temperatures.

3.2. Combustion Efficiency Calculation

In general, an efficiency definition compares a measured performance value with a theoretically evaluated one. The resulting value gives information about the quality of the examined process [9]. Equation (3.2) defines a general formula for efficiency:

$$\eta = \frac{\text{experimentally determined value}}{\text{theoretically determined value}} \quad (3.2)$$

Due to practical or traditional reasons, several definitions of combustion efficiency are in use: combustion efficiencies based on characteristic velocity, vacuum specific impulse, temperature rise and equivalence ratio [9]. Due to investigating a CAH performance, combustion efficiency definition based on temperature rise ($\eta_{\Delta T}$) has been used in present study. The value $\eta_{\Delta T}$, which is defined by Equation (3.3), shows the experimental temperature rise in comparison to the theoretical temperature rise in combustion chamber:

$$\eta_{\Delta T} = \frac{T_{outlet,exp} - T_{inlet}}{T_{outlet,th} - T_{inlet}} \quad (3.3)$$

where T_{inlet} is the air inlet temperature and $T_{outlet,exp}$ and $T_{outlet,th}$ are experimental and theoretical combustion gases temperatures, respectively.

In present study, T_{inlet} and $T_{outlet,exp}$ values have been measured directly by using thermocouples. $T_{outlet,th}$ value has been determined theoretically by using Equation (3.1) and NASA CEA code.

3.3. Equivalence Ratio Calculation

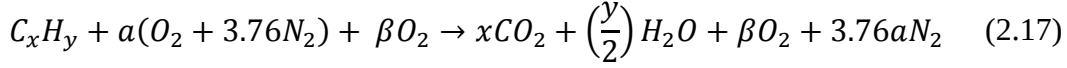
The equivalence ratio of a given mixture (Φ) is defined by Equation (3.4):

$$\Phi = s \frac{\dot{m}_F}{\dot{m}_O} \quad (3.4)$$

where $\dot{m}_F$ and $\dot{m}_O$ are mass flow rates of fuel and oxidizer, respectively. Here, s is the stoichiometric ratio and differs with fuel type.

In present study, oxygen-enriched air has been used as oxidizer and compressed natural gas (CNG) as fuel. The fuel composition mainly consists of methane. For this reason, stoichiometric ratio has been calculated for methane fuel.

Equation (2.17) from Chapter 2 can be used as stoichiometric relation for oxygen-enhanced combustion cases where $a = x + y/4$ and β is the coefficient of excess oxygen.



The stoichiometric ratio for the stoichiometric relation given with Equation (2.17) can be calculated by Equation (3.5):

$$s = \frac{aW_{O_2} + 3.76 aW_{N_2} + \beta W_{O_2}}{W_{CH_4}} \quad (3.5)$$

where W indicates the molecular weight of related species.

For methane fuel (CH_4), $x = 1$ and $y = 4$. Thus, $a = 2$.

From stoichiometric relation given with Equation (2.17), $\beta = 1.385$.

The stoichiometric ratio for methane fuel is then calculated by inserting the values above and molecular weights of species into Equation (3.5). Equation (3.6) shows that the stoichiometric ratio for methane fuel is 19.93.

$$s = \frac{2 \times 32 + 3.76 \times 2 \times 28 + 1.385 \times 32}{16} = 19.93 \quad (3.6)$$

When Equation (3.6) is introduced into Equation (3.4), the equivalence ratio formula for present experimental study is obtained by Equation (3.7):

$$\Phi = 19.93 \frac{\dot{m}_F}{\dot{m}_O} \quad (3.7)$$

In Equation (3.7), $\dot{m}_O$ is the sum of air and oxygen mass flow rates while $\dot{m}_F$ is the mass flow rate of CNG. These flow rates have been obtained by measurement.

3.4. Axial Mean Swirler Velocity Calculation

In present study, lean blowout limits of CAH have been given by means of equivalence ratio and axial mean swirler velocity. This velocity value is calculated with simple continuity equation as given with Equations (3.8) and (3.9):

$$\dot{m}_O = \rho_O UA \quad (3.8)$$

$$U = \frac{\dot{m}_o}{\rho_o A} \quad (3.9)$$

where $\dot{m}_o$ is the oxidizer mass flow rate, ρ_o is the density of the oxidizer, U is the axial mean swirler velocity and A is the swirler flow area. The flow area $A = 62.16 \text{ cm}^2$ for the swirler used within present study.

The density of the oxidizer ρ_o can be calculated with ideal gas relation which is given with Equations (3.10) and (3.11):

$$p = \rho_o R_{air} T_{inlet} \quad (3.10)$$

$$\rho_o = \frac{p}{R_{air} T_{inlet}} \quad (3.11)$$

In present study p has been measured from combustion chamber by pressure transducers. T_{inlet} has also been measured directly by thermocouples.



4. EXPERIMENTAL SETUP

In this chapter, it is mentioned about experimental and measurement methods and a detailed description of the experimental setup of present study. Measurement devices used within present study and information about their calibration are also given. The experimental methodology for both combustion performance experiments and burner characterization experiments are also explained and given in detail.

4.1. Description of Test Item and Test Facility

In ground tests of high-speed air-breathing propulsion systems, stored high-pressure air must be heated significantly to provide atmospheric flight temperature condition. One popular method for heating air up to desired temperature values is using a CAH.

At TÜBİTAK SAGE, a CAH whose side cross-section of solid model is shown in Figure 4.1 is established for heating combustion air to perform ground tests of high-speed air-breathing propulsion systems.

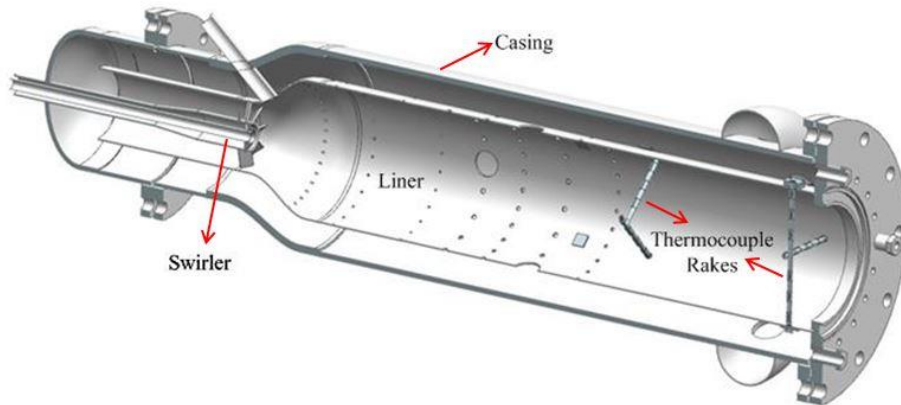


Figure 4.1: Cross-section of the solid model of the CAH.

The oxidizer flow stream enters the burner by passing through an annulus and swirler vanes, respectively. There are 160 dilution holes on the liner of the CAH. Approximately 30% of the oxidizer mass flow rate enters the combustion chamber

through swirler. The remaining 70% enters the combustion chamber through the dilution holes.

Surface type thermocouples have been positioned at specific locations on the liner of the CAH to measure wall temperatures. To measure combustion gases temperature, rake type thermocouples have been placed perpendicular to the flow field.

The CAH has a swirler and a CNG injector whose 3-D CAD model is given in Figure 4.2. The swirler has 10 vanes placed at an angle of 45 degrees. The fuel enters the CAH through 64 holes. Pure oxygen is sent to the CAH through the 14 mm diameter hole in the center of the swirler in those cases of pure oxygen lancing.

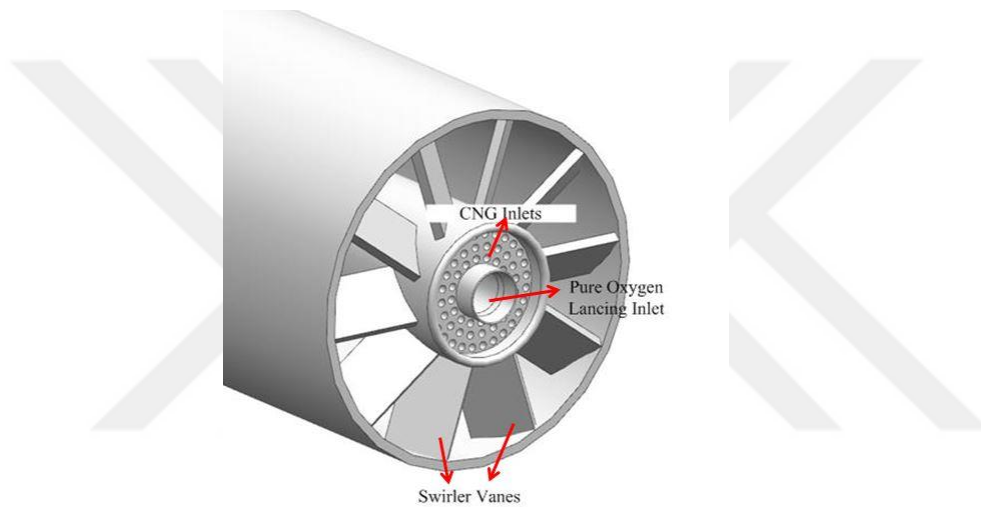


Figure 4.2: Swirler and injector of the CAH.

A picture of the CAH is given in Figure 4.3.



Figure 4.3: CAH.

An experimental setup, which serves as combustion test system have to host following features:

- Suitability for controlling the pressure of the combustion chamber
- Suitability for adjusting the fuel and the oxidizer flow rates
- Ability to measure pressure, combustion gases and wall temperatures, mass flow rates of fuel and oxidizer, composition of combustion gases mixture
- Optical access to the burner

At TÜBİTAK SAGE, an experimental setup has been established with the ability to meet the requirements listed above. The experiments have been conducted in this test facility. The general schematic of the test facility is given in Figure 4.4.

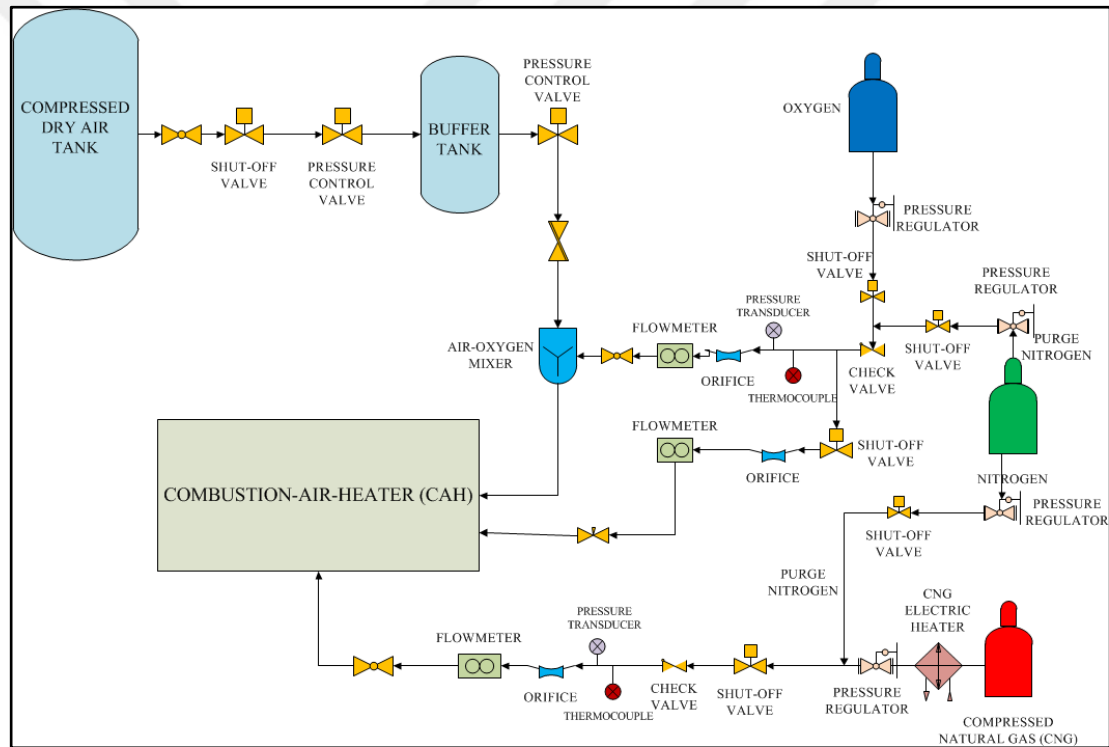


Figure 4.4: General schematic of the test facility.

Since the test facility covers a large area, it would be a good idea to introduce it in detail by separating into parts. These parts can be listed as follows:

1. Combustion air system,
2. Oxygen replenishment line,
3. Pilot oxygen line,
4. Fuel supply line,
5. Ignition system,

6. Gas sampling line,
7. Visualization equipment.

4.1.1. Combustion air system

The air required for combustion is provided by the Compressed Dry Air System shown in Figure 4.5 and Figure 4.6. This system has been available at TÜBİTAK SAGE before the establishment of experimental setup.



Figure 4.5: Compressed dry air system.



Figure 4.6: Compressed dry air system with thermal mass flow meter.

Compressed Dry Air System mainly consists of 2 tanks which have a 50 m³ of air capacity at 40 bar pressure, a 2 m³ buffer tank, 2 pressure control valves, 3 shut off valves and a manual valve. The buffer tank is used to keep the air flow rate constant. The system is capable of air supplying up to 4 kg/s.

The compressed air stored in the buffer tank, reaches the CAH after expanding in the pressure control valve and passing through the shut off valve.

4.1.2. Oxygen replenishment line

Within the scope of present thesis, experiments have been carried out with oxygen-enriched-air. The oxygen replenishment line has been established and connected to the combustion air system for the experiments. The line used to enrich the air with oxygen is shown in Figure 4.7 and Figure 4.8. Gaseous oxygen is fed into the line by commercial manifold tube bundles.



Figure 4.7: Shut-off valves and pressure regulators of the oxygen replenishment line.

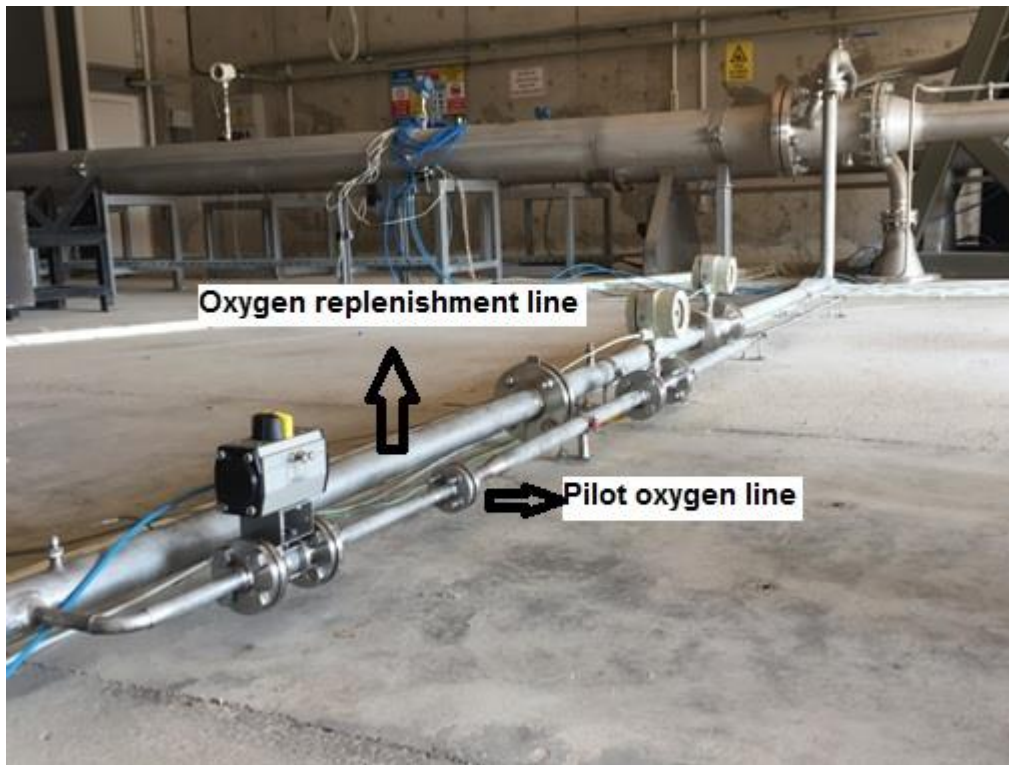


Figure 4.8: Oxygen replenishment line with oxygen lancing line.

2 pressure regulators, 2 shut off valves, a check valve, pressure and temperature transducers, an orifice plate, a thermal mass flow meter, a shut off valve for purging nitrogen gas and a manual valve have been mounted to the oxygen replenishment line. After the manual valve, gaseous oxygen enters into the air-oxygen mixer which is shown in Figure 4.9.



Figure 4.9: Air-oxygen mixer.

The oxygen flow is choked by an orifice plate shown in Figure 4.10 to ensure constant mass flow rate values.



Figure 4.10: Orifice plate placed on the oxygen replenishment line.

4.1.3. Pilot oxygen line

Within the scope of present thesis, effects of oxygen lancing on flame stabilization and lean blowout limits have also been investigated.

In Figure 4.8, a secondary line is seen after check valve exit. From this line, pure oxygen is lanced into the CAH by the central tube of swirler to stabilize the flame. This line consists of a shut off valve, an orifice plate, a thermal mass flow meter and a manual valve.

In present study, 10% of the total oxygen amount is directly lanced into the CAH as pilot oxygen. The remaining 90% of the total oxygen amount is mixed with the combustion air.

4.1.4. Fuel supply line

A fuel supply line shown in Figure 4.11 and Figure 4.12 has been established for the experiments. In the experiments carried out, compressed natural gas (CNG) fuel has been used.



Figure 4.11: Fuel supply system (fuel tubes and heat exchanger).



Figure 4.12: Fuel supply line with its instrumentation.

CNG stored in commercial manifold tube bundles at nearly 230 bar pressure, is heated firstly in the heat exchanger. Then it expands by passing through high and low pressure regulators, respectively. After passing through the low pressure regulator, it flows through the shut off valve, the check valve and the orifice plate, respectively. The CNG fuel enters the CAH from the CNG injector.

A heat exchanger, 2 pressure regulators, a shut off valve, a check valve, pressure and temperature transducers, an orifice plate, a flow meter and a manual valve have been mounted to the fuel supply line.

The reasons for using a regulator instead of a control valve for pressure control in fuel and oxygen lines are their cost-effectiveness, simple structures to easily use, accuracy and quick reaction times.

4.1.5. Ignition system

Ignition by electric sparks is one of the popular ignition methods. Giving an electric potential of several thousand volts to a pair of electrodes made of metallic bars having a diameter from 0.5 to 2 mm set in an explosive mixture, a breakdown, subsequently an electric discharge accompanied by a spark takes place. Then the mixture between the electrodes is heated to a temperature higher than 10000 K, ignited during a period from several microseconds to several milliseconds and a flame spreads from the ignition point [46].

Lewis and von Elbe have carried out many experiments to observe the effect of gap distance between the electrodes on minimum ignition energy. They have used a pair of stainless steel needles as electrodes. They have conducted experiments by varying the gap distance from 0.01 to 0.15 inches. Their result is shown in Figure 4.13 [44].

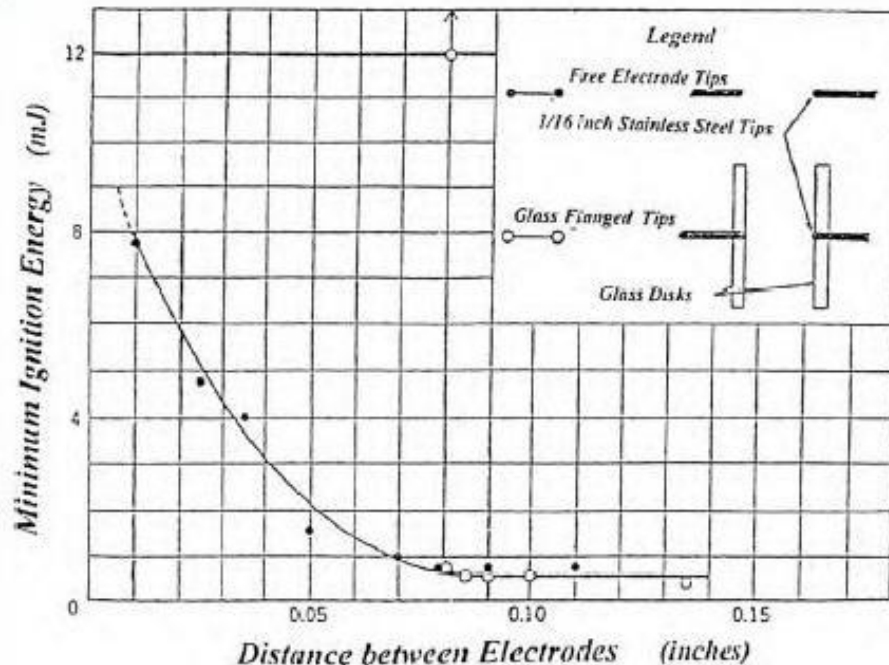


Figure 4.13: Minimum ignition energy of discharge spark in relation to the electrode gap [44].

By examining the graphical result, it is obtained that 0.09 inches is the optimum gap distance. Increasing the gap distance from 0.09 to 0.15 inches does not have any

significant effect to reduce the minimum ignition energy. On the other hand, by shortening the gap distance the minimum ignition energy increases rapidly.

In present study, the ignition method mentioned above has been used. The gap between the electrodes has been adjusted to the optimum value suggested above.

In front of the swirler, ignition electrodes have been placed vertically. The ignition system of the experimental setup, Kromschröder Automatic Burner Control Unit IFD 258, has an ultraviolet (UV) sensor. Flame control is ensured by this sensor. If there is no flame in 3 seconds after the electrical arc is jumped in the electrodes, the UV sensor cuts the fuel flow to the burner. In Figure 4.14, the ignition system, ignition electrodes and the UV sensor are shown.

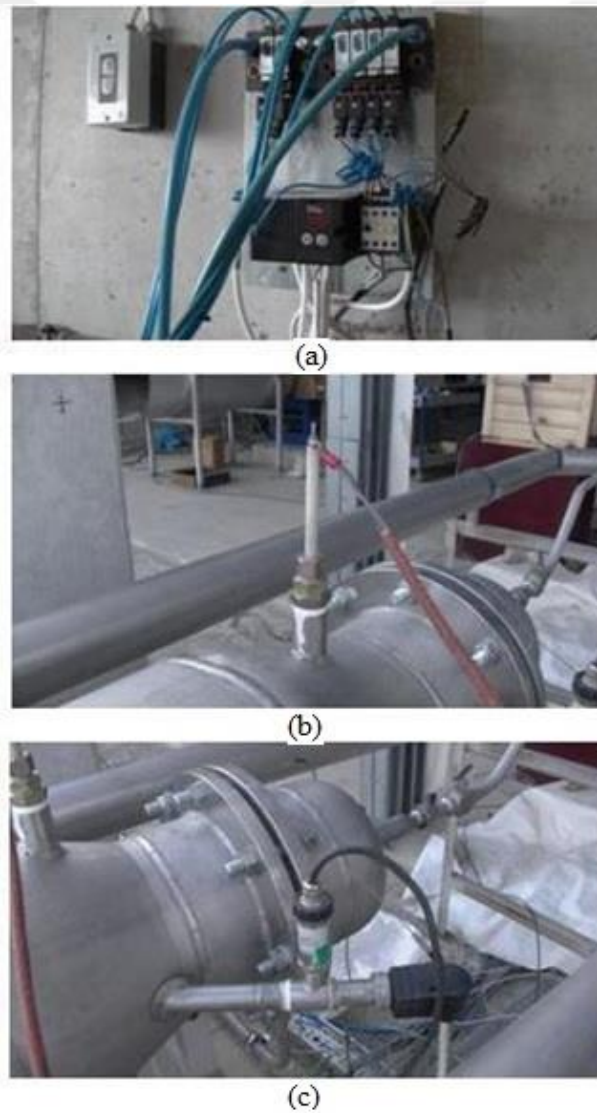


Figure 4.14: Ignition system control unit (a), ignition electrode (b) and the UV flame sensor (c).

4.1.6. Gas sampling line

The experimental setup has been brought into capable of sampling the combustion gases to analyze its composition by establishing gas sample line. In front of the CAH exit, a basic pipeline has been placed to sample the combustion gases. This pipeline is shown in Figure 4.15.

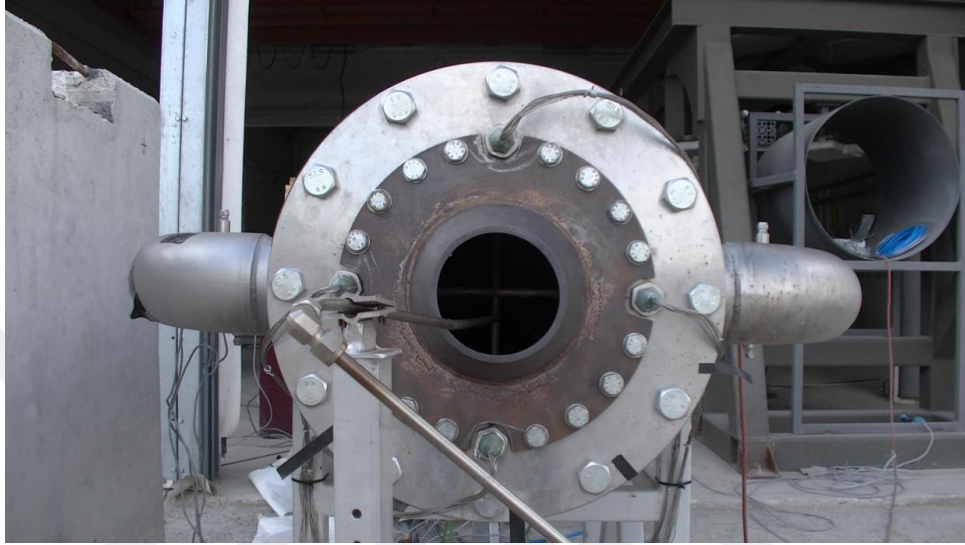


Figure 4.15: Gas sampling pipe in front of the CAH exit.

The gas sample is vacuumed from the CAH by a vacuum pump. Also, 6 shut off valves have been introduced into the system to ensure the vacuum environment. The pictures of the sample tube and the gas sampling system are shown in Figure 4.16 and Figure 4.17, respectively.



Figure 4.16: Gas sampling tube.



Figure 4.17: Gas sampling system with the sampling tube.

4.1.7. Visualization equipment

To visualize the experiments, JVC's GC-PX100B camcorder device shown in Figure 4.18 has been used. This device provides high speed and resolution (300 fps at 640x360 resolution). During the experiments, it has been desired to watch the flame in real time. Since it has Wi-Fi feature, camcorder device can easily connected to PC and fulfill this desire.



Figure 4.18: Flame visualization camcorder.

4.2. Measurement Equipment

The state of a reacting gas mixture at one spatial location is described completely when the velocity U , temperature T , pressure p , density ρ , and the mole fractions x_i or mass fractions w_i are known.

Within present study; the pressures, the temperatures and the mass flow rates of fuel and oxidizer, the temperatures of combustion gases and burner wall and the vacuum value of the gas sampling line have been measured.

The measurement equipment is briefly listed in Table 4.1.

Table 4.1: Measurement equipment.

Function	Type	Measurement Range	Accuracy [%]
Pressure Measurement	Piezoresistive Transducer	0 – 10 bar	0.5
		0 – 4 bar	0.5
		0 – 35 bar	1
Temperature Measurement	K-type	-	0.5
Flow Rate Measurement	Thermal Mass Flowmeter	0 – 14250 Nm ³ /h	1
		0 – 40 g/s	1
		0 – 160 g/s	1

4.2.1. Gas composition measurement

A method is often used in combustion diagnostics to measure the composition is the sampling by means of probes. A suction tube is introduced into the system. The sample is vacuumed from the burner environment, and then stored in a vessel. The stored sample is then analyzed for its chemical constituents using a wide variety of techniques, such as gas chromatography. Within present study gas chromatography has been used to measure the combustion gases composition. The gas chromatography device (Agilent Technologies 7890A) which is shown in Figure 4.19 has been calibrated with two sample gases. Table 4.2 indicates the composition of these sample gases.



Figure 4.19: Gas chromatography device.

Table 4.2: Composition of the sample gases.

Mixture Components	Composition 1 [%]	Composition 2 [%]	Uncertainty [%]
Ethane (C_2H_6)	0.100	0.050	3
Propane (C_3H_8)	0.051	0.025	3
Butane (C_4H_{10})	0.020	0.010	3
Carbon dioxide (CO_2)	3.992	0.994	2
Carbon monoxide (CO)	1.007	0.102	2
Oxygen (O_2)	19.500	9.750	2
Nitrogen (N_2)	69.800	34.900	2
Helium (He)	5.530	54.169	2

Analyzing the gas composition with a gas chromatography device is based on the peaks provided in certain times by software. These peaks symbolize separate gases and are introduced to the software by calibration. By calculating the area under each peak, the composition of the related gas can be measured. An example of these peaks is shown in Figure 4.20.

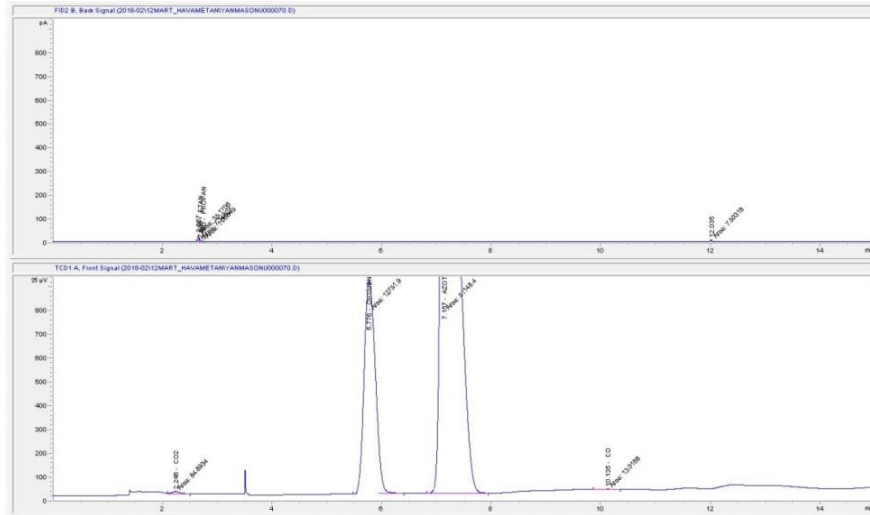


Figure 4.20: Peaks provided from the gas chromatography software.

4.2.2. Temperature measurement

For temperature measurements, thermocouples are widely used. Thermocouples are metal pairs, which induce a voltage value proportional to temperature difference between two metal junctions. Depending on the temperature range measured, thermocouples can be combined with different metals. Although temperature measurement using thermocouples has a disadvantage due to metal-metal junctions, which causes relation to the ambient gas temperature; it is a user-friendly and cost-effective method.

Within present work, K-type surface thermocouples shown in Figure 4.21 have been used to measure wall temperature of the CAH liner. To measure the temperature of combustion gases, K-type thermocouples have been used and these thermocouples have been arranged as a rake. These rakes are shown in Figure 4.22.



Figure 4.21: Surface thermocouples on the CAH liner.



Figure 4.22: Temperature measurement rakes inside the CAH.

The schematic of general thermocouple orientation on the CAH liner is given with Figure 4.23.

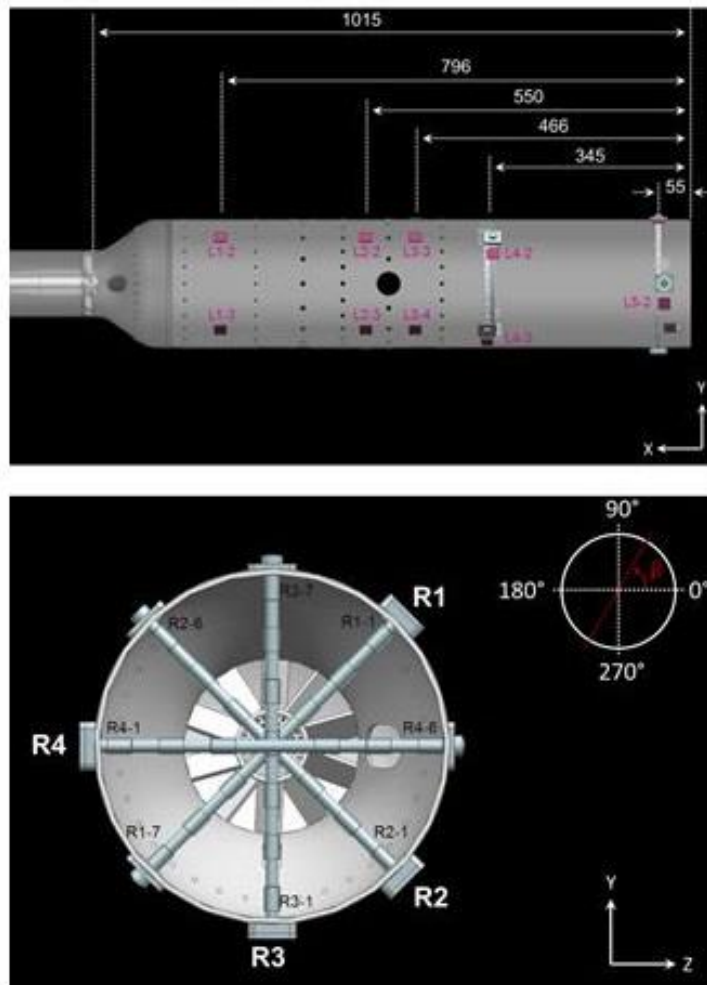


Figure 4.23: Thermocouple orientation on the CAH.

The measurement verifications of calibrated thermocouples have been made before the experiments and the results for some of them are given with Table 4.3.

Table 4.3: Measurement verifications of calibrated thermocouples.

Thermocouple Serial Number	Real Temperature [°C]	Measured Temperature [°C]	Deviation [%]
1703-05025 (K-type rake)	99.97	99.52	0.450
	399.85	400.38	0.133
	799.85	802.30	0.306
	999.92	1003.57	0.365
	1094.78	1099.66	0.446
1703-05094 (K-type surface)	99.98	99.93	0.050
	299.98	299.87	0.037
	499.99	500.00	0.002
	700.01	700.50	0.070

As seen from Table 4.3, thermocouples used in experiments have an uncertainty of 0.5%.

4.2.3. Pressure measurement

In combustion systems pressure varies in time. To measure this variation accurately, piezoresistive pressure transducers are generally used. These transducers respond pressure variations by changes in their electrical properties. Piezoresistive pressure transducers are usually wall-mounted type and they measure the pressure at the wall. Within present study, those pressure transducers (KISTLER 4260A) have been used for measuring fuel, oxygen, inlet air and combustion chamber pressures.

In Figure 4.24 a pressure transducer located on the fuel supply line is shown. The line is also equipped with a thermocouple to measure fuel temperature.

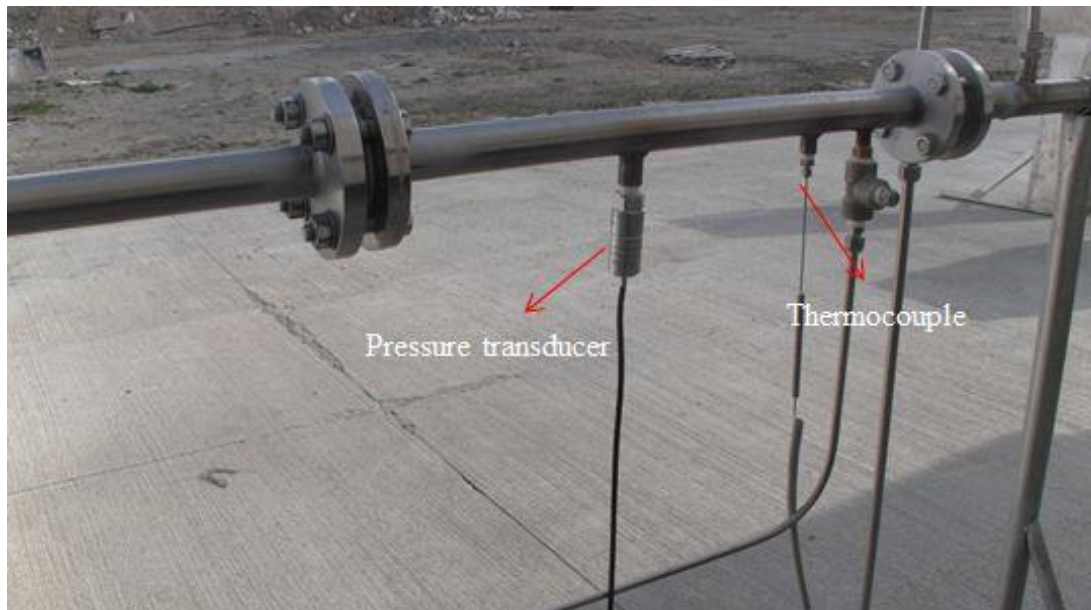


Figure 4.24: Pressure transducer and thermocouple placed on the fuel line.

A pressure transducer is mounted at the inlet of the CAH (on the left side). The second pressure transducer is mounted together with the ultraviolet flame sensor (on the right side). In Figure 4.25, the positions of these devices are marked on the test item.

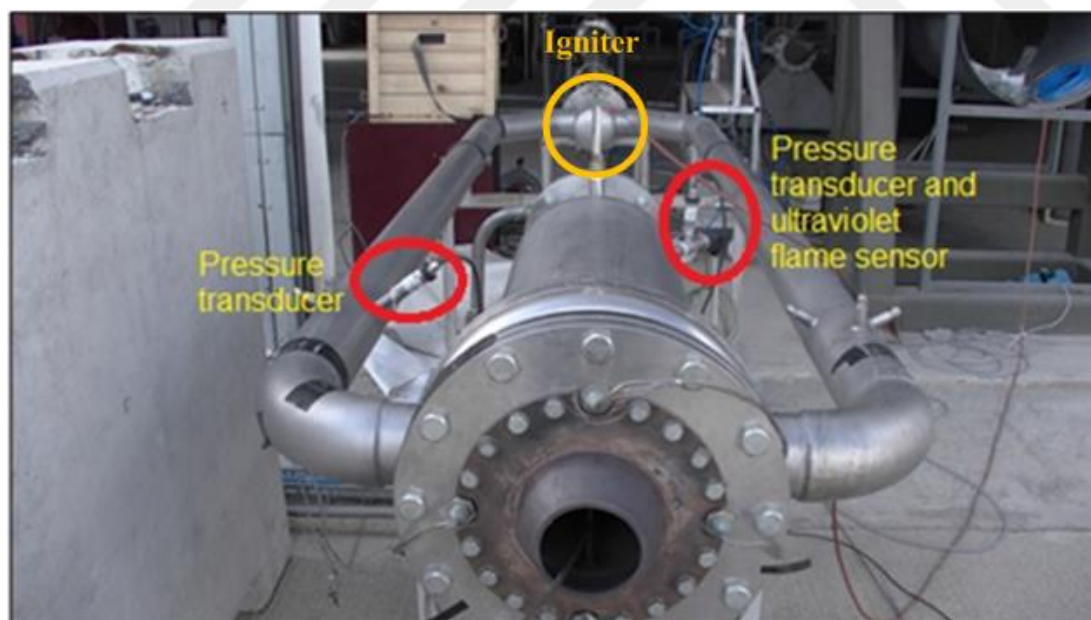
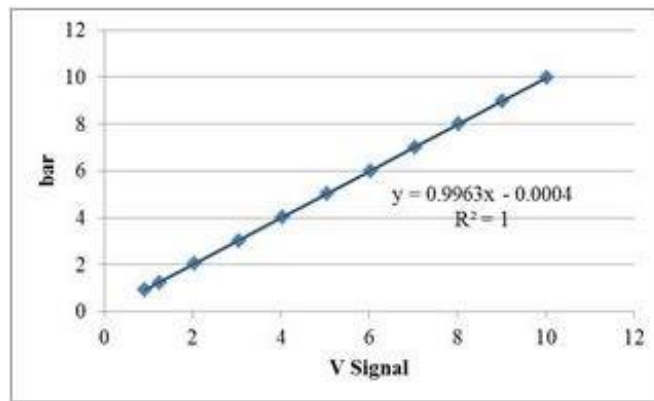
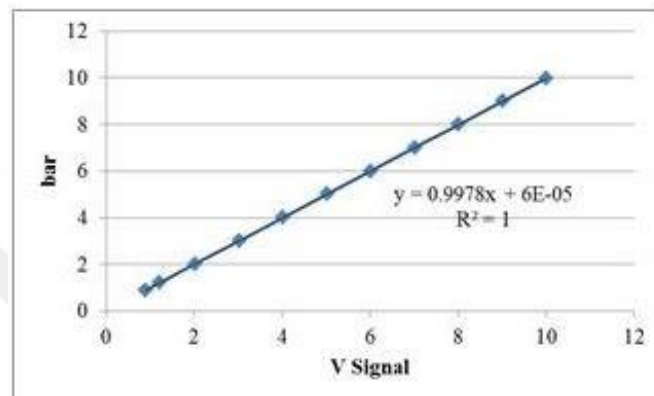


Figure 4.25: Pressure transducers and igniter positioned on the test item.

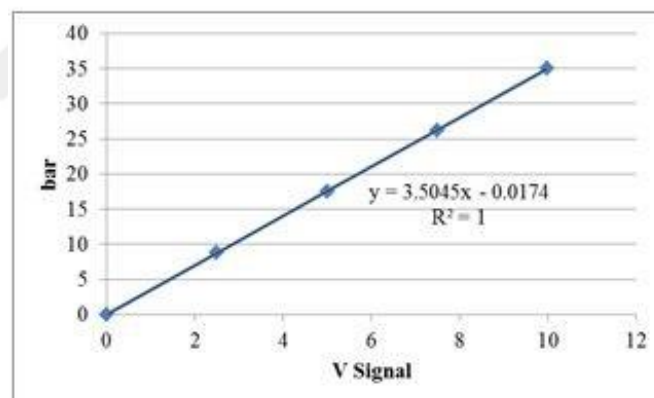
Calibration curves of pressure transducers are given with Figure 4.26. The x-axis of the graph indicates the voltage output and the y-axis indicates the pressure value, respectively.



0 – 10 bar



0 – 10 bar



0 – 35 bar

Figure 4.26: Calibration curves of pressure transducers.

4.2.4. Mass flow rate measurement

Equivalence ratio of a non-premixed combustion system is easily adjustable, as the fuel and oxidizer are injected into the burner by different paths. To calculate the equivalence ratio, the mass flow rates of the fuel and the oxidizer have to be known. By using flow meters, mass flow rates are determined real time.

Coriolis flow meters and thermal mass flow meters are often used to measure mass flow rates of gaseous medium. Their advantages and disadvantages are examined here.

Baker has researched publications about Coriolis type flow meters and summarized the advantages and disadvantages of these flow meters. Their wide range, high precision and single-transducer mass flow measurement method are the main advantages of Coriolis flow meters. However, their high pressure loss, high initial cost and sensitivity to changes in temperature and pressure and to pipe vibration are considered as main disadvantages of Coriolis flow meters [47]. Pope and Wright have investigated the performance of Coriolis flow meters in transient gas flows. They have used a Transient Flow Facility to generate transient flow. With Coriolis flow meters, they have measured the instantaneous flow within the uncertainty of the facility and totalized flow within the maximum permissible errors for flow meters in gaseous medium [48]. Parvizi et al. have investigated the thermal mass flow meter measurement performance for natural gas flow. They have got a maximum error of 1.8% and an overall average error of 0.62% in mass flow metering of natural gas. Therefore, they proved the high accuracy and reliability of the thermal mass flow meter device for natural gas [49]. Amina and Ahmed have provided an overview of using thermal mass flow meters in hydrocarbon industry. They have simulated the applicability of thermal mass flow meters. They have concluded that thermal mass flow meters offer precise measurements of gaseous flows as having an advantage to measure the direct mass flow without the need for additional density corrections [50].

Within present study, thermal mass flow meters (SAGE Metering 200) have been used to measure the fuel and oxidizer mass flow rates, due to their high turndown ratio, compatibility with oxygen and compressed natural gas, low-cost and easy applicability. Thermal mass flow meters located on oxygen replenishment and pilot oxygen lines are shown in Figure 4.27.



Figure 4.27: Thermal mass flow meters located on oxygen replenishment and pilot oxygen lines.

Calibration curves for the air, oxygen and CNG mass flow meters are shown in Figure 4.28.

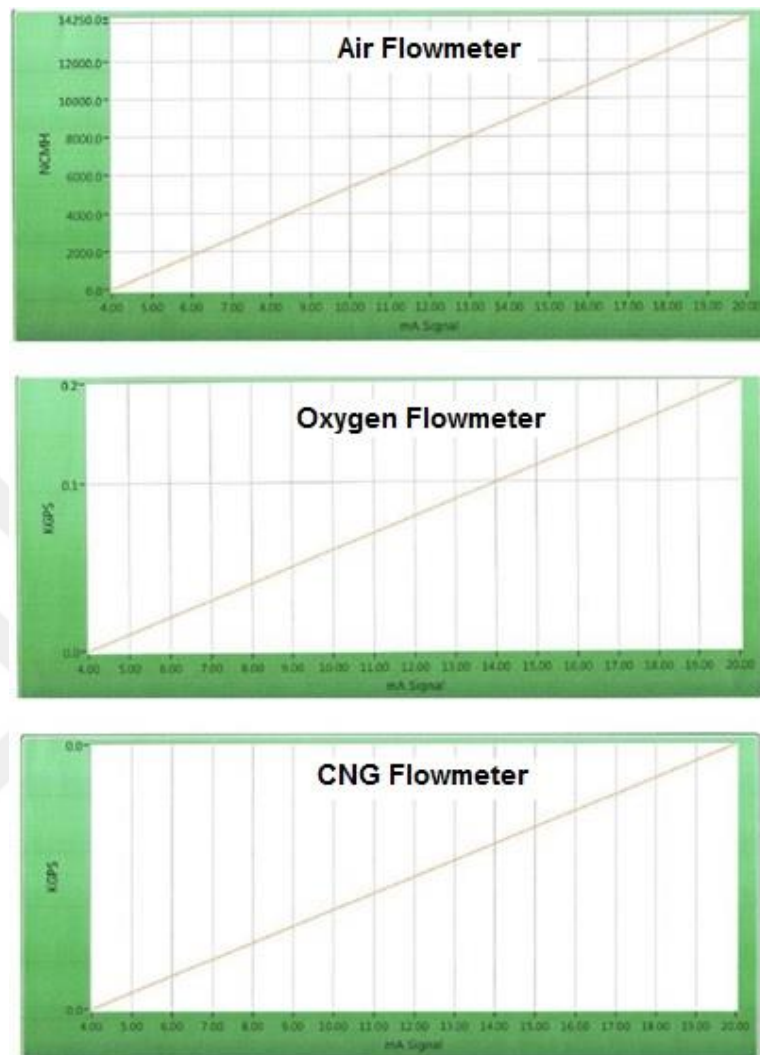


Figure 4.28: Calibration curves for thermal mass flow meters.

CNG and oxygen flows are choked by orifice plates, due to maintain the sufficient back pressure and control the flow. Some of the orifice plates are seen in Figure 4.29.



Figure 4.29: Orifice plates.

4.2.5. Data acquisition system

Thermocouples and pressure transducers generate voltage outputs. These voltage outputs are converted into meaningful values of temperature and pressure by signal conditioning device and recorded in a computer hard disk.

In present experimental study, National Instruments' cDAQ-9189 device has been used to collect temperature and pressure data. This device has 8 slots and connects with PC by Ethernet which provides high-speed data acquisition. The device and the connected PC are seen in Figure 4.30.

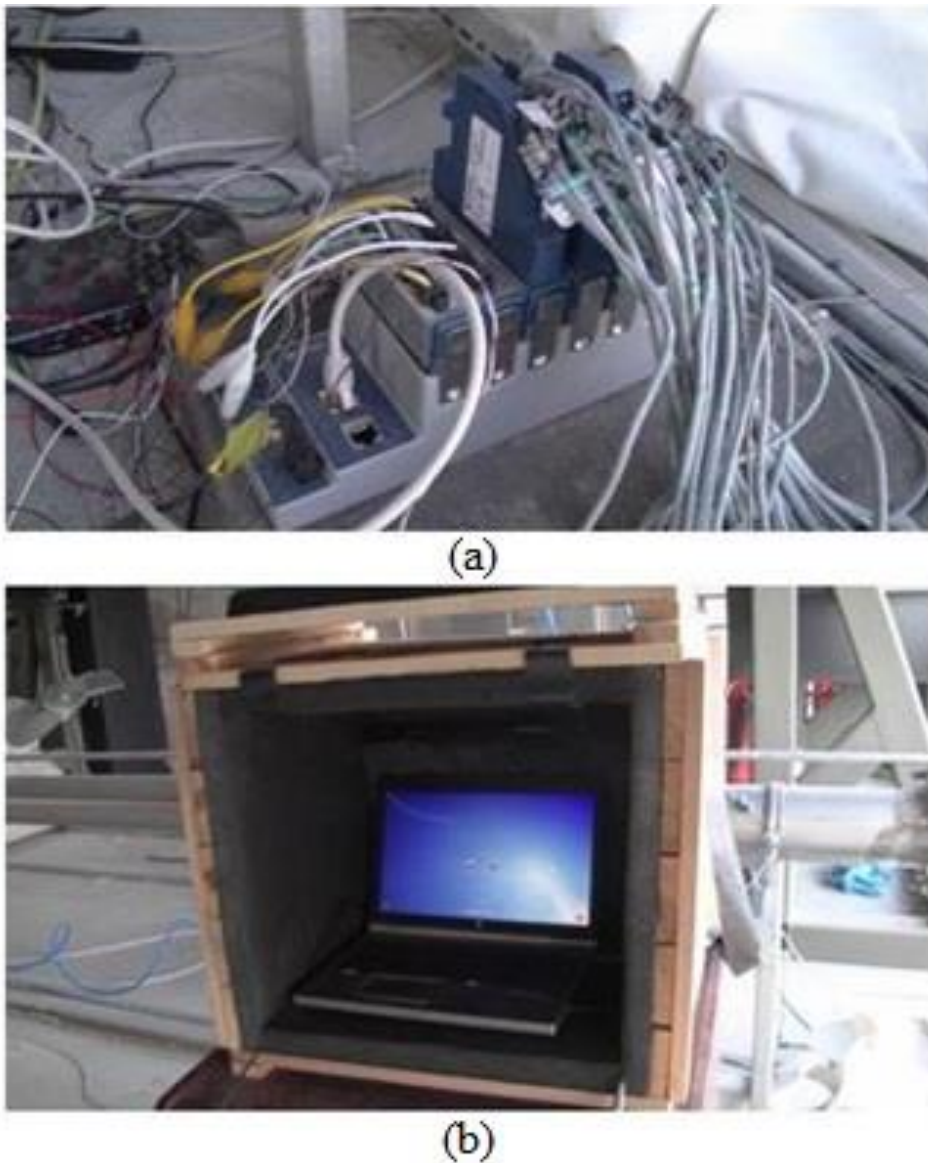


Figure 4.30: Data acquisition device (a) and the connected PC (b).

During the experiments, the collected data can be viewed in real time by using software. While conducting experiments, National Instruments' Signal Express software has been used to monitor temperature and pressure data both graphically and numerically. In Figure 4.31, user interface of the software is seen.

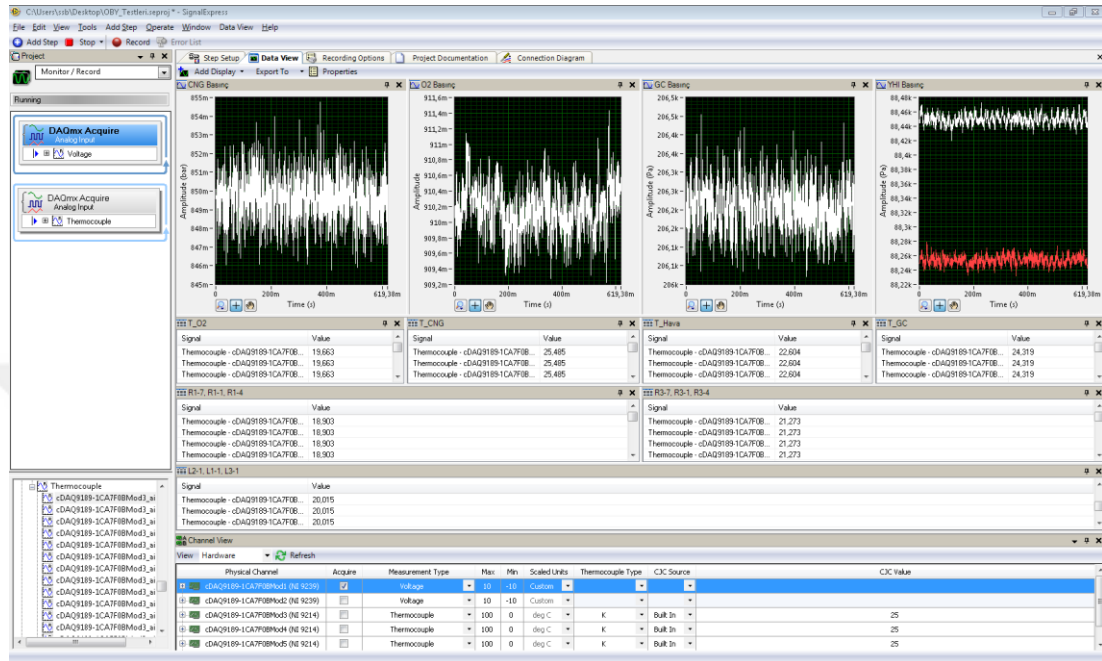


Figure 4.31: User interface of the data collection software.

4.3. Experimental Procedure

In this section, experimental methodologies of combustion performance and burner characterization experiments are explained step by step.

4.3.1. Experimental methodology for combustion performance experiments

Combustion performance experiments have been conducted to prove the capability of the CAH to satisfy different atmospheric flight temperature conditions. Durations of these experiments are 120 seconds.

A flowchart depicted in Figure 4.32 describes experimental methodology for combustion performance experiments.

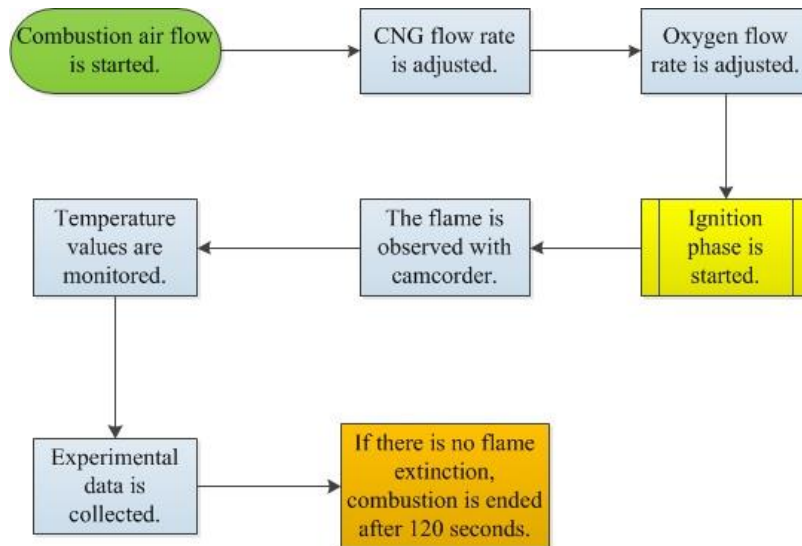


Figure 4.32: Experimental methodology for combustion performance experiments.

4.3.2. Experimental methodology for burner characterization experiments

Blowout limits are significant parameters to characterize a burner. Within present study, characterization experiments have been conducted to obtain lean blowout limits of the CAH.

The procedure before ignition phase is same with combustion performance experiments. The flowchart given in Figure 4.33 describes experimental methodology for burner characterization experiments.

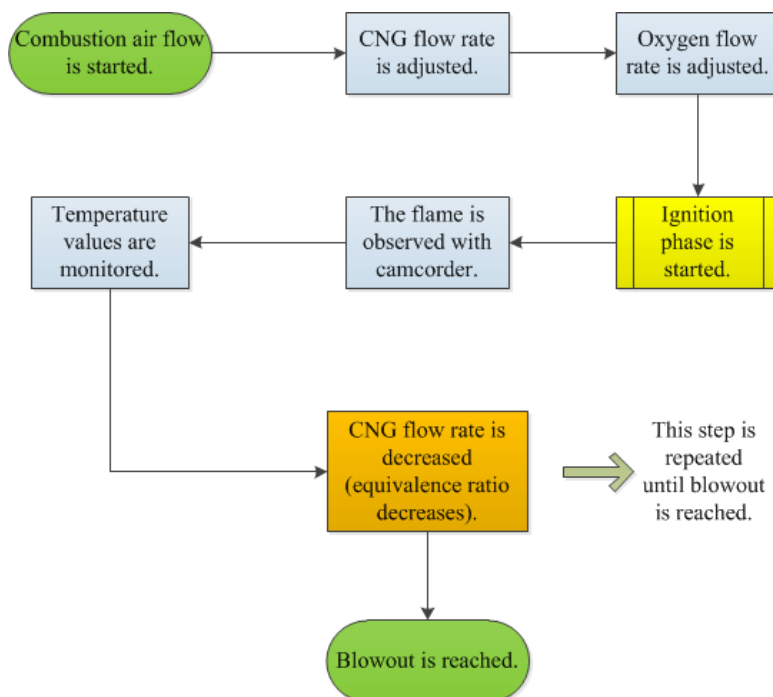


Figure 4.33: Experimental methodology for burner characterization experiments.

4.4. Error Analysis

4.4.1. Error analysis for total temperature calculation

In present study total temperature has been calculated with Equation (3.1) as mentioned before in Chapter 3:

$$T_{total} = T_0 \left(1 + \frac{\gamma - 1}{2} M^2\right) \quad (3.1)$$

In Equation (3.1), T_0 has been taken from standard atmosphere model. This model has good approach with accurate temperature values. The specific heat ratio for air has been taken as 1.4. This value has a deviation of 0.2% within a range of 270-470 K. Error analysis for total temperature can be made with an example calculation given with Equations (4.1) and (4.2) for 4 km altitude and Mach number 2:

$$T_{total,1} = 262.15 \left(1 + \frac{1.4 - 1}{2} 2^2\right) = 471.87 \text{ K} \quad (4.1)$$

$$T_{total,2} = 262.15 \left(1 + \frac{1.4028 - 1}{2} 2^2\right) = 473.33 \text{ K} \quad (4.2)$$

According to Equations (4.1) and (4.2), when the specific heat ratio for air is taken as 1.4, only 1.5 K (0.03%) error occurs in the total temperature value. This error value is negligible for temperature calculations.

4.4.2. Error analysis for combustion efficiency calculation

In present study combustion efficiency has been calculated with Equation (3.3) as mentioned before in Chapter 3:

$$\eta_{\Delta T} = \frac{T_{outlet,exp} - T_{inlet}}{T_{outlet,th} - T_{inlet}} \quad (3.3)$$

Theoretical temperature value has an error of 0.03% as calculated in the previous section. Temperature measurement equipment has an uncertainty of 0.5% as given with Table 4.3. The maximum error in combustion efficiency value can be calculated as 0.47% by Equation (4.3):

$$\eta'_{\Delta T} = \eta_{\Delta T} \frac{1.005}{1.0003} = 1.0047 \eta_{\Delta T} \quad (4.3)$$

4.4.3. Error analysis for equivalence ratio

In present study equivalence ratio has been calculated with Equation (3.7) as mentioned before in Chapter 3:

$$\Phi = 19.93 \frac{\dot{m}_F}{\dot{m}_O} \quad (3.7)$$

In Equation (3.7) the mass flow rate parameters have been measured with thermal mass flow meters. These flow meters are identical with each other and have an uncertainty of 1%. The maximum error in the equivalence ratio value can be calculated as 2% by Equation (4.4):

$$\Phi' = \Phi \frac{1.01}{0.99} = 1.02 \Phi \quad (4.4)$$

4.4.4. Error analysis for axial mean swirler velocity

In present study axial mean swirler velocity has been calculated with Equation (3.9) as mentioned before in Chapter 3:

$$U = \frac{\dot{m}_O}{\rho_O A} \quad (3.9)$$

The density of the oxidizer has been calculated with Equation (3.11) as mentioned before in Chapter 3:

$$\rho_O = \frac{p}{R_{air} T_{inlet}} \quad (3.11)$$

As pressure transducer and thermocouple have same uncertainties of 0.5%, it can be obtained that there is 0.5% error in the density of the oxidizer value.

The maximum error in the axial mean swirler velocity value can be calculated as 0.498% by Equation (4.5):

$$U' = U \frac{1.01}{1.005} = 1.00498 U \quad (4.5)$$

5. RESULTS AND DISCUSSION

In this chapter, results of the experimental study are given. In experimental setup defined in Chapter 4, over 150 runs of experiments have been carried out. Within the scope of present thesis, results of 17 of the combustion performance experiments and 14 of the burner characterization experiments are given.

5.1. Experimental Matrix

In Figure 5.1, the operating envelope of the CAH which is obtained by theoretical calculations in Chapter 3 is shown. The experimental matrix for combustion performance experiments have been derived from this envelope. Experiments have been carried out under ambient pressure by simulating the mass flow rates of experiment points given with Figure 5.1.

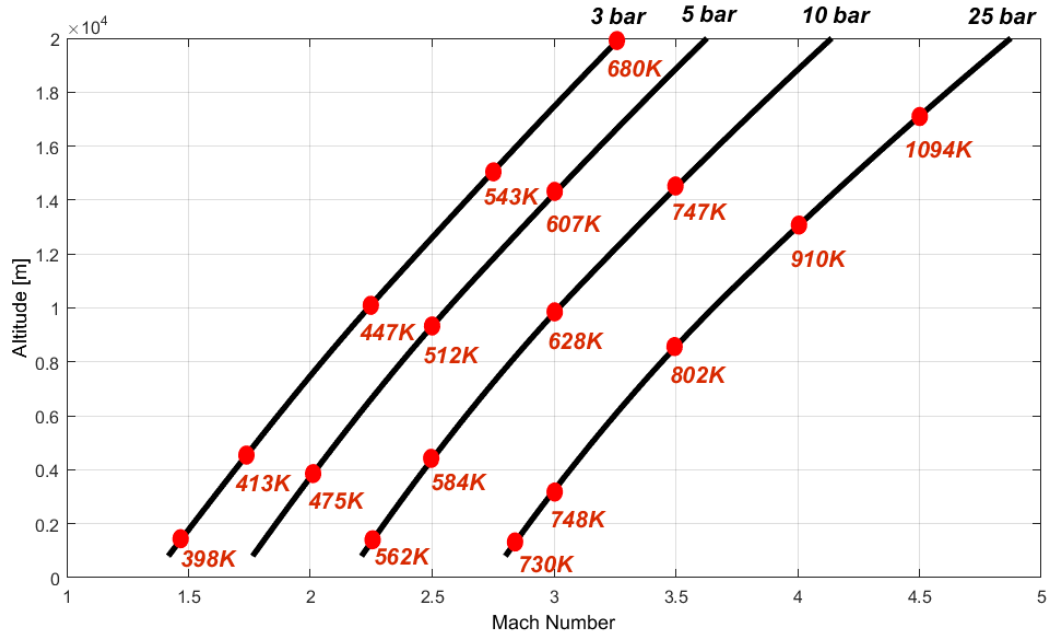


Figure 5.1: Operating envelope of the CAH.

Combustion performance experiments and burner characterization experiments within the scope of present study can be listed as shown in Table 5.1 and Table 5.2, respectively.

Table 5.1: Combustion performance experiments.

	Test Point	Altitude [m]	Mach Number	Total Temperature [K]
Experiment Set 1 (3 bar Curve)	1	1500	1.5	398
	2	4500	1.7	413
	3	10000	2.2	447
	4	15000	2.7	543
	5	20000	3.2	680
Experiment Set 2 (5 bar Curve)	1	4000	2.0	475
	2	9000	2.5	512
	3	14000	3.0	607
Experiment Set 3 (10 bar Curve)	1	1500	2.2	562
	2	4500	2.5	584
	3	10000	3.0	628
	4	14500	3.5	747
Experiment Set 4 (25 bar Curve)	1	1200	2.8	730
	2	3200	3.0	748
	3	8500	3.5	802
	4	13000	4.0	910
	5	17000	4.5	1094

Table 5.2: Burner characterization experiments.

	Axial Mean Swirler Velocity [m/s]
Case 1 (0% Oxygen Enrichment)	5
	20
	30
Case 2 (5% Oxygen Enrichment without Oxygen Lancing)	5
	15
	30
	50
Case 3 (1% Oxygen Enrichment with 10% Oxygen Lancing)	5
	30
	70
	100
Case 4 (8% Oxygen Enrichment with 10% Oxygen Lancing)	5
	30
	70

5.2. Combustion Performance Experiments

Combustion performance experiments have been carried out for providing atmospheric flight temperature conditions given with Figure 5.1 and Table 5.1. In these experiments, temperature values with a deviation of 5-15% from the target temperature values are considered good. However, a deviation of 20% can also be accepted as reasonable.

5.2.1. Experiment Set 1 (3 bar curve)

Within the scope of Experiment Set 1, experiments for 3 bar curve of the operating envelope have been carried out. Since it is difficult to adjust the theoretical mass flow rates accurately during the experiments, these values have been set as close as possible. As a result of this situation, target and adjusted temperature values were different as seen in Table 5.3. Oxygen enrichment conditions for the experiments are also given in Table 5.3.

Table 5.3: Temperature values and oxygen enrichment conditions for Experiment Set 1 (3 bar curve).

Test Point	Temperature [K]		Oxygen Enrichment	
	Target Value	Adjusted Value	Enrichment [%]	Oxygen Lancing (% of total oxygen enrichment)
1	398	394	1.15	Yes (8.4%)
2	413	421	1.36	Yes (5.6%)
3	447	449	1.81	Yes (6.8%)
4	543	534	2.75	No
5	680	682	4.37	No

398 K, 413 K and 447 K test points could not be ignited with the theoretical fuel and oxidizer mass flow rates. Oxygen lancing method has been successfully used to ignite these test points.

The flame shapes of each test point are shown in Figure 5.2. As having a very light blue color, the flame of 543 K test point is not visible.

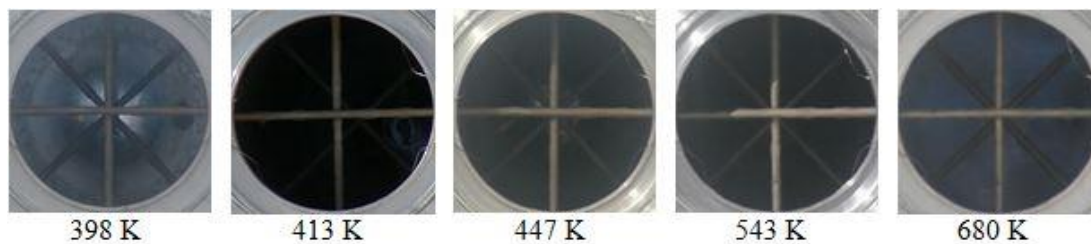


Figure 5.2: Flame shapes for Experiment Set 1 (3 bar curve).

The results of combustion gases temperature for 3 bar curve experiment set are given in Figure 5.3.

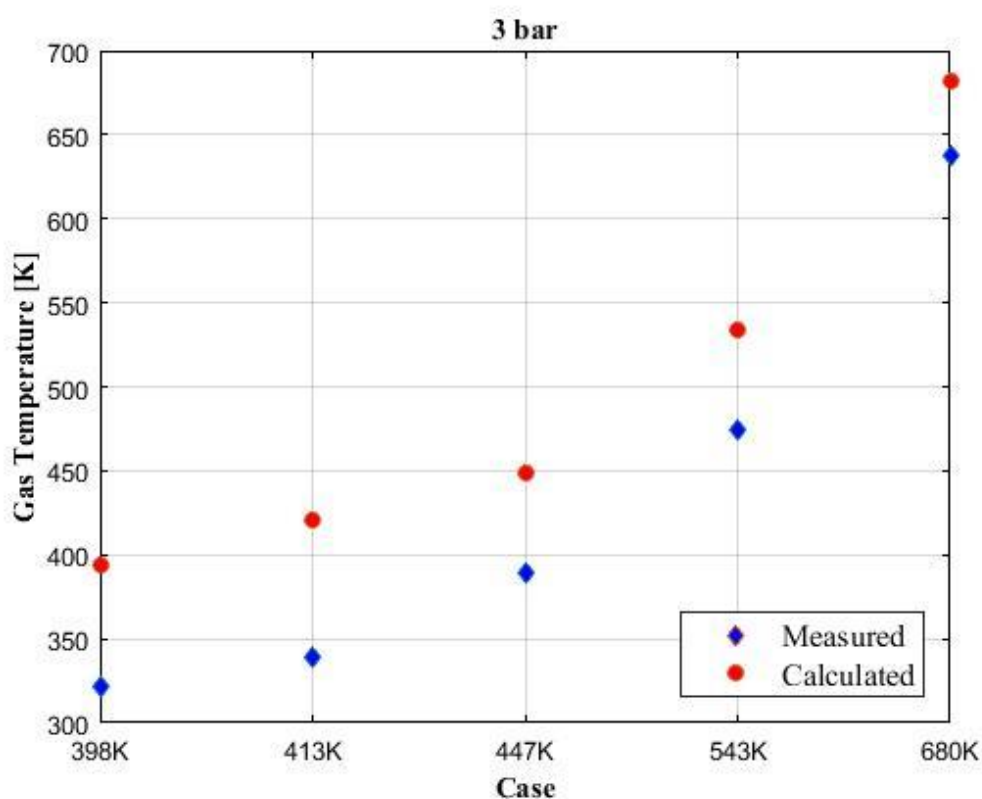


Figure 5.3: Calculated and measured temperature values for Experiment Set 1 (3 bar curve).

Figure 5.3 shows that the measured temperature values of 447 K, 543 K and 680 K test points are below 13.4%, 11.2% and 6.5% of the theoretical values, respectively. These values are considered good for such burner. In 398 K and 413 K test points, these percentages are 18.5% and 19.5%, respectively, which can be accepted as reasonable.

Combustion efficiencies for 3 bar curve are given with Figure 5.4. As oxygen enrichment amount increases, combustion efficiencies are also increased.

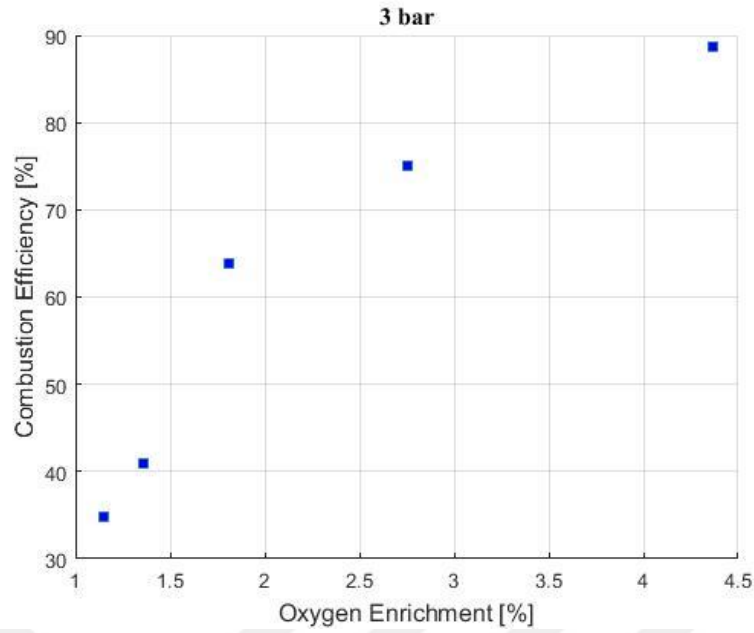


Figure 5.4: Combustion efficiencies with oxygen enrichment percentage for Experiment Set 1 (3 bar curve).

It is also observed from Figure 5.4 that combustion efficiencies of cases with oxygen lancing are lower. The flame is attached to the center by lanced oxygen and combustion does not take place in outer regions. Thus, some amount of fuel could not be burned. This causes low combustion efficiencies.

In Figure 5.5 and Figure 5.6, time histories of the temperature of combustion gases and the burner wall temperature for Experiment Set 1 are given.

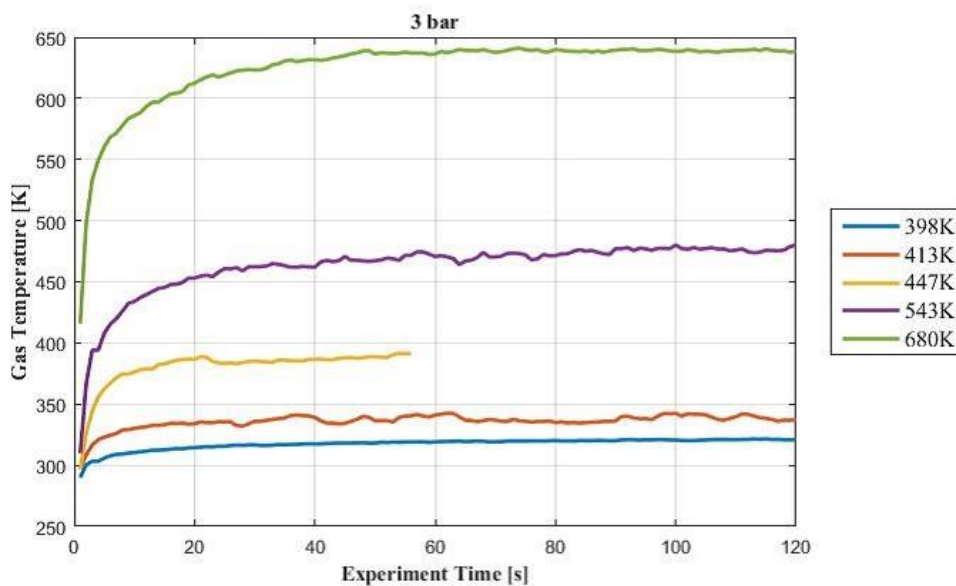


Figure 5.5: Time histories of the temperature of combustion gases for Experiment Set 1 (3 bar curve).

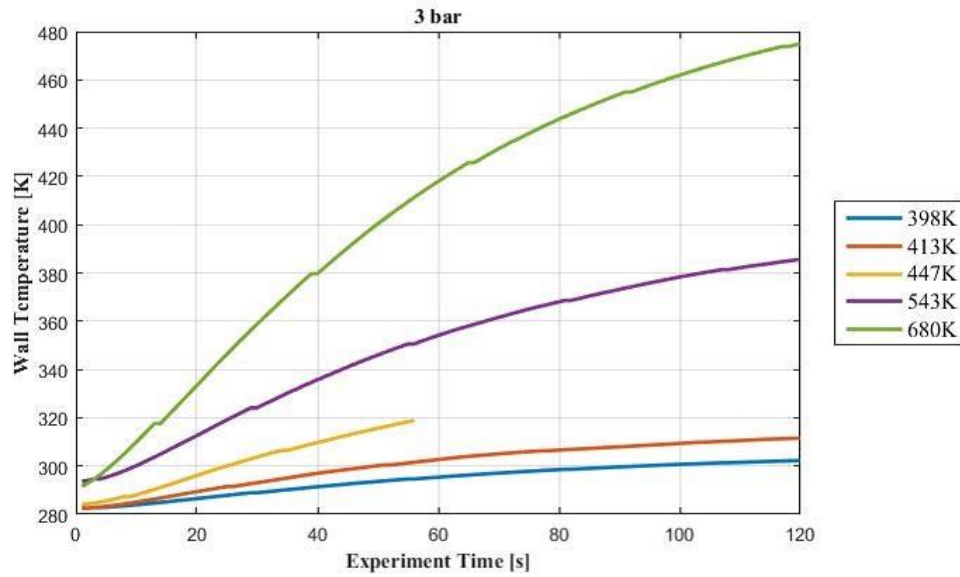


Figure 5.6: Time histories of the burner wall temperature for Experiment Set 1 (3 bar curve).

Figure 5.5 and Figure 5.6 clearly show that; after combustion takes place, heat transfer from combustion gases to the burner wall occurs. For 680 K test point, 50 seconds are needed to provide constant temperature values of combustion gases.

5.2.2. Experiment Set 2 (5 bar curve)

Within the scope of Experiment Set 2, experiments for 5 bar curve of the operating envelope have been carried out. Information about experiment set is given in Table 5.4.

Table 5.4: Temperature values and oxygen enrichment conditions for Experiment Set 2 (5 bar curve).

Test Point	Temperature [K]		Oxygen Enrichment	
	Target Value	Adjusted Value	Enrichment [%]	Oxygen Lancing (% of total oxygen enrichment)
1	475	469	2.13	No
2	512	501	2.37	No
3	607	592	3.41	No

The flame shapes of each test point are shown in Figure 5.7. As having a very light blue color, the flame of 475 K test point is not visible. Other cases have yellow flame colors.

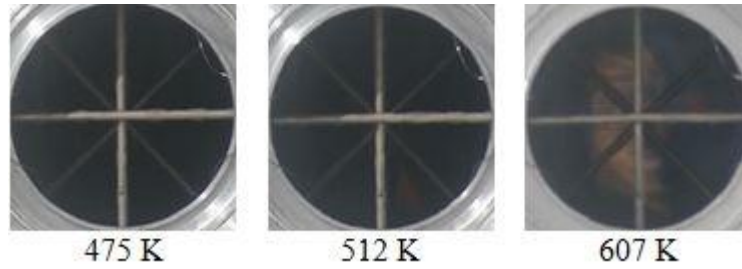


Figure 5.7: Flame shapes for Experiment Set 2 (5 bar curve).

The results of combustion gases temperature for 5 bar curve experiment set are given in Figure 5.8.

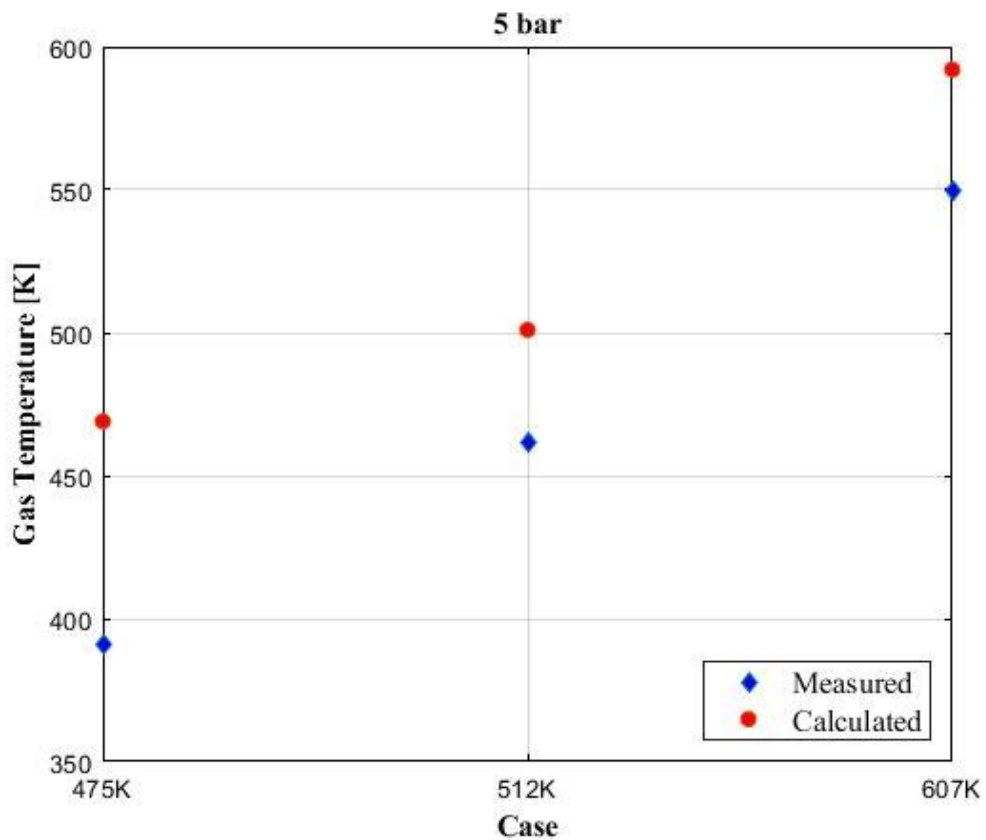


Figure 5.8: Calculated and measured temperature values for Experiment Set 2 (5 bar curve).

Figure 5.8 shows that the measured temperature values of 512 K and 607 K test points are below 7.8% and 7.1% of the theoretical values, respectively. These values are considered good for such burner. In 475 K test point, this percentage is 16.6%, which can be accepted as reasonable.

Combustion efficiencies for 5 bar curve are given with Figure 5.9. As oxygen enrichment amount increases, combustion efficiencies are also increased.

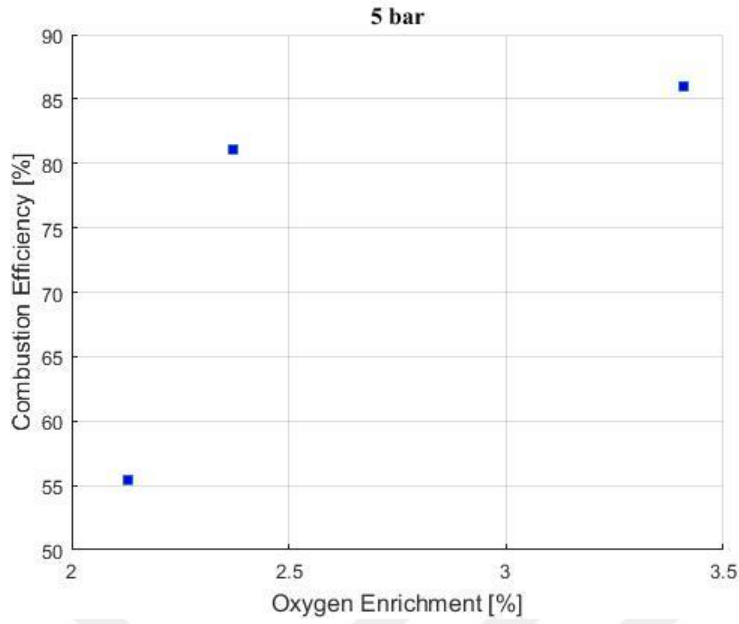


Figure 5.9: Combustion efficiencies with oxygen enrichment percentage for Experiment Set 2 (5 bar curve).

In Figure 5.10 and Figure 5.11, time histories of the temperature of combustion gases and the burner wall temperature for Experiment Set 2 are given.

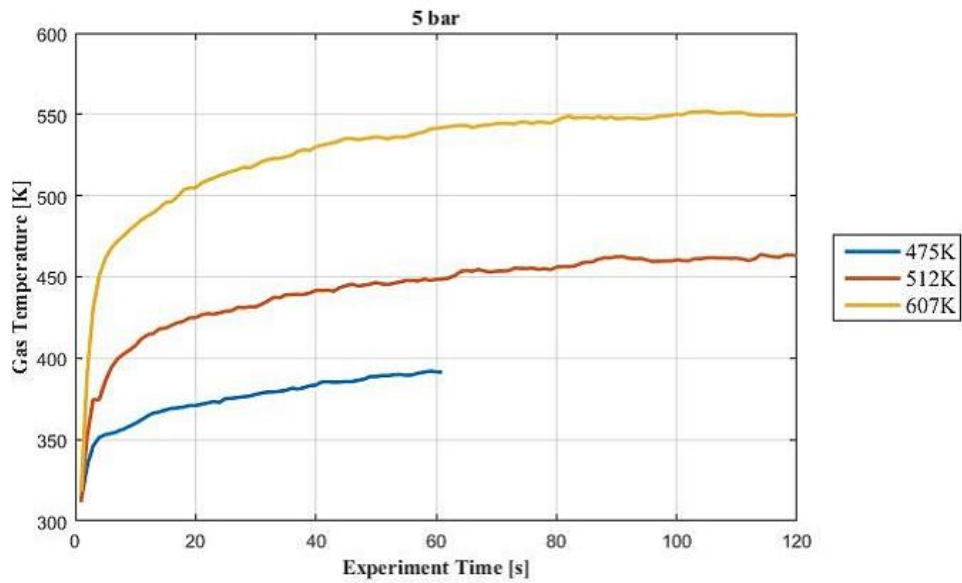


Figure 5.10: Time histories of the temperature of combustion gases for Experiment Set 2 (5 bar curve).

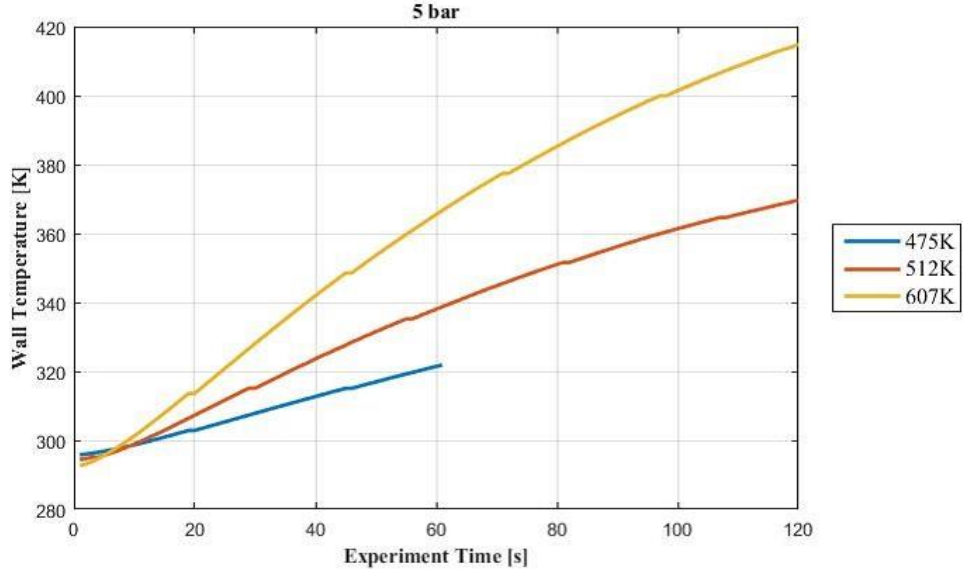


Figure 5.11: Time histories of the burner wall temperature for Experiment Set 2 (5 bar curve).

Figure 5.10 and Figure 5.11 clearly show that; after combustion takes place, heat transfer from combustion gases to the burner wall occurs. For 607 K test point, 60 seconds are needed to provide constant temperature values of combustion gases.

5.2.3. Experiment Set 3 (10 bar curve)

Within the scope of Experiment Set 3, experiments for 10 bar curve of the operating envelope have been carried out. Information about experiment set is given in Table 5.5.

Table 5.5: Temperature values and oxygen enrichment conditions for Experiment Set 3 (10 bar curve).

Test Point	Temperature [K]		Oxygen Enrichment	
	Target Value	Adjusted Value	Enrichment [%]	Oxygen Lancing (% of total oxygen enrichment)
1	562	572	3.18	No
2	584	589	3.31	No
3	628	622	3.71	No
4	747	806	5.70	No

The flame shapes for each test point are shown in Figure 5.12. All cases have yellow flame colors.

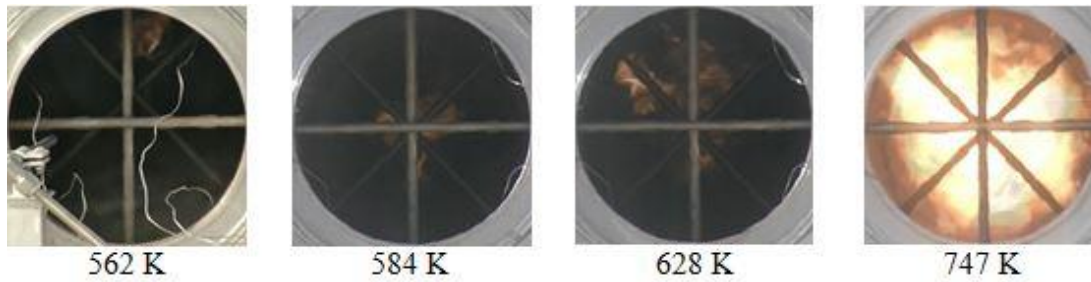


Figure 5.12: Flame shapes for Experiment Set 3 (10 bar curve).

The results of combustion gases temperature for 10 bar curve experiment set are given in Figure 5.13.

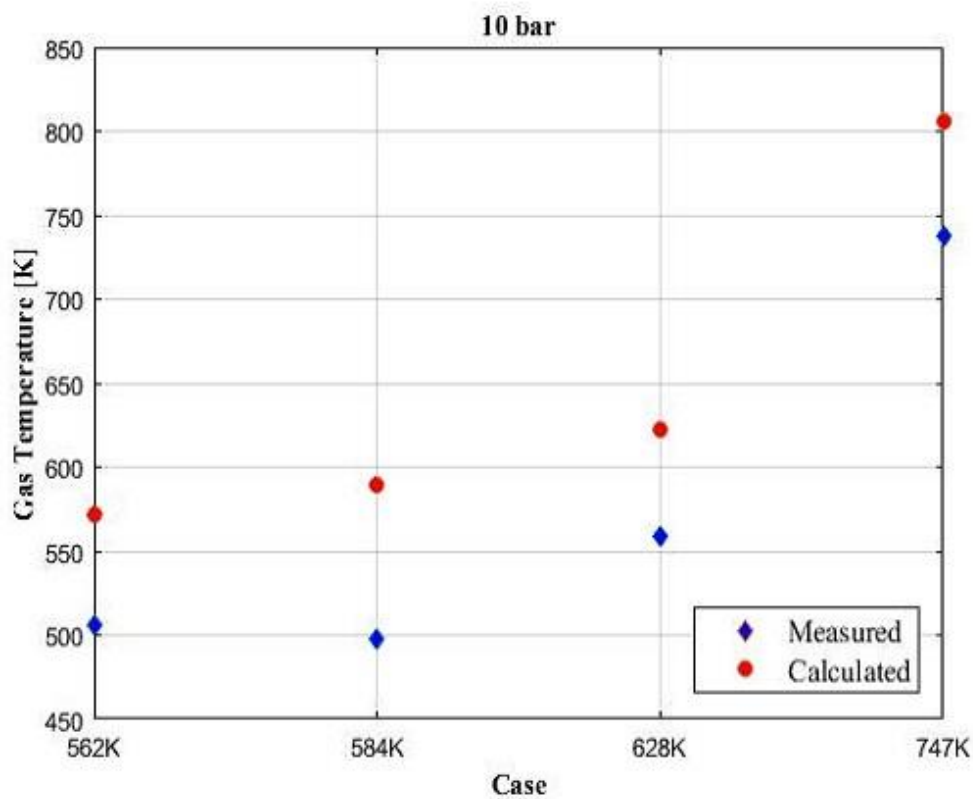


Figure 5.13: Calculated and measured temperature values for Experiment Set 3 (10 bar curve).

Figure 5.13 shows that the measured temperature values of 562 K, 628 K and 747 K test points are below 11.5%, 10.1% and 8.4% of the theoretical values, respectively. These values are considered good for such burner. In 584 K test point, this percentage is 15.4%, which can be accepted as reasonable.

Combustion efficiencies for 10 bar curve are given with Figure 5.14. As oxygen enrichment amount increases, combustion efficiencies are also increased. It is

observed from Figure 5.14 that 584 K test point has lower combustion efficiency than 562 K test point even its oxygen enrichment amount is higher. In that case, some amount of fuel has left the burner unburned.

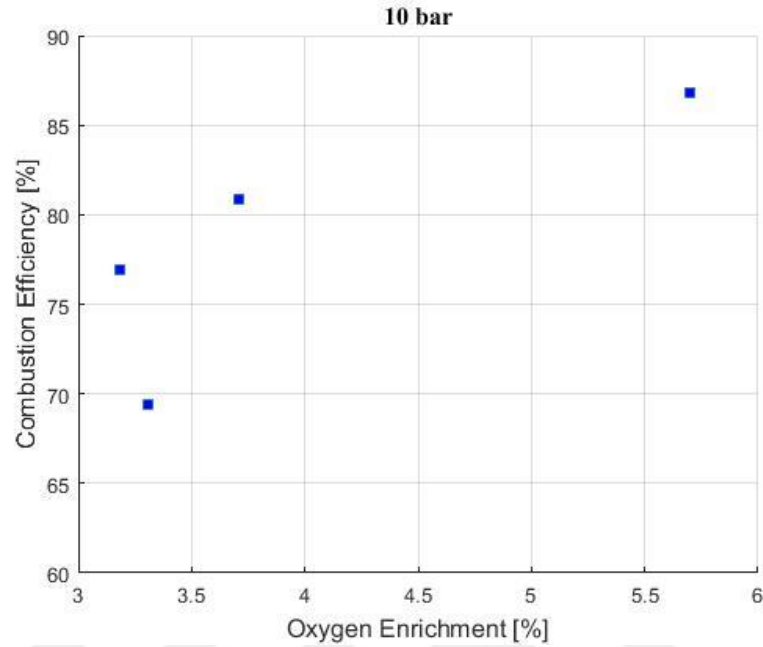


Figure 5.14: Combustion efficiencies with oxygen enrichment percentage for Experiment Set 3 (10 bar curve).

In Figure 5.15 and Figure 5.16, time histories of the temperature of combustion gases and the burner wall temperature for Experiment Set 3 are given.

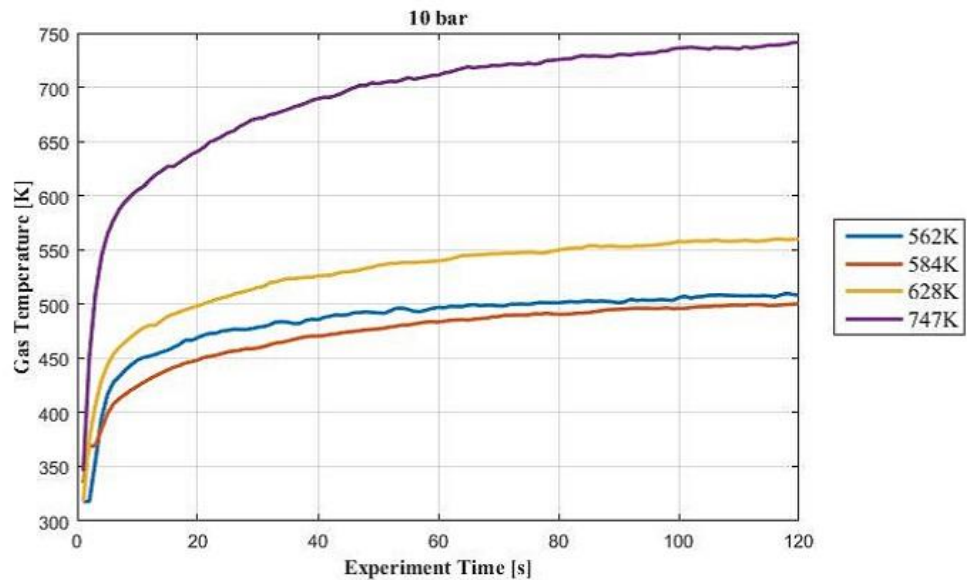


Figure 5.15: Time histories of the temperature of combustion gases for Experiment Set 3 (10 bar curve).

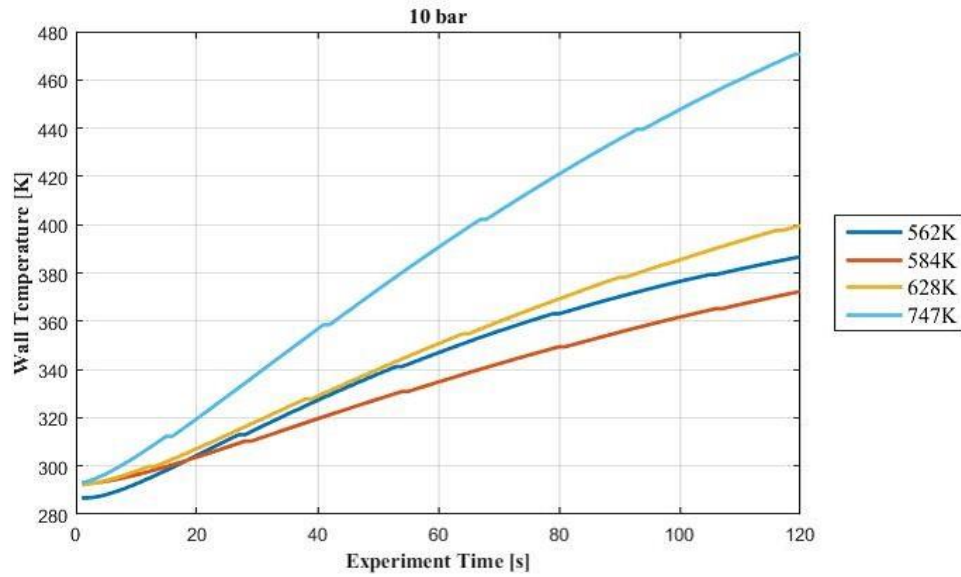


Figure 5.16: Time histories of the burner wall temperature for Experiment Set 3 (10 bar curve).

Figure 5.15 and Figure 5.16 clearly show that; after combustion takes place, heat transfer from combustion gases to the burner wall occurs. For 747 K test point, 100 seconds are needed to provide constant temperature value of combustion gases.

5.2.4. Experiment Set 4 (25 bar curve)

Within the scope of Experiment Set 4, experiments for 25 bar curve of the operating envelope have been carried out. Information about experiment set is given in Table 5.6.

Table 5.6: Temperature values and oxygen enrichment conditions for Experiment Set 4 (25 bar curve).

Test Point	Temperature [K]		Oxygen Enrichment	
	Target Value	Adjusted Value	Enrichment [%]	Oxygen Lancing (% of total oxygen enrichment)
1	730	843	7.32	No
2	748	752	5.74	No
3	802	771	5.50	No
4	910	909	7.53	No
5	1094	1135	11.41	No

The flame shapes of each test point are shown in Figure 5.17. All cases have yellow flame colors.

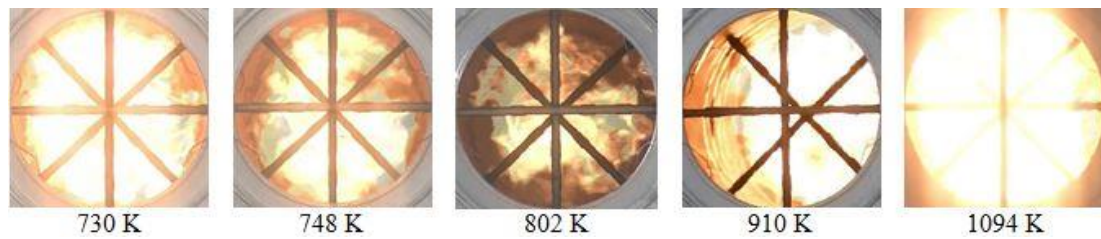


Figure 5.17: Flame shapes for Experiment Set 4 (25 bar curve).

The results of combustion gases temperature for 25 bar curve experiment set are given in Figure 5.18.

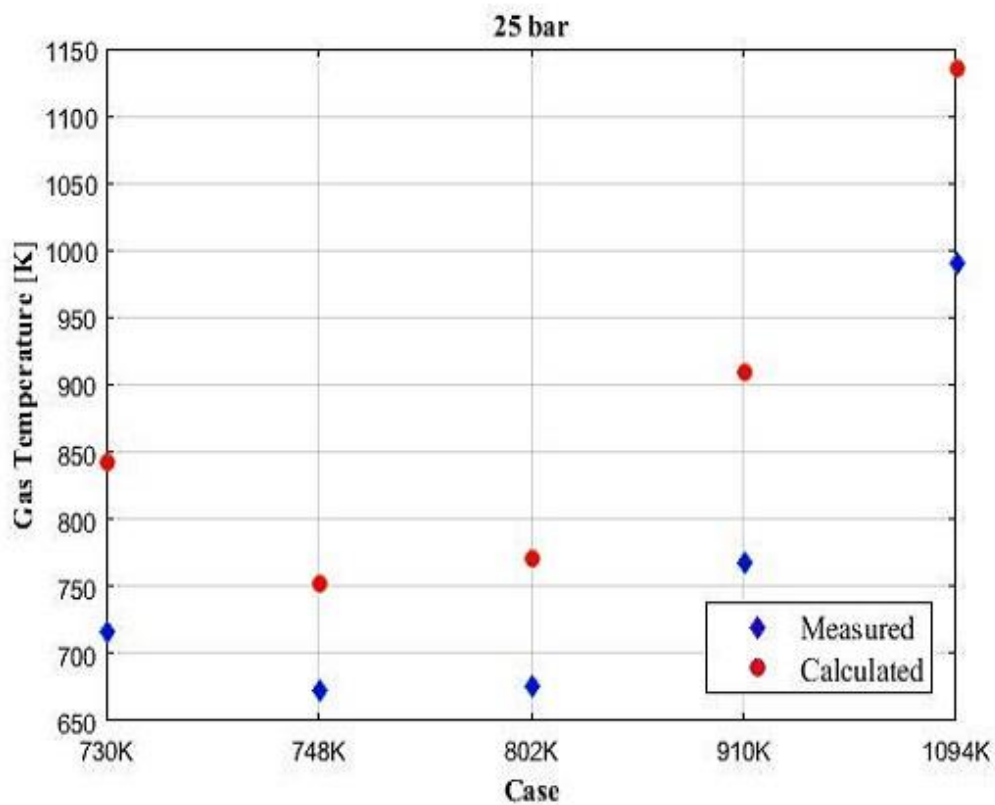


Figure 5.18: Calculated and measured temperature values for Experiment Set 4 (25 bar curve).

Figure 5.18 shows that the measured temperature values of 748 K, 802 K and 1094 K test points are below 10.6%, 12.5% and 12.8% of the theoretical values, respectively. These values are considered good for such burner. In 730 K and 910 K test points, these percentages are 15.1% and 15.5%, respectively, which can be accepted as reasonable.

Combustion efficiencies for 25 bar curve are given with Figure 5.19. For 25 bar curve experiments, combustion efficiencies do not indicate the trend achieved in

other experiment sets. This is because the fuel regulator has sent excess fuel to the burner during 730 K and 910 K tests.

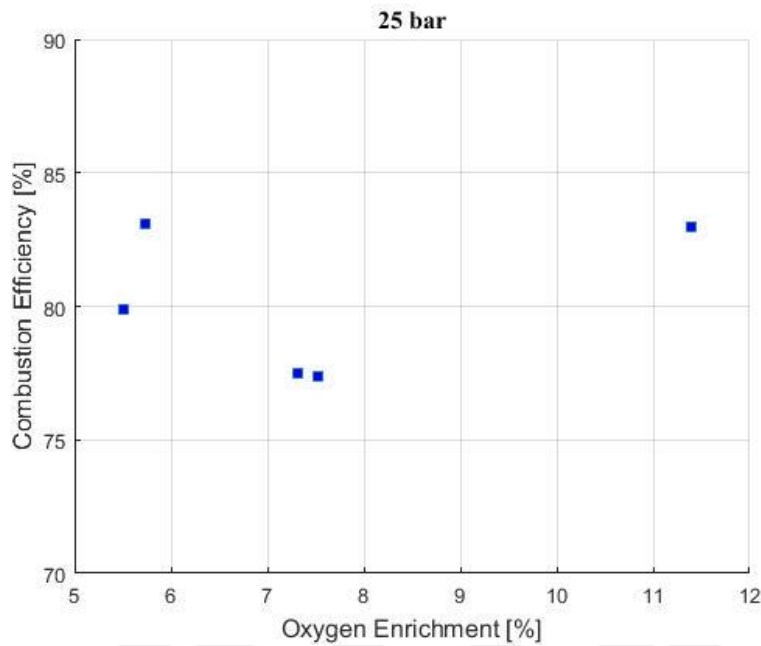


Figure 5.19: Combustion efficiencies with oxygen enrichment percentage for Experiment Set 4 (25 bar curve).

In Figure 5.20 and Figure 5.21, time histories of the temperature of combustion gases and the burner wall temperature for Experiment Set 4 are given.

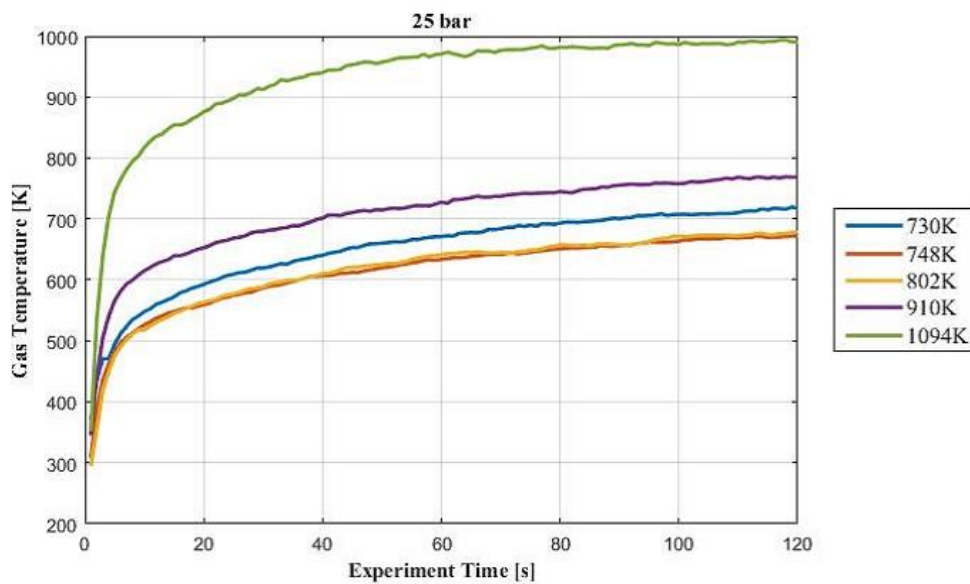


Figure 5.20: Time histories of the temperature of combustion gases for Experiment Set 4 (25 bar curve).

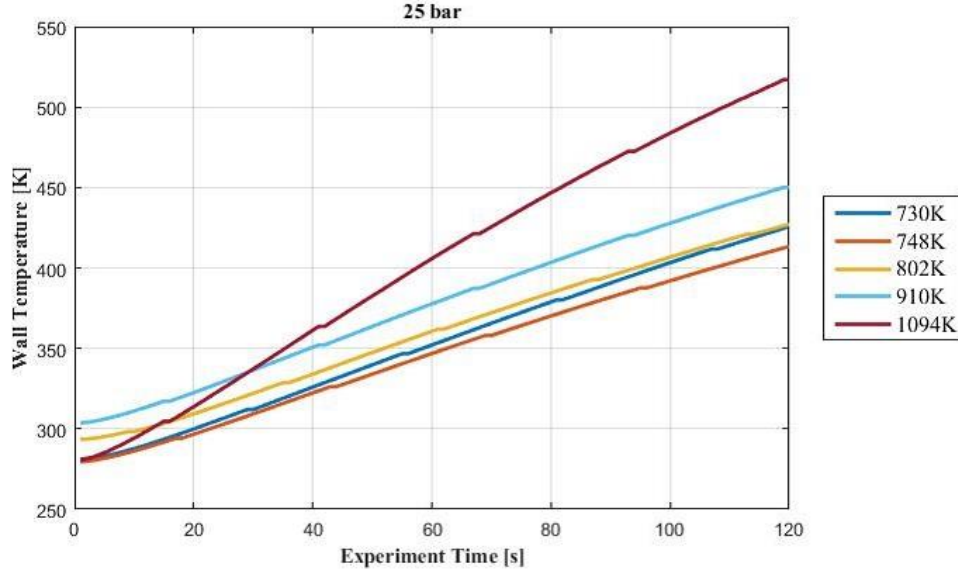


Figure 5.21: Time histories of the burner wall temperature for Experiment Set 4 (25 bar curve).

Figure 5.20 and Figure 5.21 clearly show that; after combustion takes place, heat transfer from combustion gases to the burner wall occurs. For all cases, 100 seconds are needed to provide constant temperature values of combustion gases.

Combustion performance experiments show that the burner established at TÜBİTAK SAGE can be used as a CAH to perform ground tests of high-speed air-breathing propulsion systems by providing atmospheric flight temperature conditions at different altitudes and Mach numbers.

5.3. Burner Characterization Experiments

Burner characterization experiments have been carried out for obtaining lean blowout limits of the CAH established at TÜBİTAK SAGE. The present study gives an opinion about the operating range of the burner. With these experiments, lean blowout limits have been obtained by means of equivalence ratio. Axial mean swirler velocity is the parameter, which is calculated by simple continuity equation.

5.3.1. Case 1 (CNG/air flame without oxygen enrichment)

In this case, lean blowout limits of CNG/air flame have been investigated without oxygen enrichment. Flame structures at the beginning of experiments, in the middle of experiments and near-blowout are shown in Figure 5.22.

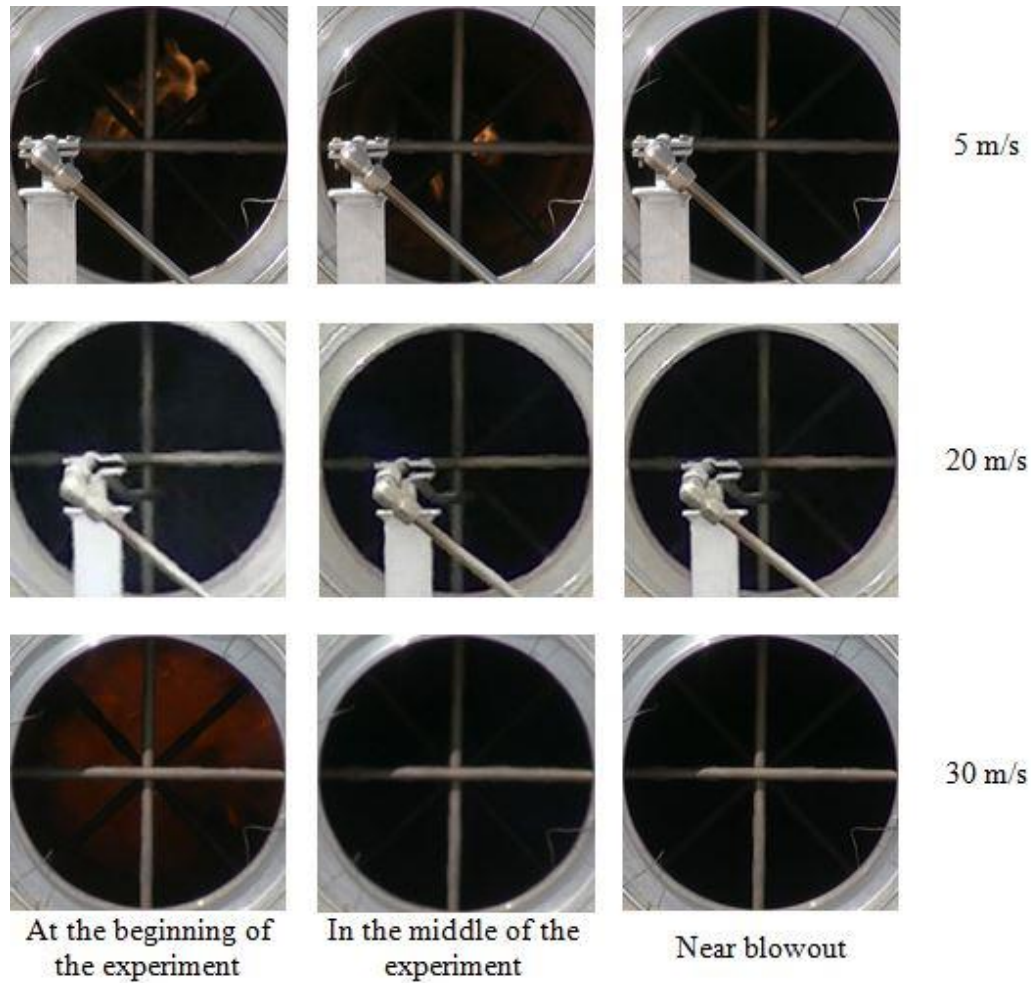


Figure 5.22: Flame structures for different axial mean swirler velocities for Case 1 (CNG/air flame without oxygen enrichment).

Figure 5.22 shows that, the flame is thick at the beginning of the experiments. The flame becomes thinner, while decreasing the fuel mass flow rate. At $U = 20$ m/s, the flame color is light blue, so it is not clearly visible.

As burner characterization experiments are based on decreasing the fuel/oxidizer equivalence ratio, fuel mass flow rate is being decreased step by step during the experiment while keeping the oxidizer mass flow rate constant. In Figure 5.23, time histories of the decreasing fuel pressures, the temperature of combustion gases and equivalence ratio are shown. Initial fuel pressure differs with respect to orifice plate used in the experiment. At the beginning of the experiments (at high equivalence ratio), the temperature is high. By decreasing the equivalence ratio, the temperature of combustion gases is also being decreased.

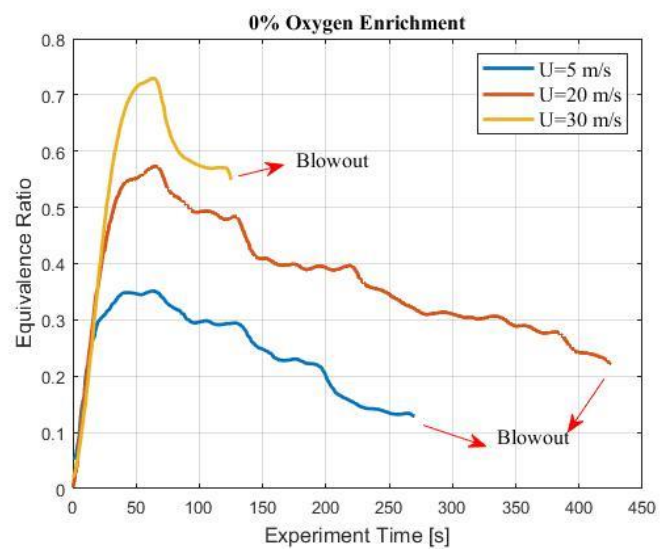
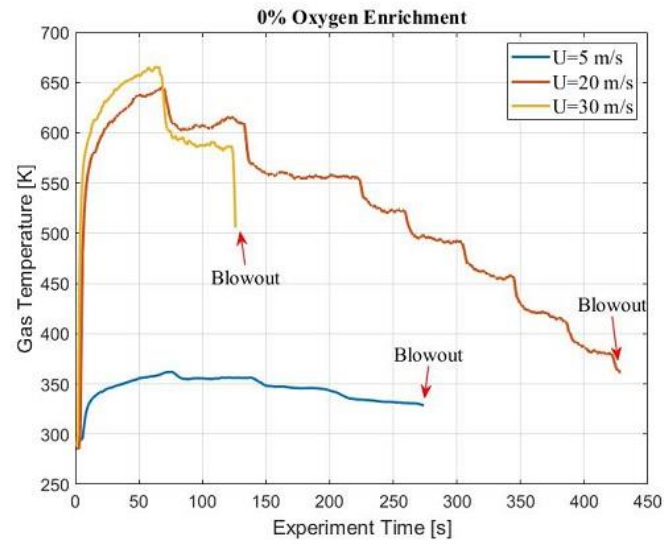
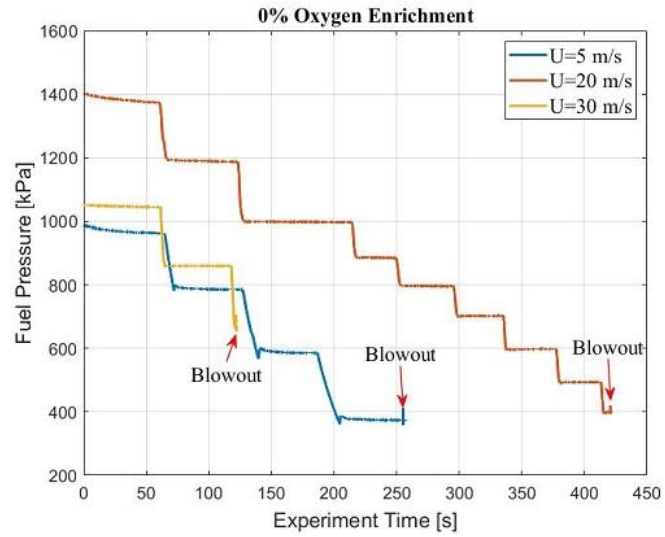


Figure 5.23: Time histories of the decreasing fuel pressure, the temperature of combustion gases and equivalence ratio for Case 1 (CNG/air flame without oxygen enrichment).

5.3.2. Case 2 (CNG/oxygen-enriched-air flame without oxygen lancing)

In this case, lean blowout limits of CNG/oxygen-enriched-air flame have been investigated without pure oxygen lancing. In this case oxygen enrichment was 5%. Flame structures at the beginning of experiments, in the middle of experiments and near-blowout are shown in Figure 5.24.

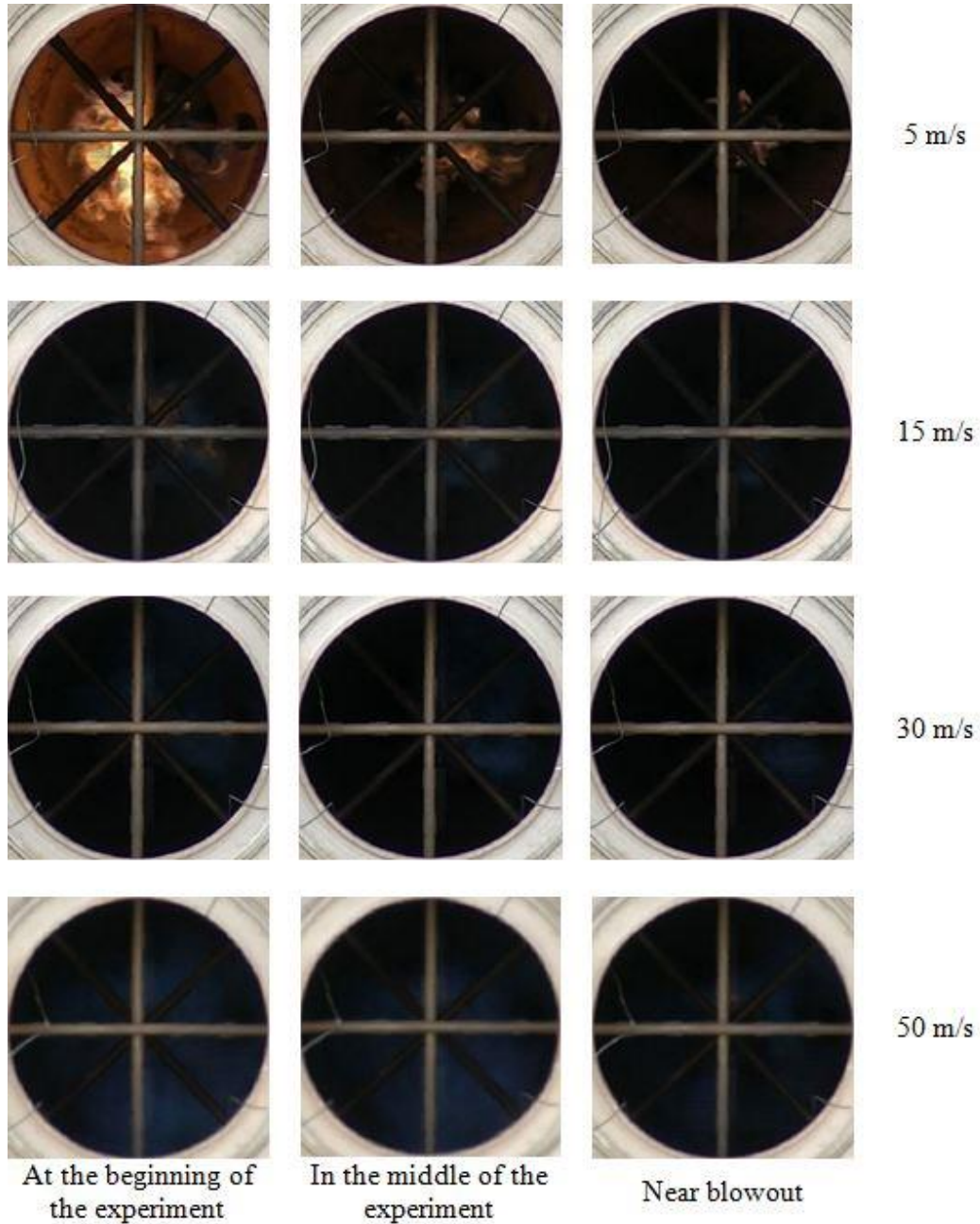


Figure 5.24: Flame structures for different axial mean swirler velocities for Case 2 (CNG/oxygen-enriched-air flame without pure oxygen lancing).

Figure 5.24 shows that, the flame is thick at the beginning of the experiments. The flame becomes thinner, while decreasing the fuel mass flow rate. The flame color becomes light blue by increasing axial mean swirler velocity. At low velocities, the flame color is yellow.

As burner characterization experiments are based on decreasing the fuel/oxidizer equivalence ratio, fuel mass flow rate is being decreased step by step during the experiment while keeping the oxidizer mass flow rate constant. In Figure 5.25, time histories of the decreasing fuel pressure are shown. Initial fuel pressure differs with respect to orifice plate used in the experiment.

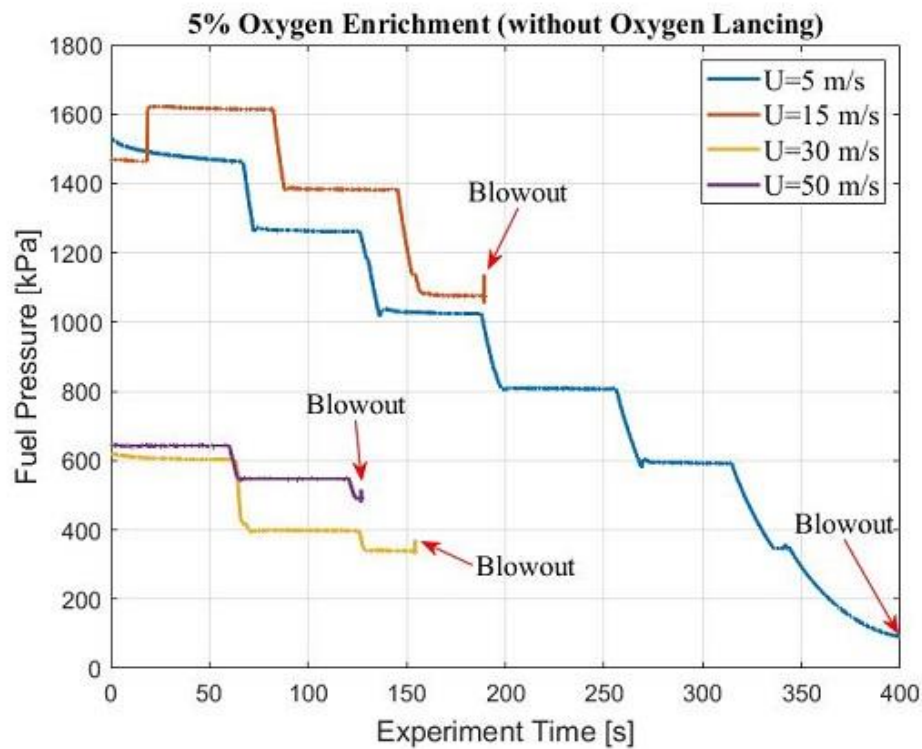


Figure 5.25: Time histories of the decreasing fuel pressure for Case 2 (CNG/oxygen-enriched-air flame without pure oxygen lancing).

In Figure 5.26, time histories of the temperature of combustion gases and equivalence ratio are given. At the beginning of the experiments (at high equivalence ratio), the temperature is high. By decreasing the equivalence ratio, the temperature of combustion gases is also being decreased.

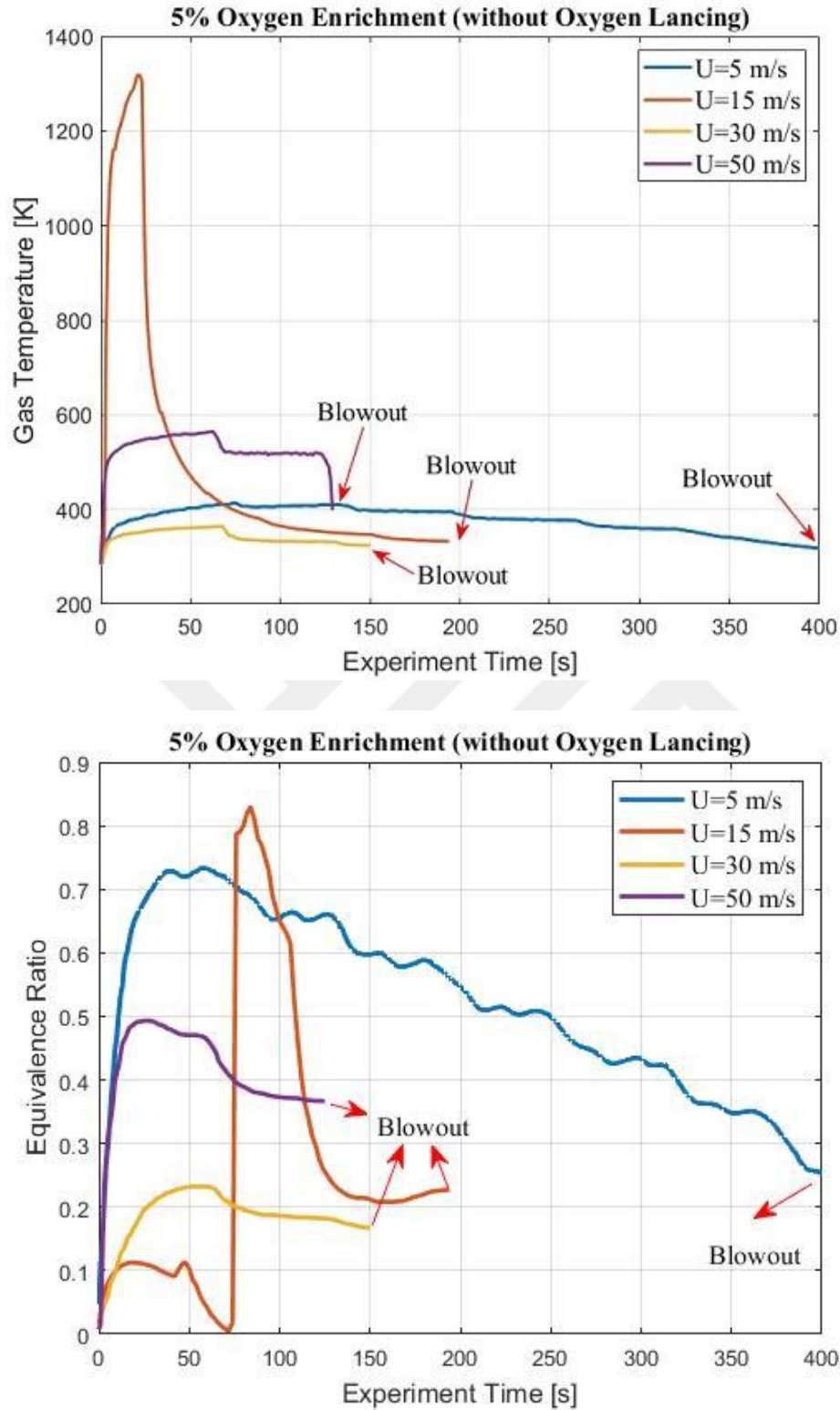


Figure 5.26: Time histories of the temperature of combustion gases and equivalence ratio for Case 2 (CNG/oxygen-enriched-air flame without pure oxygen lancing).

5.3.3. Case 3 (CNG/oxygen-enriched-air flame with oxygen lancing)

In this case, lean blowout limits of CNG/oxygen-enriched-air flame have been investigated with pure oxygen lancing. In this case oxygen enrichment was 1% while 10% of this value has been lanced directly into the burner. Flame structures at the beginning of experiments, in the middle of experiments and near-blowout are shown in Figure 5.27.

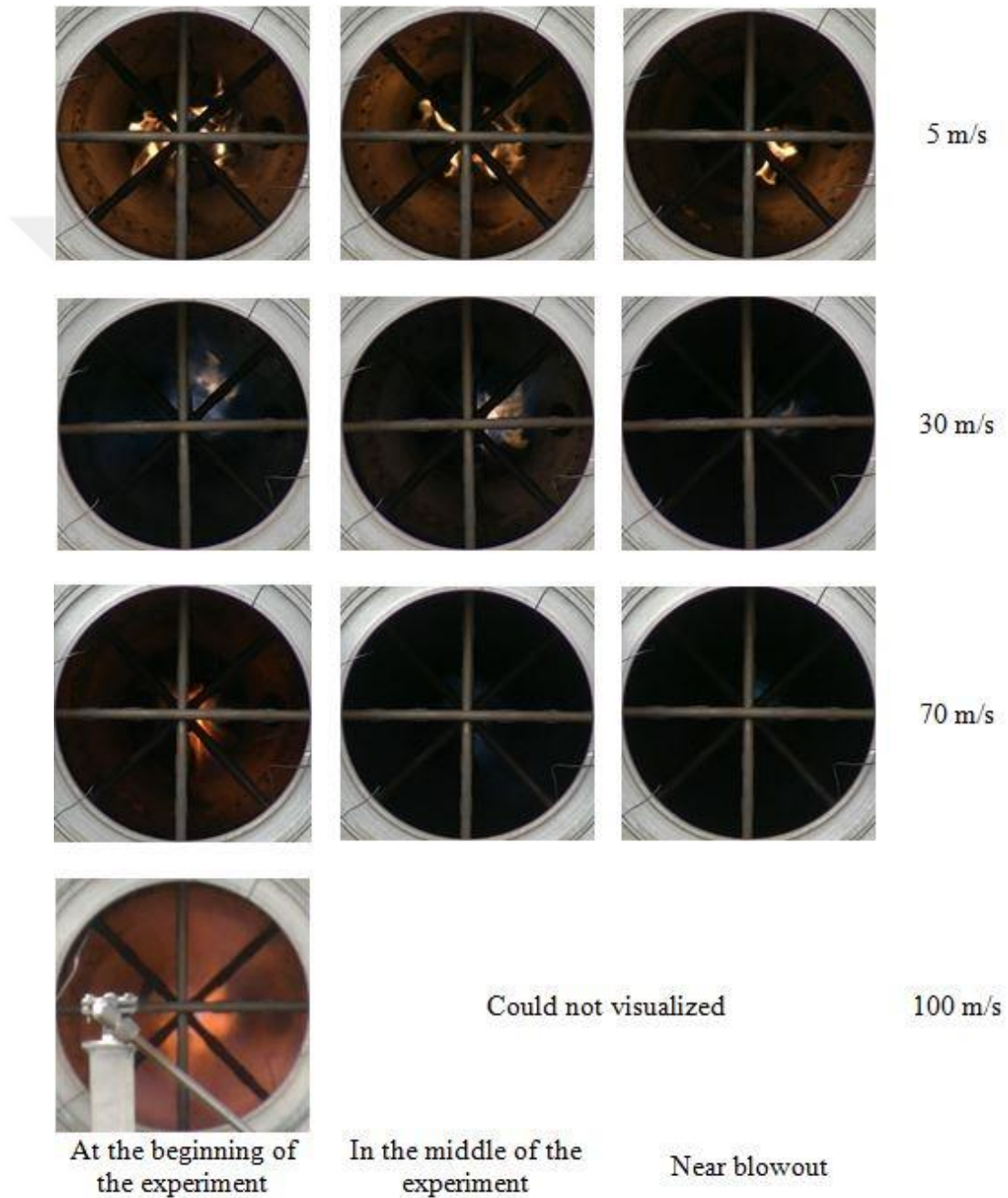


Figure 5.27: Flame structures for different axial mean swirler velocities for Case 3 (CNG/oxygen-enriched-air flame with pure oxygen lancing).

Figure 5.27 shows that, the flame is thick at the beginning of the experiments. The flame becomes thinner, while decreasing the fuel mass flow rate. The flame color is yellow in this case.

As burner characterization experiments are based on decreasing the fuel/oxidizer equivalence ratio, fuel mass flow rate is being decreased step by step during the experiment while keeping the oxidizer mass flow rate constant. In Figure 5.28, time histories of the decreasing fuel pressure are shown. Initial fuel pressure differs with respect to orifice plate used in the experiment.

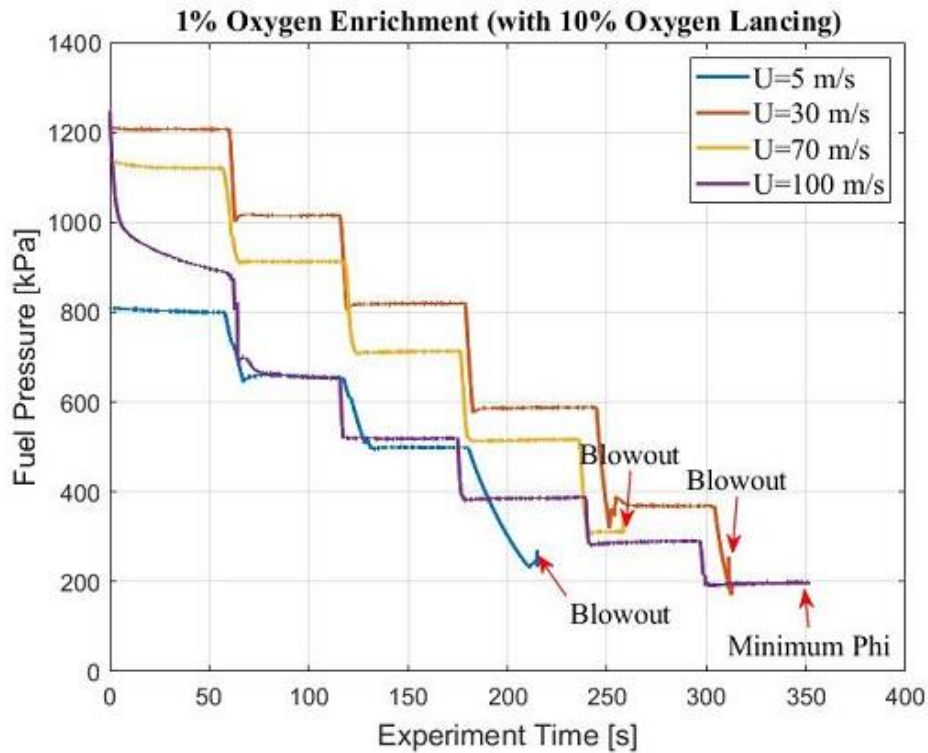


Figure 5.28: Time histories of the decreasing fuel pressure for Case 3 (CNG/oxygen-enriched-air flame with pure oxygen lancing).

At $U = 100$ m/s, the blowout could not be reached with the experimental setup. The reason was that the fuel mass flow rate could not be decreased any more. The minimum equivalence ratio is given for this experiment point.

In Figure 5.29, time histories of the temperature of combustion gases and equivalence ratio are given. At the beginning of the experiments (at high equivalence ratio), the temperature is high. By decreasing the equivalence ratio, the temperature of combustion gases is also being decreased.

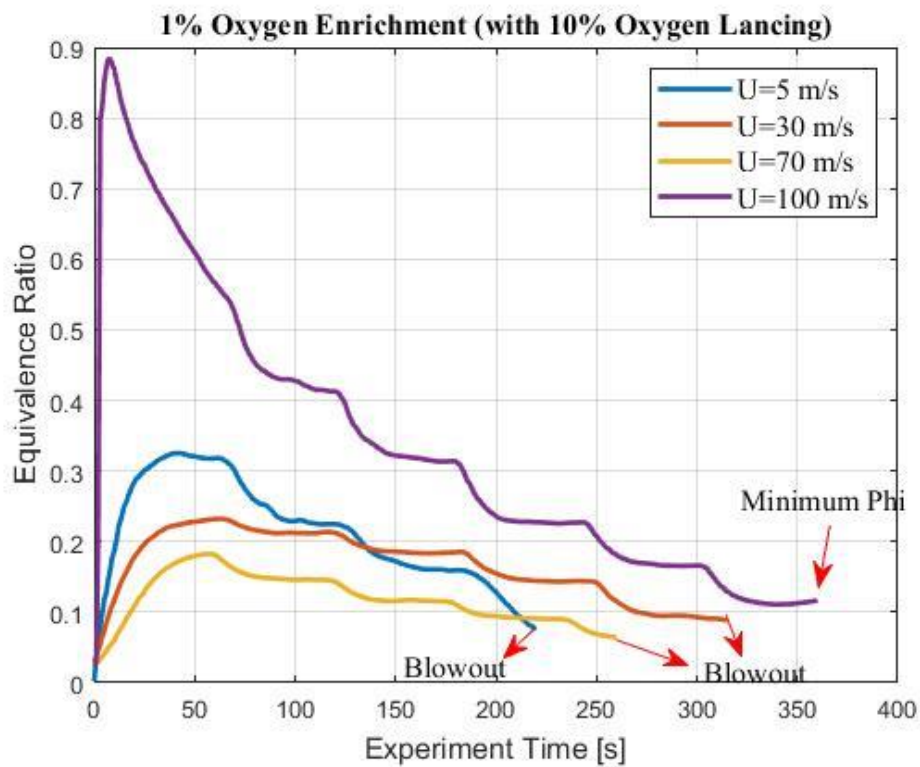
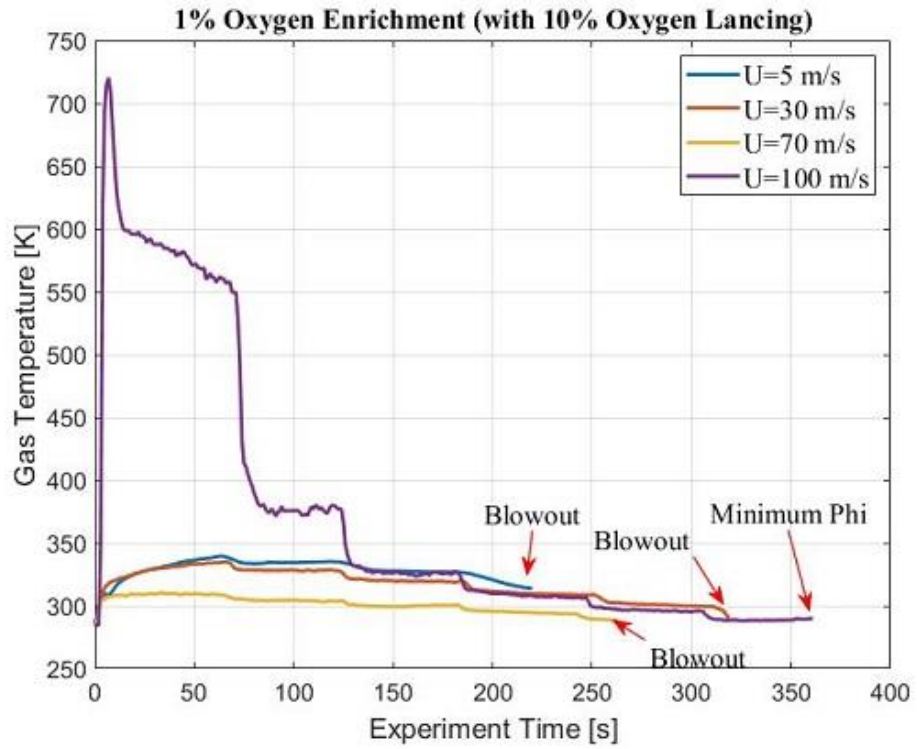


Figure 5.29: Time histories of the temperature of combustion gases and equivalence ratio for Case 3 (CNG/oxygen-enriched-air flame with pure oxygen lancing).

5.3.4. Case 4 (CNG/oxygen-enriched-air flame with oxygen lancing)

In this case, lean blowout limits of CNG/oxygen-enriched-air flame have been investigated with pure oxygen lancing. In this case oxygen enrichment was 8% while 10% of this value has been lanced directly into the burner. Flame structures at the beginning of experiments, in the middle of experiments and near-blowout are shown in Figure 5.30.

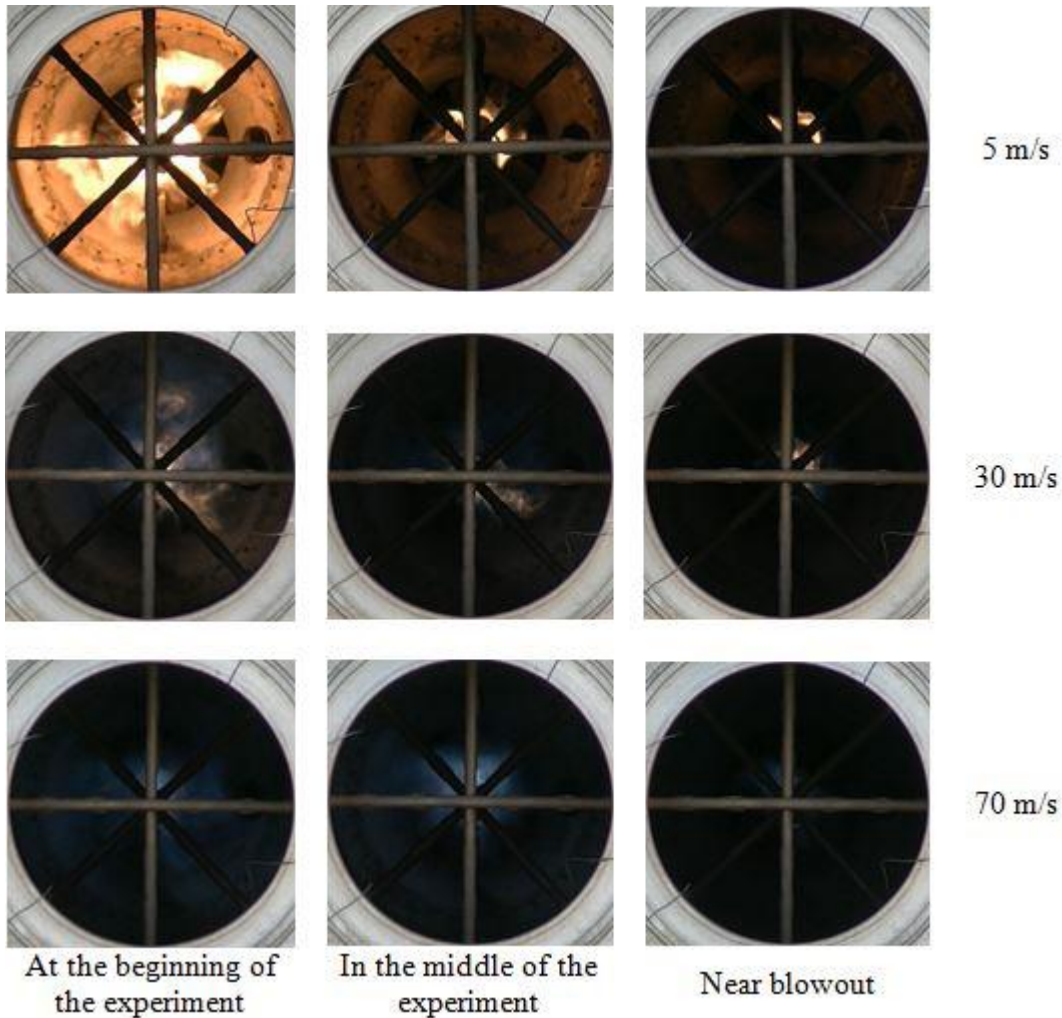


Figure 5.30: Flame structures for different axial mean swirler velocities for Case 4 (CNG/oxygen-enriched-air flame with pure oxygen lancing).

Figure 5.30 shows that, the flame is thick at the beginning of the experiments. The flame becomes thinner, while decreasing the fuel mass flow rate. The flame color becomes light blue by increasing axial mean swirler velocity. At low velocities, the flame color is yellow.

As burner characterization experiments are based on decreasing the fuel/oxidizer equivalence ratio, fuel mass flow rate is being decreased step by step during the experiment while keeping the oxidizer mass flow rate constant. In Figure 5.31, time histories of the decreasing fuel pressure in time are shown. Initial fuel pressure differs with respect to orifice plate used in the experiment.

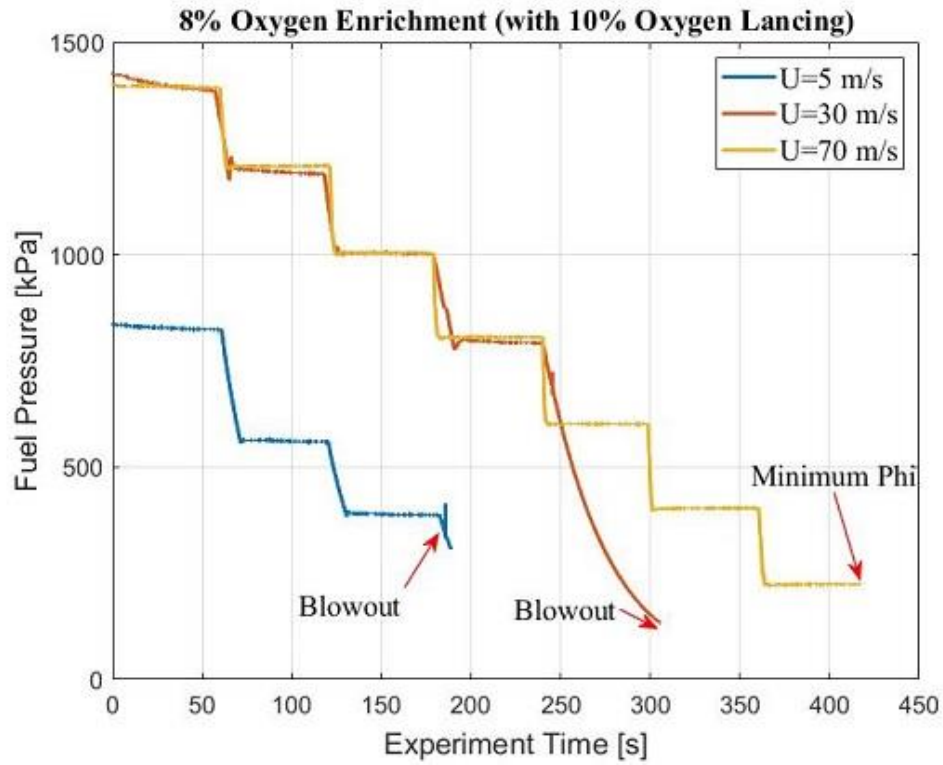


Figure 5.31: Time histories of the decreasing fuel pressure for Case 4 (CNG/oxygen-enriched-air flame with pure oxygen lancing).

At $U = 70$ m/s, the blowout could not be reached with the experimental setup. The reason was that the fuel mass flow rate could not be decreased any more. The minimum equivalence ratio is given for this experiment point.

In Figure 5.32, time histories of the temperature of combustion gases and equivalence ratio are given. At the beginning of the experiments (at high equivalence ratio), the temperature is high. By decreasing the equivalence ratio, the temperature of combustion gases is also being decreased.

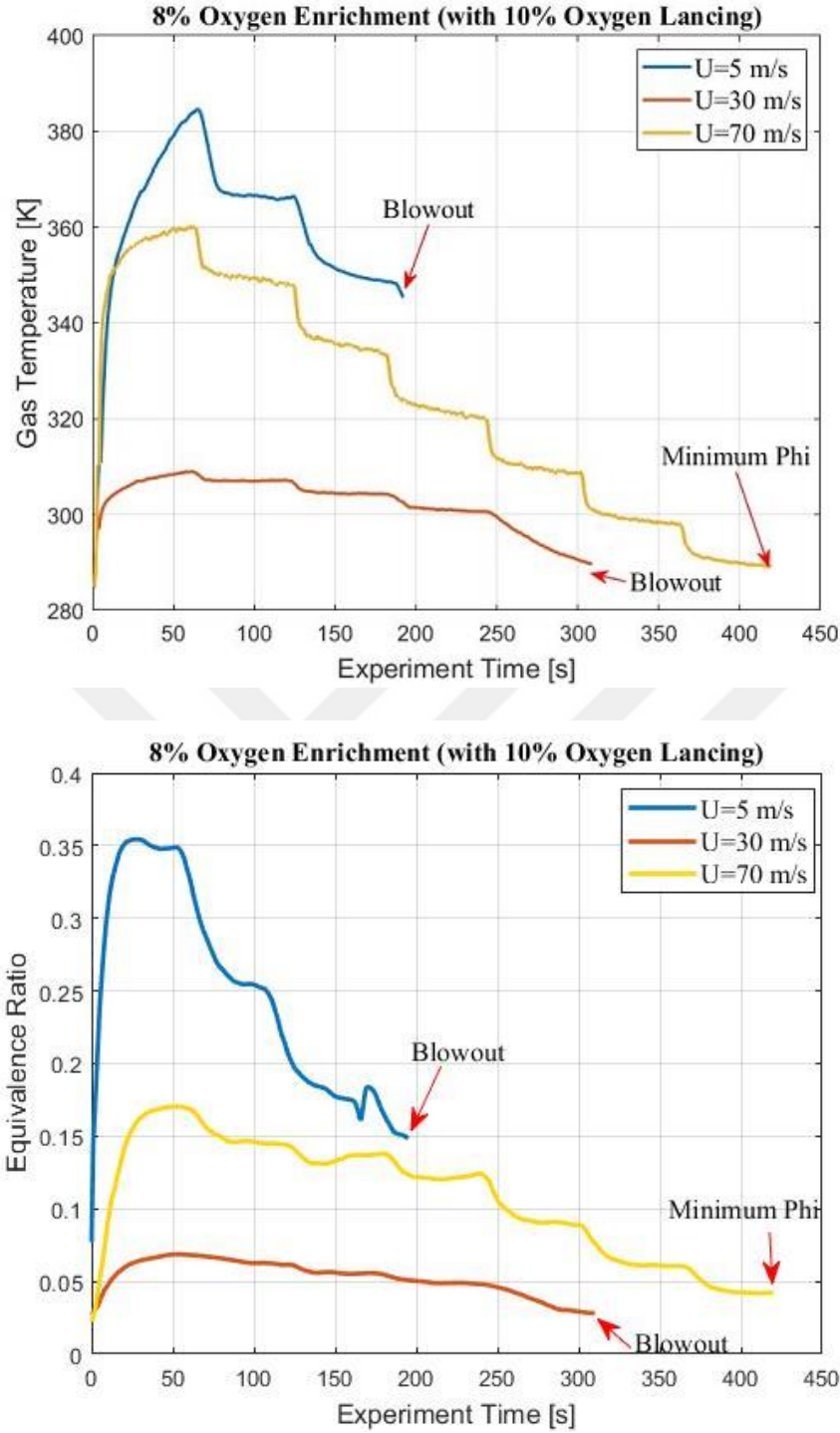


Figure 5.32: Time histories of the temperature of combustion gases and equivalence ratio for Case 4 (CNG/oxygen-enriched-air flame with pure oxygen lancing).

5.3.5. Lean blowout limits

Lean blowout limits of the CAH for 4 cases given above have been obtained by performing the burner characterization experiments. Lean blowout points are given in Figure 5.33 for 4 cases. The region over the related points is the operating region of the CAH, which has been determined by present study.

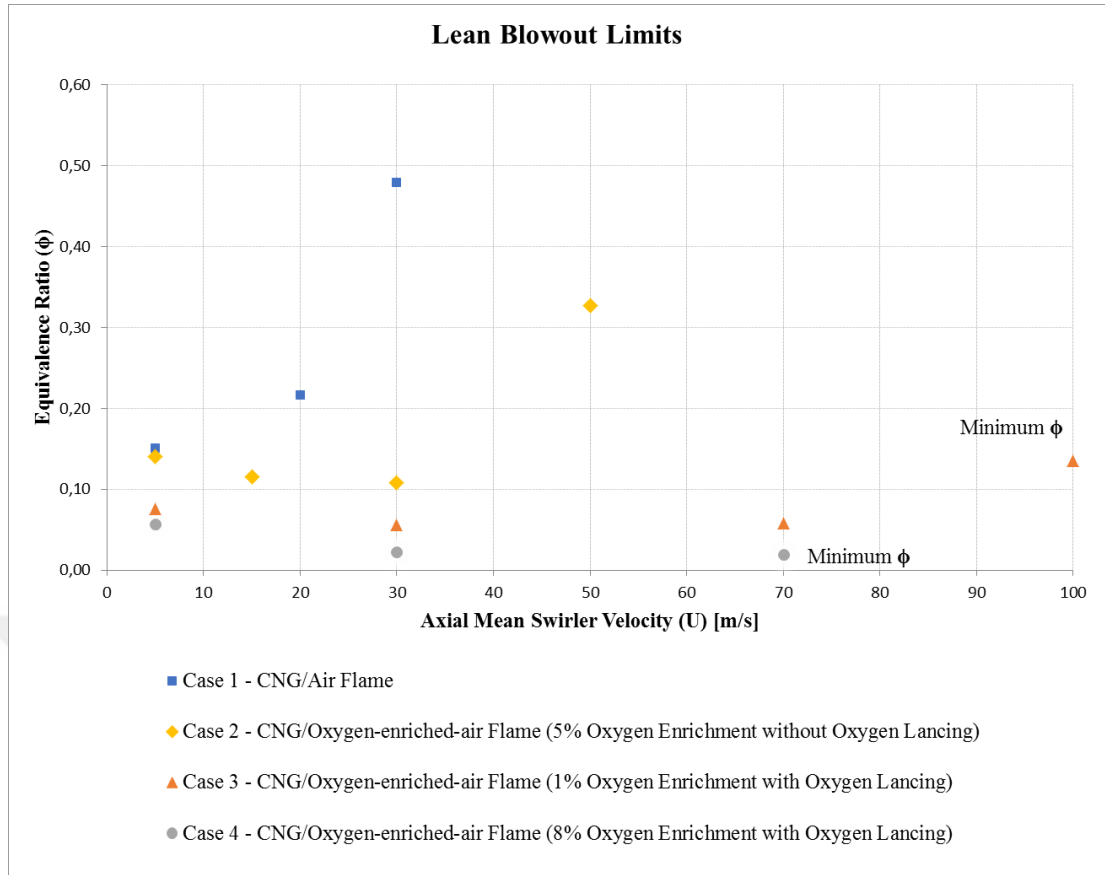


Figure 5.33: Lean blowout limits and the operating region of the CAH.

Graphical results given with Figure 5.33 indicate that oxygen enrichment improves the stability of the flame and widens the operating range of the CAH. Another important finding is that the pure oxygen lancing into the CAH improves the flame stability at high axial mean swirler velocities. When Case 2 and Case 3 are compared in terms of oxygen enrichment percentage, it is also observed that oxygen lancing has a significant effect on improving lean blowout limits.

If there is no oxygen enrichment as in the Case 1, the operating envelope of the CAH gets strongly narrowed.

5.3.6. Gas sample analysis

Gas samples from burner characterization experiments have been taken for 3 experiment points (from Case 1 at $U = 5$ m/s and $U = 20$ m/s, from Case 3 at $U = 100$ m/s). These samples have been analyzed with gas chromatography device to determine the unburned fuel amount. Since the gas samples have been taken at near blowout conditions and the thin flame is anchored in the central region of the burner, it is expected to encounter with high percentage of unburned fuel.

The composition of gas sample (at equivalence ratio of 0.1) of Case 1 at $U = 5$ m/s is shown in Figure 5.34. In this experiment point, 21.74% of the fuel was unburned.

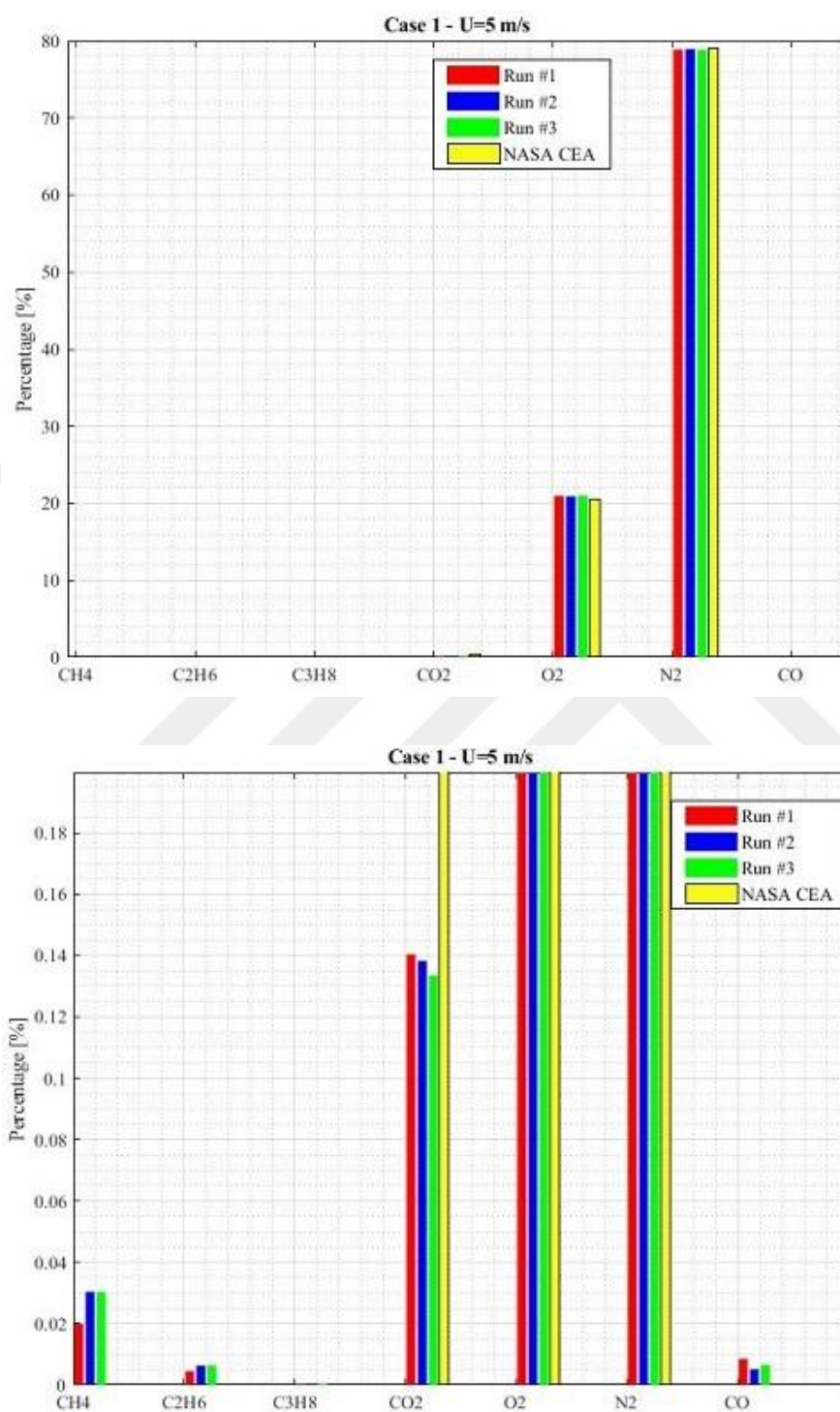


Figure 5.34: Gas sample analysis for Case 1 at $U = 5$ m/s.

The composition of gas sample (at equivalence ratio of 0.34) of Case 1 at $U = 20$ m/s is shown in Figure 5.35. In this experiment point, 12.84% of the fuel was unburned.

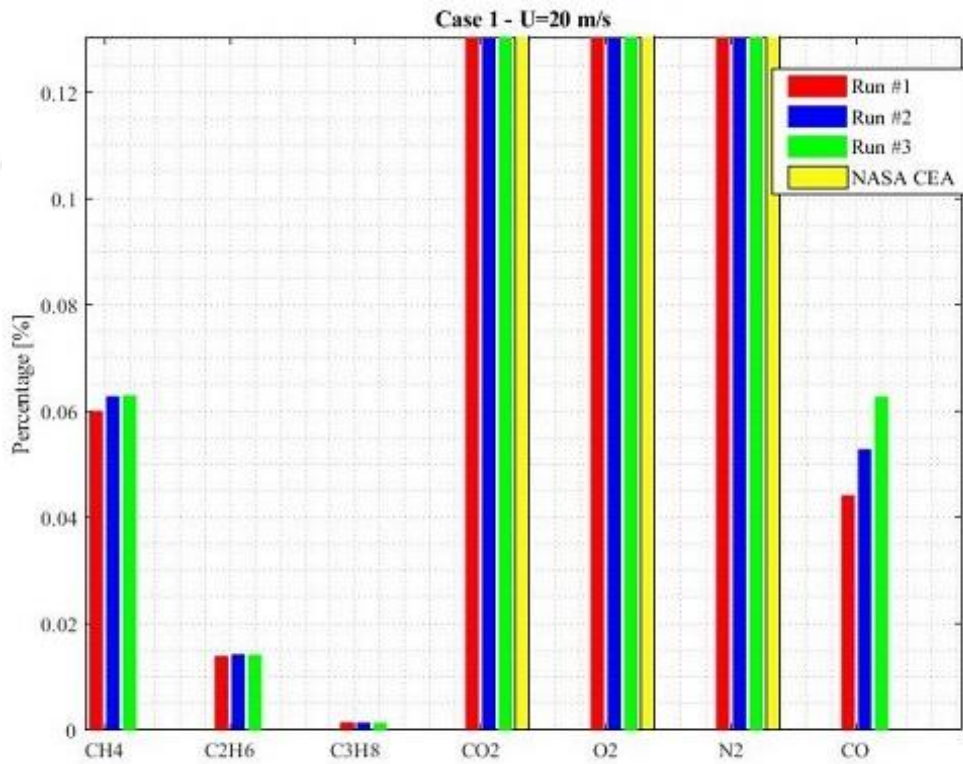
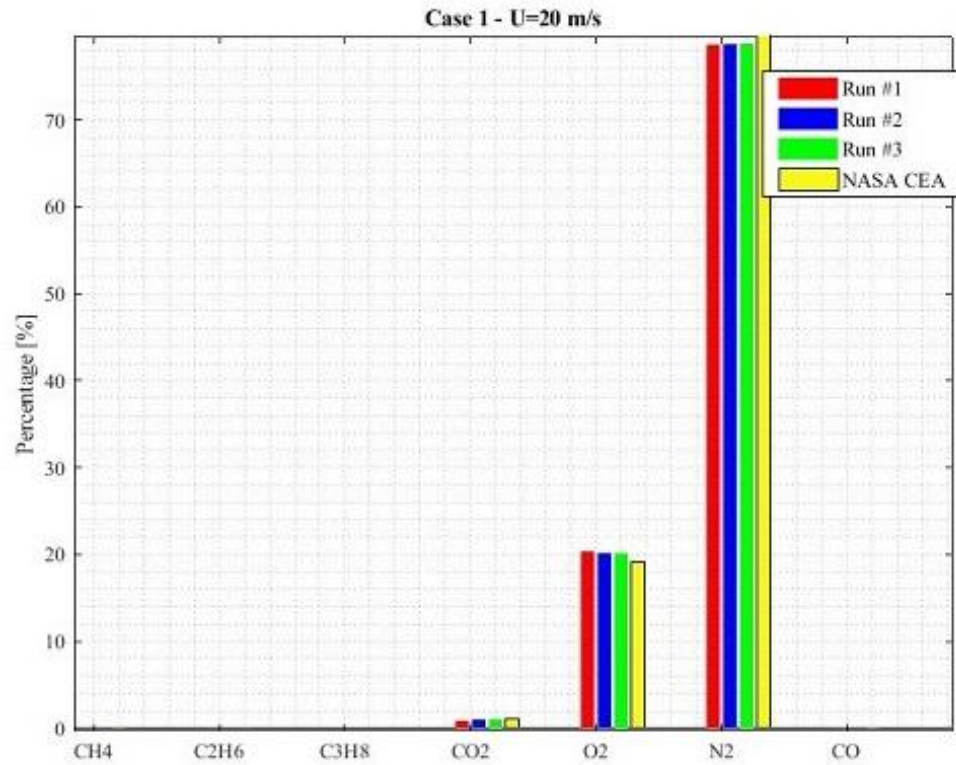


Figure 5.35: Gas sample analysis for Case 1 at $U = 20$ m/s.

The composition of gas sample (at equivalence ratio of 0.28) of Case 3 at $U = 100$ m/s is shown in Figure 5.36. In this experiment point, 63.52% of the fuel was unburned.

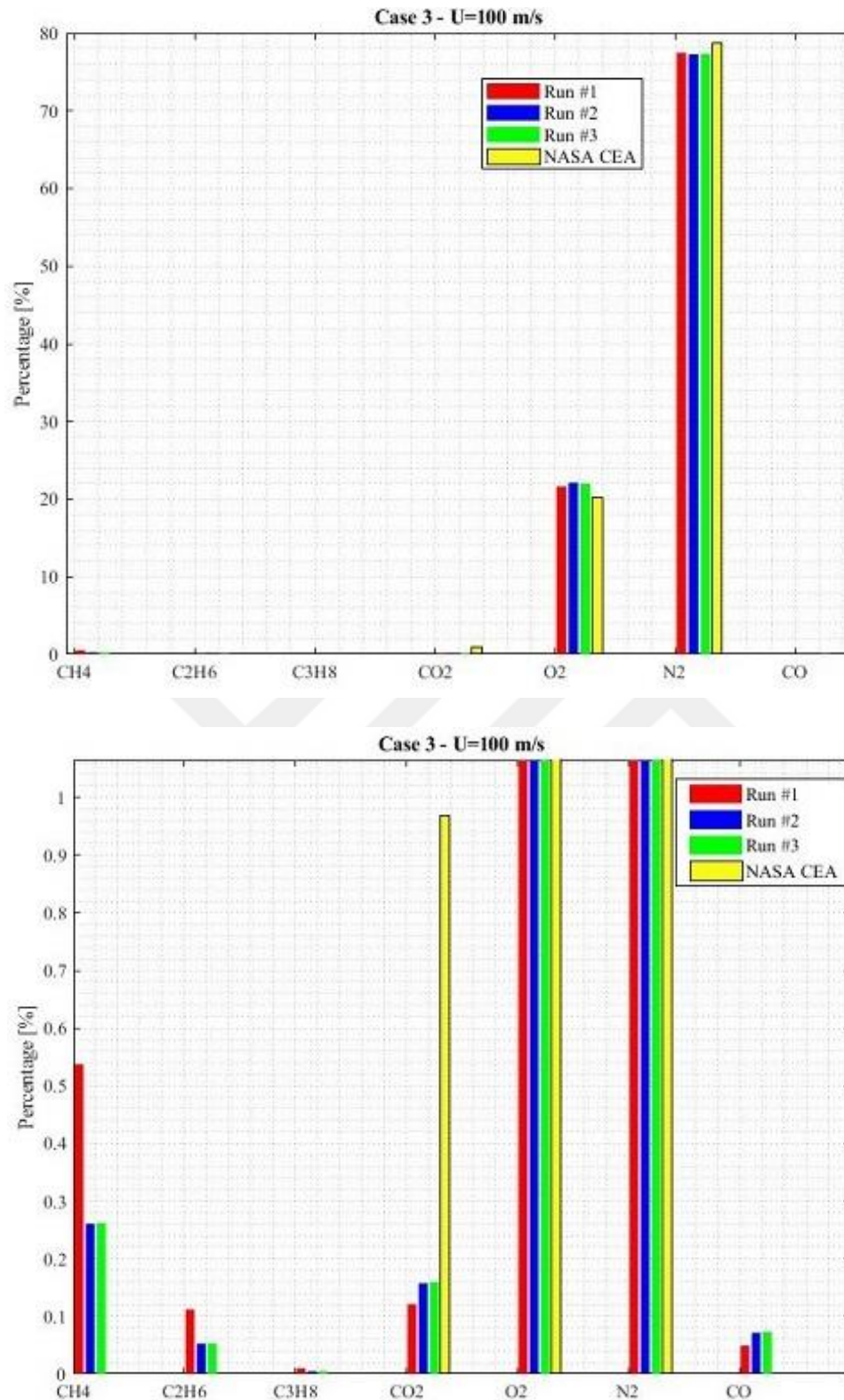


Figure 5.36: Gas sample analysis for Case 3 at $U = 100$ m/s.

Gas sample analysis shows that at high axial mean swirler velocities such as 100 m/s, air and fuel cannot mix as expected. More than half of the fuel amount leaves the burner unburned.

6. CONCLUSIONS AND RECOMMENDATIONS

With present study, it has been investigated whether the CAH established at TÜBİTAK SAGE operates to provide atmospheric flight temperature conditions for high-speed air-breathing propulsion systems ground tests at different altitudes and Mach numbers. Combustion performance experiments with oxygen-enriched-air have been conducted within the range of the CAH operating envelope. Measured temperature values were close to theoretically calculated temperature values within the reasonable range. By examining the experimental results, it is concluded that the CAH used within present study is capable of providing the atmospheric flight temperature conditions for high-speed air-breathing propulsion systems ground tests. It is observed that the flame becomes more stable by increasing oxygen amount in the oxidizer. Three experiment points of the 3 bar curve of operating envelope, could not be ignited even the CAH has been fed with oxygen-enriched-air. Those points have been ignited by lancing pure oxygen directly into the CAH. Oxygen lancing helps the flame to stabilize better.

When combustion takes place, heat transfer occurs between the hot combustion gases and the cold burner wall. This heat transfer prevents to obtain the steady-state gas temperature in the first 60-100 seconds of the experiment. For this reason, the CAH must be operated for at least 60 seconds in order to obtain the steady-state gas temperature while the ground tests are being carried out. The wall temperatures measured during the experiments did not appear to be a problem in terms of material strength.

Results also show that, combustion efficiency increases as the percentage of oxygen-enrichment in air increases. For 3 bar curve, at oxygen-enrichment percentages of 1.8, 2.7 and 4.4 combustion efficiencies are 64%, 75% and 89%, respectively. For 5 bar curve, at oxygen-enrichment percentages of 2.1, 2.4 and 3.4 combustion efficiencies are 55%, 81% and 86%, respectively. Another important result observed in present study is that combustion efficiencies of cases with oxygen lancing are lower. The flame is attached to the center by lanced oxygen and combustion does not

take place in outer regions. Thus, some amount of fuel could not be burned. This causes low combustion efficiencies.

The second objective of present study is to determine the lean blowout limits and the operating range of the CAH. Within the scope of the study, the effect of the oxygen enrichment percentage on lean blowout limits has been investigated. Experimental results show that lean blowout limits are improved while oxygen enrichment percentage is increasing. Therefore, oxygen enrichment broadens the operating region where the flame is stable. At an axial mean swirler velocity of 30 m/s, the lean blowout limit in terms of equivalence ratio is 0.48 for CNG/air flame. This value is 0.11 for CNG/oxygen-enriched-air flame of 5% oxygen enrichment. It is also observed that as axial mean swirler velocity increases, the operating envelope of the burner gets narrowed. For CNG/air flame, lean blowout limits at $U = 5$ m/s, $U = 20$ m/s and $U = 30$ m/s are 0.15, 0.22 and 0.48, respectively. For CNG/oxygen-enriched-air flame, lean blowout limits at $U = 30$ m/s and $U = 50$ m/s are 0.11 and 0.33, respectively.

Except those, the effect of pure oxygen lancing on lean blowout limits have also been investigated. It is observed that oxygen lancing strongly improves lean blowout limits. Oxygen lancing decreases the lean blowout value below 0.06, even at higher axial mean swirler velocities as 70 m/s.

While the burner characterization experiments have being conducted, gas samples have taken at near blowout conditions to analyze the combustion gases composition. The unburned fuel amount has been determined by analyzing the gas sample. Since gas samples have been taken at near blowout conditions and the thin flame has been anchored in the central region of the burner, high percentages of unburned fuel are observed. This may appear as a problem in terms of high-speed air-breathing propulsion systems ground tests. When vitiated air with a high percentage of unburned fuel (hydrocarbons in this case) enters into the test engine, it affects the performance and safety of the test engine adversely as there exists another undesirable fuel. Vitiating the test engine combustion air under very lean conditions may have undesirable results.

Flame stabilization is by far the most challenging phenomena in practical combustion studies. Within present study, combustion experiments have been carried out under

ambient pressure condition and oxygen lancing has been used to improve the flame stability. When there exists a converging nozzle at the burner exit, combustion takes place under high-pressure condition. In that case it is more difficult to observe an anchored, stable flame rather than an oscillating, unstable one. To overcome this difficulty, the following optimizations can be investigated in future studies:

- Changing liner hole configuration to reduce oscillation amplitudes,
- Changing swirler geometry to ensure better mixing of fuel and oxidizer,
- Changing fuel inlet velocity by configuring fuel injector,
- Changing the oxygen lancing inlet geometry to position the flame a better place,
- Changing the position of the ignition electrodes.



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