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Experimental Investgation of The Effect of Burner Geometrey on Flame Stability

A Thesis

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بسم الله الرحمن الرحيم

أَنْ يَشَاءَ اللَّهُ نَرْفَعُ دَرَجَاتٍ مَنْ
نَشَاءُ وَفَوْقَ كُلِّ ذِي عِلْمٍ عَلِيمٌ

يوسف﴿٧٦﴾

Dedication

This work dedicates to:

The soul of Who Draws My Dreams and Wisdom

My Father

The Love Kindness Merciful Spring

My Mother

The Strength Source and the Loving Partner of My Life

My Wife

The Play Partner in Childhood and the Success Partner during Adulthood

My Brothers

The Treasure Gift and Blessing of God

My Children

The Candles of My Way and My Supporting

My Friends

The Virtue Crowns and Knowledge Laws

My Teachers

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ABSTRACT

Combustion and its control are essential to our existence on this planet since we knew it. Nowadays, the largest share of the world's electricity and most of our transportation systems are powered by combustion. In addition, industrial processes also rely heavily upon combustion. In most industrial combustion systems, combustion occurs under turbulent now conditions that can produce combustion instabilities. These are problematical since they can result in oscillations in thrust, low- or high-cycle fatigue of system components, flame blowoff or flashback, and oscillations in combustion efficiency together with high emission levels or even damage to the combustion systems. Thus, flame stabilization is of fundamental importance in the design, the efficient performance and the reliable operation of the combustion systems.

The effect of the burner geometry on operation window of small commercial burner (12-14 Kwh) was studied. The burner in origin using diesel as a fuel and modified by the researcher to operate with LPG. The length of the burner rim was studied by taking three values of length (5 cm , 10cm and 15cm) which represent a ratio of (1,2 and 3) to burner diameter respectively . The modification shows that the ability to use dual fuel in such small combustion unit is possible with minimum additional cost for control. To enhance the combustion stability, a swirl vane guide was used to obtain swirl flow and improve the flame structure. The results show that the increase in length of burner neck will decrease the swirl coherent structure and turn the flow to diffusion flow which increase the ability to have boundary layer flashback. However with the limit of burner used, increasing the length of burner neck gives a good result in blowoff side by bushing it to leaner limits around ϕ=0.38 but in term of flashback it will bring it to leaner limits too, which is not

preferable. In term of the burner power, the LPG fuel combined with swirl flow increase the burner power to around 130Kwh. Although, this improvement is linked to the fuel type in first place but the flow structure has a significant impact on flame stability.

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Nomenclature

Alphabetic Symbols		
A_O	The nozzle exit area	[m^2]
A_t	Total area of tangential inlets	[m^2]
D	Exhaust diameter of swirl burner	[m]
FAR_{act}	Actual fuel air ratio	-
FAR_{stoich}	Stoichiometry fuel air ratio	-
g_c	The critical velocity gradient	[1/s]
g_f	The flow velocity gradient	[1/s]
g_t	The critical velocity gradient (pipe)	[1/s]
G_x	Axial flux of axial momentum	-
G_Θ	Axial flux of tangential momentum	-
$\dot{m}$	Mass flow rate	Kg/s
P	Pressure	[bar]
Q_{ta}	Tangential volume flow rate	[m^3/s]
Q_{to}	Total volume flow rate	[m^3/s]
Q	Heat generation	Kw
r	Nozzle radius	m
R	Radius	m
R_o	Exit radius	-

R_{eff}	Effective swirl radius	m
S	Swirl number	-
$S_{g, comb}$	Combustion swirl number	-
$S_{g, iso}$	Swirl number at isothermal conditions	-
T_{inlet}	Fluid inlet temperature	k
T_{outlet}	Fluid outlet temperature	k
U_a	Annular velocity flow	m/s
U_i	Jet velocity central	m/s
u	Axial velocity	m/s
u'	Fluctuating axial velocity	m/s
w	Tangential velocity	m/s
w'	Fluctuating tangential velocity	m/s
Greek symbols		
ρ	Density	kg/m^3
Φ	Equivalence ratio	-
λ	Air excess ratio	-
α	Vane stagger angle	Deg.
List of abbreviations		
BLF	Boundary Layer Flashback	-
C_3H_8	Propane	-
CCS	Carbon Capture and Storage	-
CFCS	Chlorofluorocarbons	-
CH_4	Methane	-
CIVB	Combustion Induced Vortex Breakdown	-

CRZ	Central Recirculation Zone	-
EUETS	European Union Emission Trading Scheme	-
FBC	Fluidized-Bed Combustion Systems	-
H_2	Hydrogen	-
HFC_S	Hydro fluorocarbons	-
IRZ	Internal Recirculation Zones	-
ISL	Inner Shear Layer	-
LDA	Laser Doppler Anemometry	-
LDV	Laser Doppler Velocimetry	-
LHV	Lower Heating Value	-
LNG	Liquefied natural gas	-
NH3	Ammonia	-
NO_x	Nitrogen oxides	-
OH-PLIF	Hydroxyl Planar Laser Induced Fluorescence	-
ORZS	Outer Recirculation Zones	-
OSL	Outer Shear Layer	-
PVC	Processing Vortex Core	-
SL	Shear Layer	-
So_x	Sulphur Oxides	-
UHC	unburned hydrocarbons	-
UNFCCC	United Nations Framework Convention on Climate Change	-
VB	Vortex breakdown	-

CHAPTER ONE

Introduction

INTRODUCTION

1.1. Burner

A burner is a mechanical device that supplies required amount of fuel and air, creates condition for rapid mixing of fuel and air and produces a flame which transfers thermal energy to furnace and charge . In oil burners, oil is atomized into a fine spray by a spray nozzle and air is supplied for combustion in the spray chamber[1]. Alternatively oil may be atomized by high speed air to produce a fine dispersion of droplets into air as shown in Fig. 1.1.

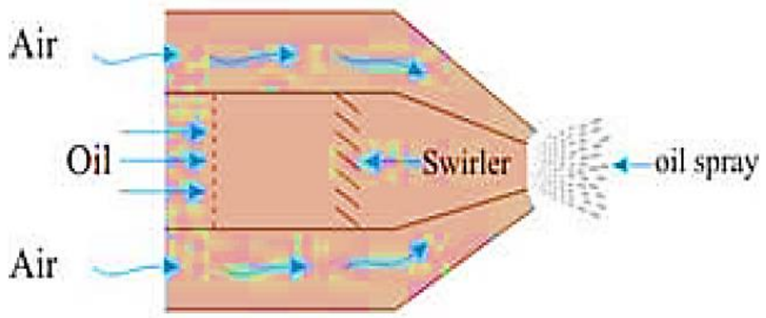


Fig.1. 1 Swirl burner [1]

There are liquid fuel and gaseous fuel burners. In liquid fuel burner, oil is heated and atomised either mechanically or by high speed gaseous jet. In mechanical methods oil is atomised by means of a rotating disc or cup or by swriler. Mechanical atomization produces wider spray of oil and wide flame area with uniform droplet size.

In atomization, compressed air or steam is the atomizing fluid. Air atomization produces higher flame temperature than steam atomization. Steam atomization is preferred for viscous oil. Some ways of air atomization. A gaseous fuel burner could either be of premixed type or diffusion type. In a pre-mixed type gas and air are mixed prior to passing through the nozzle. In diffusion type fuel and some amount of air is mixed and the mixture is passed through the burner. Rest air for combustion is supplied in the furnace chamber. Combustion of fuel is controlled by the rate of mixing of air and fuel. In these burners small portion of air is mixed with fuel as primary air and the rest amount, known as secondary air is supplied in the furnace[1].

1.2. Combustion

the combustion is a chemical energy in the fuel is converted into useful mechanical energy that powers the engine. The combustion is distributed randomly and therefore the excessive combustion is called (explosion). The blast moves the piston or rotor motor. The engineering of high-pressure systems provides many features that affect the generation of pollutants from the chemical combustion process[2].

The difference between internal and external combustion engines, as their names suggest, is that the former burn their fuel within the power cylinder, but the latter use their fuel to heat a gas or a vapour through the walls of an external chamber, and the heated gas or vapour is then transferred to the power cylinder. External combustion engines therefore require a heat exchanger, or boiler to take in heat, and as their fuels are burnt externally under steady conditions, they can in principle use any fuel that can burn, including agricultural residues or waste materials[2].

1.3. Combustible Mixtures Types

The mixing process of combustible mixtures in gas turbine systems is different from system to system, depending on many factors such as the required output power, efficiency, operation stability demands, nature of duty and even environment protection regulations. There are three mixing techniques used in gas turbines.

1.3.1. Premixed Mixtures

In premixed mixtures, fuel and oxidiser are intimately mixed at a molecular level before combustion is initiated. The mechanism of combustion is based on the propagation of the flame front into the unburnt mixture. The equilibrium between a chemical reaction and the amount of heat generated at the reaction zone determines the premixed flame structure and its characteristics, flame propagation speed or the so-called burning velocity, which is one of the characteristics that can address flame stability. In some cases, the burning velocity may become so fast that causes a dramatic transition to detonation, i.e. when the combustion wave moves at supersonic velocity with the possibility of severe damages by an explosion [3].

Premixed mixtures are relevant to gas phase combustion, and it is not applicable with liquid fuel droplets or solid particles. Until now it is commercially limited to natural gas and a small fraction of other active components. Other fuels are usually burned using diffusion systems or non-premixed combustion systems with special burner designs [4], [5].

1.3.2. Partially Premixed Mixtures

Partially premixed mixtures are used to achieve some operation requirements in certain systems. In this method, part of the fuel or air is injected axially with a premixed blend, or both fuel and air entered separately and mixed partially by turbulence [88]. Partially premixed is used when it is required to have both the operation features of premixed and non-premixed mixtures. It is utilized in some applications that need to reduce pollutant emissions as well as have wider operation stability. Partial diffusion injection can affect the process positively ensuring ignition at the injection plane in addition to a reduction of pressure fluctuations [6].

1.3.3. Non-Premixed Mixture

In non-premixed or diffusive combustion systems, fuel and oxidant enter separately to the reaction zone. This mode of mixing is used in some combustion systems like internal combustion engines, turbojet afterburners, oil refinery flares and pulverised coal furnaces. One of the important features of non-premixed combustion is the uniform temperature distribution inside the furnace that allows low flame temperatures, consequently low NOx emissions. It can be achieved through mutual dilution between recirculated burned gases and both fuel and oxidizer. Fuel and air jets are injected at high momentum into the combustion chamber, hence allowing a considerable increase in chemical residence time [7]. In other words, the jet of gaseous fuel is mixed with sufficient quantities of air. Hence all fuel can burn at a suitable distance from the nozzle [8]. High stability and flame anchorage are also features of this technique. However, despite some positive outcomes of using non-premixed combustion, soot formation seems to be one of the undesirable features of this mixture. Soot formation of a particular fuel is governed by physical and operating parameters. The amount of soot formation in such systems can be reduced by using oxy-fuel combustion and adding CO_2 to the fuel or oxidizer.

In order to achieve a deep understanding of non-premixed combustion systems, several experimental and numerical studies have been developed. Some mathematical models have proven to be the best tool for these investigations. The models are based on the assumption launched [9] that the mixture fraction is a conserved scalar, hence the global properties of non-premixed combustion such as flame length is predicted and all scalars can be related to the mixture fraction.

1.4. Swirl Burners

Swirl burners have been widely used in many industrial and technical applications for decades; this includes gas turbine combustors, internal combustion engines, pulverised- coal power station, refineries and process burners [10]. Swirling flows have the ability to control the combustion process through mixing improvement rates between the reactants, reducing emissions with an increase of output power. Wider ranges of operational stability represented by flashback and blowoff limits can be achieved accompanied by high levels of turbulent flame speed and reduction of combustor size using these flows[10].

Historically, there has been a significant development in designing and manufacturing swirl burners in order to meet operational requirements of combustion systems such as duty nature, working environment, fuel cost, running efficiency, maintenance cost, and recently low pollutant demands, therefore swirl burners used in the aviation sector are different to those used in stationary gas turbines or marine propulsion systems. Swirl burners can be used to burn different fuel types with different calorific values. Multi-inlet cyclone combustors and swirl burner furnace systems have the ability to burn even poor quality and low caloric value fuels (1.3-1.4 MJ/m^3) without any supporting fuel[11] .

1.5. Operability Issues of Swirl Combustors

All swirl combustors are designed to work efficiently, safely and reliably with reasonable operability limits. This means the burner should have the ability to hold a flame at a variety of equivalence ratios, different fuel types and different environmental conditions (stationary gas turbines or aviation applications). However, most industrial combustors have undergone some operational issue that can cause considerable degradation of their performance and as consequence overall system efficiency. The common operability problems of swirl combustors are as follows:

1.5.1. **Blowoff**

Blowoff means the flame is being detached from its stable position and physically blown out. The most common reason that can cause flame blowoff is very lean mixtures or robust combustion instabilities. Recently swirl combustors have been extensively employed with lean premixed combustion to reduce NOx emissions, which are required to operate close to their blowoff limits, hence the strong possibility of being subjected to this issue. This problem becomes significantly important, especially for aircraft engines. Blowoff is a complicated phenomenon that involves interaction between chemical reactions, flame propagation and flow dynamics[12]. Blowoff phenomena have been extensively investigated, and a variety of experimental techniques and numerical simulations have been employed to achieve better understanding to prevent its occurrence[13].

It is thought that blowoff is governed by the equilibrium between chemical kinetics and fluid mechanics. Thus this relation can be described by using a Damköhler number based on a well-stirred reactor [12] which represents the relation between residence time and chemical kinetic time.

Thus blowoff will occur if the residence time is shorter than the chemical time. The residence time is denoted by the ratio between the characteristic length (recirculation zone), and the characteristic velocity scale, while chemical time scale represents the ratio between thermal diffusivity, and laminar flame speed S_L, thus blowoff can be correlated with the Damköhler number. However, determining the characteristic velocity, the characteristic length and hence the residence time is not simple. The characteristic velocity is a function of approaching flow velocity Ub which may change with Reynolds number due to changes in burning gas temperature while the characteristic length is a function of the recirculation zone shape. Additionally, calculations of thermal diffusivity for a fuel of different blends is sophisticated. Hence the evaluation of chemical time scale becomes more complex. This investigation of the chemical kinetic is not sufficient to have a comprehensive understanding about blowoff; fluid mechanics must be accounted too [14]. Nonetheless, blowoff trends of a wide range of fuel compositions can be determined by using the Damköhler number.

Many mechanisms can be used to enhance flame resistance to blowoff. Swirl burners and bluff-body techniques have been employed in many applications to achieve flame stability. They can work as premixed flame holders, enabling mixing between combustible mixture with hot combustion gases and promote the continuous ignition of reactants. The flame holding represents a crucial factor in flame stability. Consequently, many studies have demonstrated different characteristics of flame holding and its effect on blowoff limits by using bluff-bodies. The effect of bluff-body geometries studied , the team pointed out that vortex shedding results from the bluff-body playing an important role in the ratio of gas expansion across the flame and hence the level of flame extinction, and as a consequence the blowoff mechanism [15]. Correlated the turbulence level with strain rate; they found that strain rate increased with increasing turbulence, consequently leading to localised extinction zones along the flame surface [16]. Also, indicated that blowoff equivalence ratios are affected directly by upstream flow extinction [17].

1.5.2. **Flashback**

Flashback is the upstream flame propagation from the combustion zone to the premixing zone inside the combustor. It occurs when the flame speed exceeds the approaching flow velocity [18]. Flashback is a main operability issue and an inherent instability problem of lean premixed combustion systems which can cause the burner to overheat with considerable damages to the system hardware and increase in pollutant emissions as can be seen from Fig. 1.2.

Fig.1 2 System hardware damages due to flashback.

Fuel composition represents an important factor affecting flashback mechanisms. This effect is characteristic of turbulent flame speed ST variations. Thus introducing hydrogen or hydrogen fuels to premixed combustion systems that use swirl combustors have brought many concerns regarding flashback. More reactive gases than a natural gas such as hydrogen can present flame speeds about four times greater than those of natural gas [19]. Swirl lean premixed flames are more likely to be subjected to flashback. Swirling flows are complex and can interact with the flame in these systems causing flame flashback .

1.6. Alternative Fuels

Recently, various fuels are introduced to several combustion systems to permit consumption reduction of fossil fuels also on meeting clean energy necessities[6],[18],[20]. Different fuels like biofuels are multifunctional energy careers and well geographically distributed resources[21].There has been a powerful trend to seek out additional reliable and additional environmentally friendly energy resources. Therefore renewable energy that comes from natural resources like sunlight, wind, tides, rain, waves and geothermal heat area unit a stimulating energy supply. However, this contribution to the general international energy sector remains low and comprise concerning Revolutionary Organization 17% of the overall world energy consumption, as are often seen in figure 1.3[22].

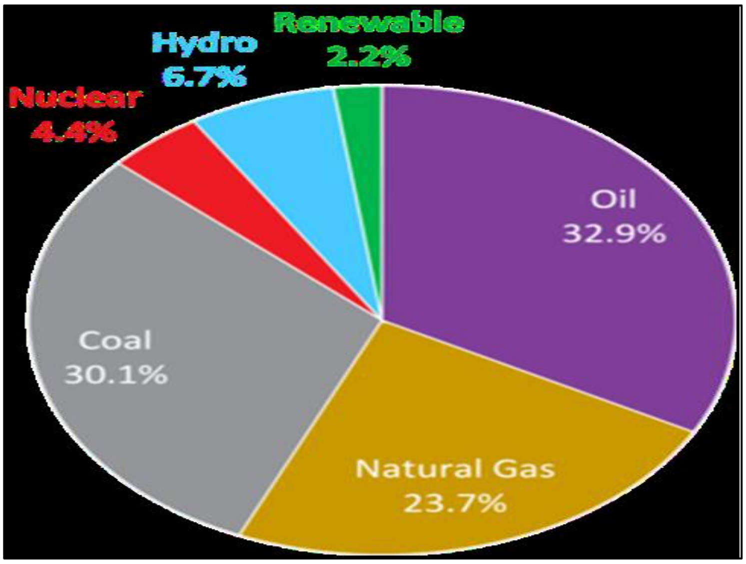


Fig.1 3 Global primary energy consumption share by fuel type in 2012[16].

Nevertheless, increasing this share looks to be tough and faces a lot of obstacles described by their intermittent nature, high cost, and accessibility of appropriate technology additionally because of the limitation of these resources.

So the importance of exploitation of various fuels rather than ancient fossil fuels has enhanced considerably within the last decade to scale back high pollutant levels and to lower energy value some common different fuels for power generation area unit as follows figure 1.4 [13].

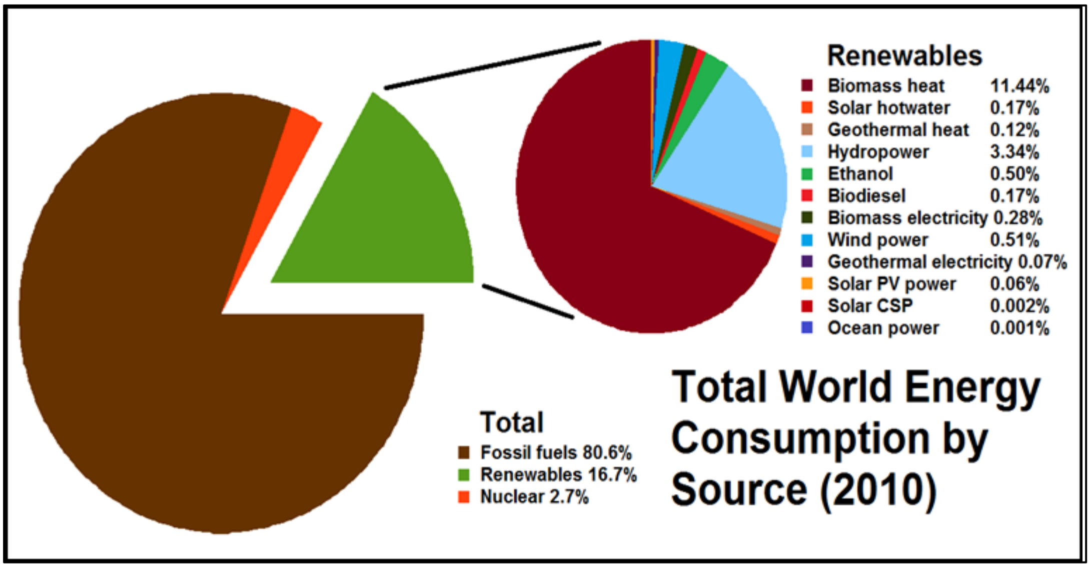


Fig.1 4 Renewable energy share in the world energy sector in 2010[17]

1.6.1. Biofuels

Fuel made of renewable biological materials sources are like plants and animals. Liquid and vaporized fuels from biomass can do low emission necessities, consequently, may be used as potential fuels[23]. Common biofuels area unit biodiesel, ethanol, biogas, syngas, solid biofuels, oil, bio-ethers, biofuel gasoline, green diesel and different bio-alcohols[24].

1.6.2. Hydrogen

It is thought-about the fuel of the long run. It is often made from a variety of sources like water, organic compound fuels, biomass, element compound, and chemical parts with the element. As a result of hydrogen, it is not available. It is not out there as a separate element. It is needed to be separated from the sources mentioned on top [9].

1.6.3. Liquefied Natural Gas (LNG)

It consists of fossil fuel (mainly methane, CH4) and it is made by liquefying fossil fuel taken from gas fields when removing impurities. This method ends up in condensation of the gas into liquid its volume 1/600th that of the fossil fuel. Consequently, it's rather more energy density than receiving fossil fuel[25]. Though it comes from fossil fuels, a rise of energy density includes a direct impact on value.

1.6.4. Ammonia NH_3

Considered as a secure hydrogen holder. It is a high gas content per unit volume, which makes it promising green energy storage. It may be created commercially by exploitation synthesis strategies. Its most advantageous feature is its little Co_2 production and high octane number[26].

1.6.5. Liquefied Petroleum Gas (LPG)

Liquefied petroleum gas (LPG) is one of the sources of fuel formed by processing petroleum when it is visible from the bottom, it is chemical composition consists of a series of gas C_3H_8 and alkane series C_4H_{10}. In addition to propane gas, liquefied petroleum gas (LPG) has a low concentration of butylene with CH_3CH_2SH which gives it a strong odor so that leaks can be identified. LPG is less polluted compared to diesel and gasoline engines and has lowest contains greenhouse gas emissions. Fig 1.5 shows the level of greenhouse gases of different fuels[27]. LPG has good combustion properties and low emissions compared to other fuel sources, so it is used as an alternative fuel in cars. The octane rating of LPG (105-112) is higher than the octane rating of gasoline (91-97), so the thermal efficiency of engines running on LPG is better compared to gasoline as a result of using a higher compression ratio. The deviation in air-fuel ratio decreases the laminar flame speed, and the highest deviation rate is in the rich mixture. To remedy this deviation, the engine must be operated at light combustion, with the equivalence ratios changing to be the

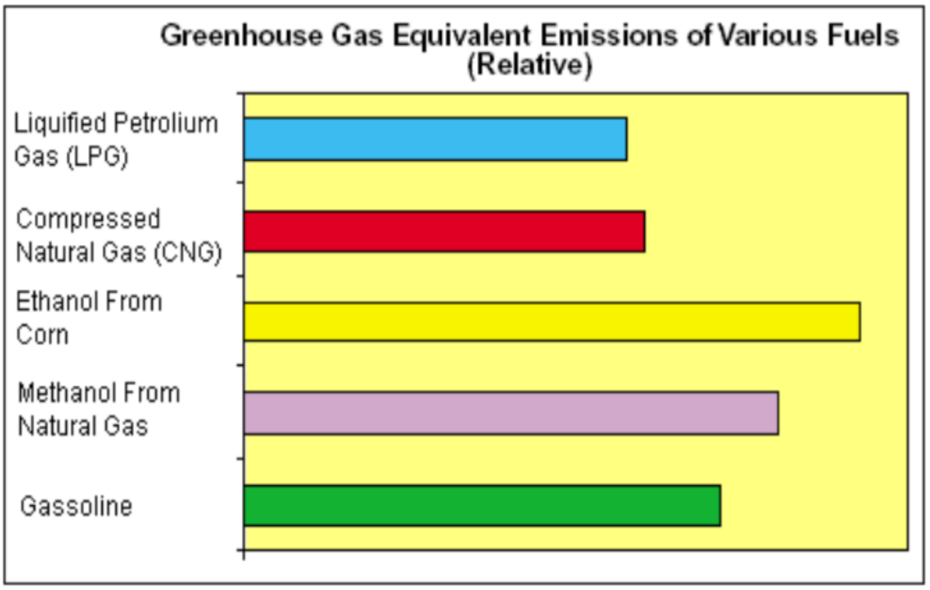


Fig.1 5 Greenhouse Gas emissions of multiple fuels[27]

lean mixture. LPG is the main source of a wide range of applications when liquefied by moderate pressure or heat reduction, so it can be condensed and packaged because the liquid forms 270 times its volume as a gas. LPG has very low sulfur content and is unleaded so it is a low pollutant or green fuel[28].

1.7. Objectives

The objectives of this study are:

1) Modifying an exist small commercial diesel burner to work with LPG without any additional cost.

2) Finding the operation widow (stability map) of the burner after using LPG.

3) Investigating the effect of burner geometry on the operation window of the burner . The blowoff limits and flashback limits will be addressed for different diameter to length ratio burner .

CHAPTER TWO

Literature Review

LITERATURE REVIEW

2.1. Introduction

Different techniques to stabilize a flame on swirl and jet burners that use LPG as a fuel will follow a brief introduction of combustion types and the main challenges that face the combustion process previous in this chapter. Challenges such as stability, and operational issues will be discussed through next chapter in the theoretical part.

2.2. Stability

Swirl-stabilized combustion is the most widely spread deployed technology used to stabilise and control combustion in gas turbines and numerous other systems. However, the interaction of the swirling flows with the burner geometries is very complex, and it has been proved that any change in the burner geometry can affect the flow field inside the combustion chamber, close to the burner mouth and downstream the combustion zone. Thus, most burners are provided with a central fuel injector that centrally delivers well-known fuels allowing the stabilisation of the system previous to operation under entirely premixed conditions. Moreover, the injector anchors the central recirculation zone formed downstream of the nozzle [29].

2.3. Alternative Fuel and Stability

Most of the gas turbines are using the natural gas as a fuel. During the last few decades, the using lean premixed combustion of natural gas has been developed to achieve low NO_x and minimal cycle efficiency drawbacks [30]. Alternative methods of lowering NO_x such as fuel staging, inert species dilution as well as exhaust gas clean-up in a non-premixed combustion system. Also to be limited in their NO_x emission, these methods usually are associated with increased operating and basic costs as well as efficiency penalties[31], contrary to premixed combustion. However, operating a combustor in a lean premixed mode brings its own challenges [32]. It raises operability concerns because of the increased risk of combustion instability, as well as possible higher CO emissions, leading to a potentially narrow window of safe, stable and clean operation regarding both CO and NOx. Promising methods for reducing emissions, combined with the high efficiency, fast ramp rate, and relatively low cost makes gas turbines – especially in a combined cycle configuration – one of the best candidates to enable a transition toward a low carbon-based power mix[31]. Such methods the hydrogen is produced as a by-product. Hence the gas turbine combustion system would need to be operated using a synthetic gas (a mixture of H_2, CO, and CH_4 mainly) or potentially pure hydrogen. But, this option faces two major issues: first, is the design of gas turbine itself since most of the designs focused and optimised to use natural gas as a fuel. Second, the issue is the variation in the fuel composition which leads to operability issues[33]. Although Hydrogen and syngas are considered as promising fuel, high instability operation risks also addressed, such as a flashback. Hydrogen and other fuel blends can cause main issues with many swirl combustors, due to the considerable variation in flame velocity with such fuel blends compared to natural gas [34].

2.4. Flame stabilization in premixed flows

Because flow velocities in aero-engines are generally severe, special consideration is needed to determine conditions of flame stability. Flashback or blowoff are two critical examples arising when the flame is not anymore stabilized[35]. Specific methods are introduced to create a stabilization point / region in the burner and to ensure that the flame is spatially and temporally anchored.

2.5. Flames Stabilised by Swirl Flow

As mentioned above, the development of dry low emission (DLE) burner concept in industrial context lead to the use of lean premixed gas turbine systems as well as high performance flame stabilization techniques. In lean premixed gas turbine combustors, swirl flows are commonly employed. The primary role of swirl is to create a low velocity region where the flame can be anchored [36].Moreover, the inner recirculation zone of the swirl flow acts as an aerodynamic blockage in stabilizing the flame. The combustion products recirculate in the inner recirculation zone and thus continually ignite fuel mixture. The hot burnt gases transfer heat to the recirculation zone to balance out the heat lost in igniting the combustible mixtures.

2.6. Swirl Flow

2.6.1. Swirl Strength

Two different types of mixing swirls have been used: a guiding vane swirl directed at a specific angle to mix the air with fuel and another swirl tangential to enter the air with fuel. These two types work to create a mixture swirl to raise the flame from the edge of the burner, especially in the systems of external combustion of gas turbines. In terms of performance, the system of tangential entry has a better performance in forming a swirl in the core of the internal wall of the burner. However, the tangential system of a swirl has defects in the higher degree of variability as well as the associated effects of the eddies formed on the inner wall of the burner [37]. Mixing the flow generates a tangential momentum (centrifugal force) directed at the inner wall of the burner. In order to maintain equilibrium with the centrifugal force, the gradient is formed in the pressure in a radial direction, this is called a simple radial balance flow [38].

It was found that when the flow expands and degrades the azimuth velocity with an increase in the axial distance, the pressure in the lower region resumes[39]. The positive gradient is created to press along the axis, thus forming the recirculation zone, providing a high swirl force. In some gas turbine systems, a swirl breakdown occurs in terms of pressure gradient due to sudden expansion of the cross section of the burner: The core of the vortex grows rapidly and produces a harmful gradient in pressure, which is further enhanced by pressure recovery due to the overall reduction in axial velocity [40] . Several types of vortex breakdown have emerged that have been described both as laminar and turbulent flows [35][36]. The way in which the flow was created (i.e. the use of guided blades), as well as the geometry of the burner has a significant effect on the breakdown of the vortex and thus affects the flow field [40][43]. Several parameters were suggested in the turbulent swirling flow description. These include swirl ratio, Strouhal number, swirl number, Reynolds number, circulation number, geometrical swirl number [38][39]. A swirl numbers were selected to identify and evaluate the swirl force in the flame investigations in burner . It is defined as the ratio of the axial flow of the axial momentum to the axial flow of the tangential momentum at a characteristic length, the radius of the output of the burner[46]:

$$S = \frac{3}{2} tan\alpha \frac{1 - R^3}{1 - R^2 + \left[m\left(\frac{1}{R^2} - 1\right)\right]^2 R^2} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots . \ldots \ldots (2.1)$$

Here R, m and α is a radius ratio, mass ratio, and the vane stagger angle, respectively.

2.6.2. Swirl Flow Structure

As shown in figure 2.1 and described in [46], when a central vortex breakdown is strong and the (IRZ, the inner recirculation area, known as the central recirculation zone) are generated. The stability of the flame in the breakdown vortices is enhanced by the presence of inverse flows as well as internal recessions. The breakdown of the vortex is associated with the negative axial velocity field in the swirling flow field, although the breakdown structures that have emerged are different [45]. A swirl breakdown occurs due to the negative pressure gradient that grows along the burner walls during high swirl [47]. The internal shear layer (ISL) is formed between the recirculation zone and the main flow, and the outer shear layer (OSL) is formed between the recirculation zone.

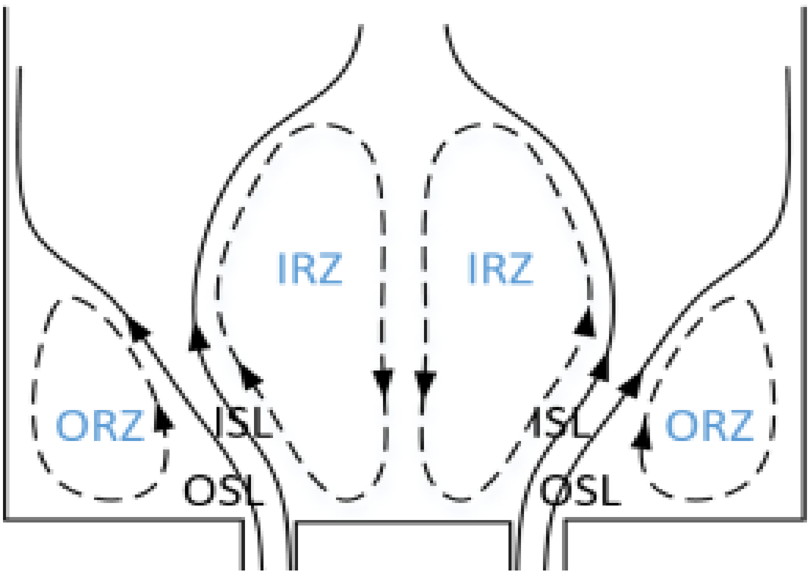


Fig.2 1 flow structure in confind zone [44]

In addition, there is a type of vortex that is called processing vortex core (PVC). This type of vortex is most common processing vortex core (PVC) [42][43].

As shown above, in industrial applications of premixed gas turbine systems as well as high-performance flame stabilization techniques, and therefore the application and development of low-emission burner (DLE), swirl flows are used to combustors premixed lean gas turbines to create a low-velocity zone, thus the flame can be anchored, depending on the main role of the swirl [50]. In addition, the internal recirculation zone of the swirl flow serves as a dynamic barrier in stabilizing the flame. The balance between the recirculation zone and the missing heat occurs in igniting the combustible mixture. The combustion products are recycled in the internal recirculation area and Thus helping to continually ignite the fuel mixture.

In recent years, the types of flame have been studied in the combustion of the premixed gaseous turbine systems (called flame topologies or total flame structures). Operating conditions have an important role in the effect of the flame shape, as well as heat transfer to the wall of the burner as well as forms of burner and confinement [45- 47]. As shown in figure 2.2_(a, b and c) there are two basic types of flame shape [52]: Flame M- shape and Flame V- shape . Flame M shape is formed with reaction zones in each of the outer shear layer(OSL) with the inner shear layer(ISL) , while the V- shape is stabilized on the shape of the inner shear layer (ISL) The sudden transition from V-shaped flame to M -shaped flame, so it was suggested using the flashback for the edge of the flame in shape V along the burner wall [48][47].

A flame-shaped V is preferred because it is supported by digital calculations indicating heat loss of the burner walls [54] in conclusion, it is possible to predict the transmission of flame well through the strength of a fixed swirl and small proportions of confinement as well as the number of Karlovitz Stable flame structures are observed for other types.

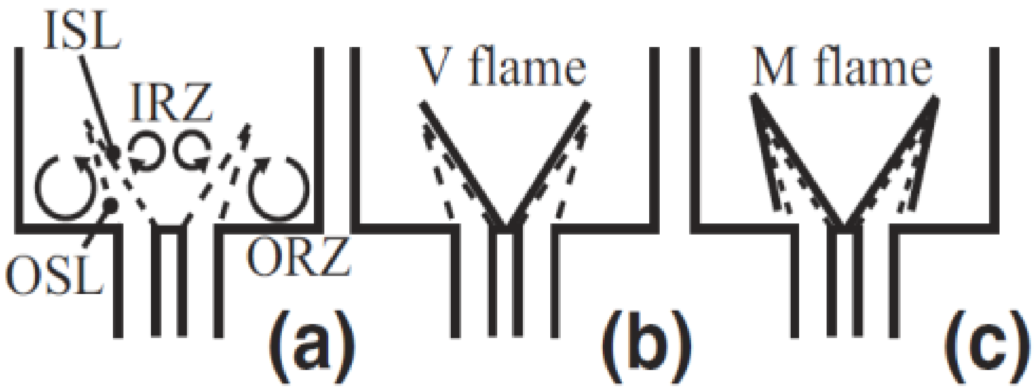


Fig.2 2 a) A schematic of flow fields in a swirling jet flow with a central bluff-body; (b) the V-shape flame and (c) the M-shape flame [51].

Flame instability refers to the rate of heat release from combustion as well as to damaging oscillations in pressure [55]. In the gas combustion system, several mechanisms have been identified that can cause combustion instability in the swirl flow. The mechanisms are summarized according to the following points: (1) fuel line feeder line connection, (2) equivalence ratio change, (3) collapse oscillator, evaporation, mixing, (4) the difference of flame fluctuation zones and (5) vortex fatigue[44]. It has been observed that the flame and flow structures change during the flame fluctuation process. The reason for the low frequency of flammable flame is the circular motion that occurs in the outer recirculation area around the center of the confinement [52] [53]. Note that the intensity of the flame infrastructure is linked to its instability. The transmission of the total flame structures led to fluctuations in the flame as they found intermittent ignition of the external recirculation zones as well as sudden ignition [58]. Other things related to flame instability are Flashback, lean blowout and auto ignition. Flashback occurs when the flame moves to the direction of the fuel source or to the fuel mixing area or along the boundary into the upstream region [55][56]. There are four mechanisms for Flashback to summarize: flashback in the boundary (FBL) , flashback due to combustion induced vortex breakdown (CIVB), auto ignition in the premixing zone upstream and flame propagation in high velocity core flow. What is more, [61] suggest there is a fifth factor of the flashback is the instability of the flame. There are two theories that explain the lean blowoff phenomenon of premixed combustion systems: (l) as characterized [62], The phenomenon of blowoff occurs when there is not enough time to continue the flow of fuel and thus separate the flame, (2) The equilibrium between the oxidation rate of mixture and the rate of reactive material entering the recirculation area leads to the phenomenon of blowoff as shown in the following sources: [55][60][63][64]. The standard Darmkohler number blow-off can be reduced, taking advantage of the chemical time of the reactor that has been well moved [64]. Auto ignition occurs in the case of increased temperature, pressure and equivalence ratio. Auto ignition Can lead to an increase in emissions and possibly cause damage to the burner body.

2.7. Interaction Between Flame and Swirl Flow Field

Flow fields in a swirl stabilized combustion with heat emitted from combustion can change, often near the combustion axis. Stagnation point location and flow structures are affect by the fuel to air ratio and mass flow rate [65][66]. In the meantime, the characteristics of flame stability affect the size of the internal recirculation area [11] showed that there are two sides of PVC that affect the flames. Firstly, by PVC, chemical reaction rates were accelerated near the inner shear layer and the stagnation point. Secondly, through PVC, the mixture of air and unburned fuel was enhanced with mixed gas burns. By increasing the flame surface or the occurrence of laminating due to stress they can change the flame behavior. Thus, in some cases of gas turbine combustion systems, low-frequency sound oscillations occur. The peculiarity of the flame caused by PVC is harmful to the spread of flame in the source and is also effective in the occurrence of flashback in the gas turbine systems installed in the swirl [67]. Because of the other factors and the warmth that results from combustion, the behavior of PVC is changed radically [68].

2.8. Flow Field Downstream of A Bluff-Body

Stabilization of premixed fire and diffusion can be achieved by using the bluff-body. If the premixed flame is installed in the typical flow fields that are below the downstream of the body as shown in figure 2.3. In this way, three areas can be identified: the waking zone, the separate cut-off shear layer and the boundary layer along the bluff-body. A relatively low pressure zone has been created with two areas of recirculation at the bottom of the bluff-body[39].

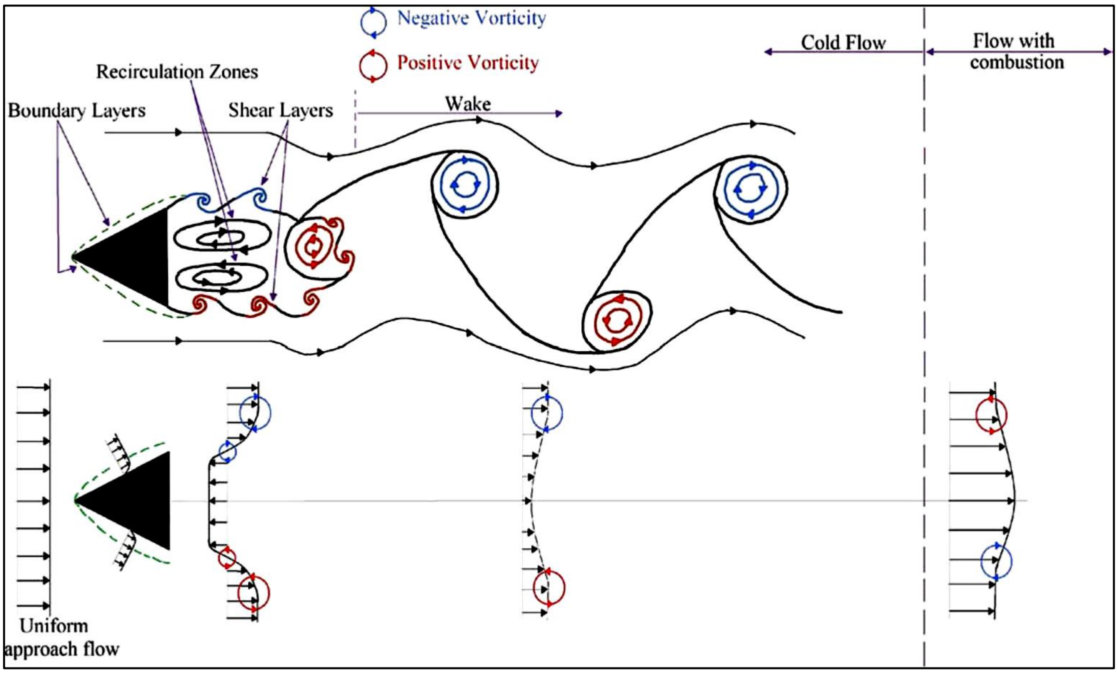


Fig.2 3 Key flow features in an isothermal bluff body flow, with instantaneous flow topology depicted on top, and time averaged velocity profiles on bottom[36].

Flow fields are more complex in the case of a central fuel jet as well as the diffusion of stabilized fire to the bluff-body. Use a central jet in the typical flow fields at the bottom of the bluff-body as in figure 2.4[69].

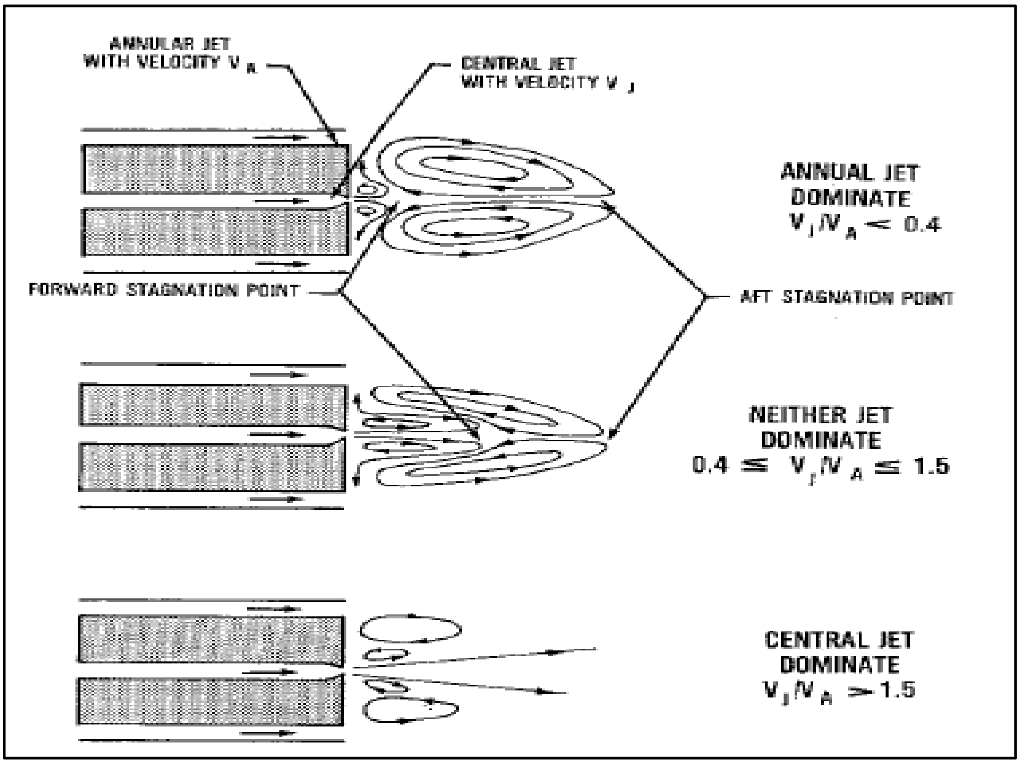


Fig.2. 4 Illustrations of the time-averaged flow fields for different[66]

There are two recirculation zones, indoor and outdoor. The internal recirculation zone is rotated by the central jet while the external recirculation zone is activated by ring flow. Flame stability depends on two regions of the external and internal reorientation as well as play an important role in flame diffusion structures. [70] three mixing layers were identified in the recirculation zone: an internal mixing layer located between the air flow zone and the external recirculation area, an intermediate layer located between the external and internal recirculation zones, an inner layer located between the central fuel jet and the swirl (the above three areas are show in figure 2.4. Flow structures that fall down the downstream depend on the central bluff-body strongly on the speed ratio [69] or the momentum ratio [70] of the ring flow to the central plane. For an axisymmetric bluff-body burner, The flow topologies was divided into three sections, the air, speed ratio and the iso-thermal flow as shown in figure 2.4 above [69]. The annular dominance and central dominance were changed to a transitional pattern by increasing the velocity of the central jet to annular airflow, thus finding variable flow structures. Numerically studied the results of the blockage magnitude relation, the cone angle and fuel-air rate magnitude relation on the flow fields downstream of the bluff-body[71]. It had been found that once the blockage magnitude relation was high, a bigger recirculation zone would be fashioned. However, a less degree of variation within the rate gradient within the major compounding zone can be ascertained within the case with a high blockage magnitude relation. it had been foreseen that in cases of a better blockage magnitude relation, the blending of the central fuel jet with the circular air flows would proceed less effectively. The effect of the turbulence that generated due the bluff body presence studied visually using high speed optical diagnostics was studied by [47]. The concluded that stabilization of combustion is controlled by the presence of the recirculation zone which induces some periodic ejection of burning pockets. It is allow for ignition of the main trailing flame downstream in the flow.

2.9. Flame Structure Within a Bluff-Body Burner

Bluff-body stabilised diffusion flame structures area unit of sizeable interest to researchers since they will be powerfully associated with the flame stabilization characteristics concerned. Projected a regime diagram of bluff-body stabilised flame patterns applying to (a) a recirculation zone flame, (b) a central jet dominated flame, (c) a jet-like flame, (d) apart quenched flame and (e) an upraised flame [72]. Mentioned flame structures considering stable flames, transitional-state flames, unstable flames and flame blowout [73]. They conjointly determined split-flashing flames, split flames and lift-off flames showing beneath certain operative conditions. Studied rifled bluff-body frustums and that they divided the flame patterns into the classes of jet flames, unsteady flames, bubble flames, upraised flames and turbulent flames [74]. Classified diffusion flames behind the disc stabilizer into five different modes: (l) recirculation zone flames, (2) central jet dominated flames, (3) jet-like flames,

(4) partly quenched flames and (5) lift-off flames [3]. Additionally according to there to be three varieties of bluff-body stabilised turbulent fossil fuel and liquefied hydrocarbon gas flames: (A) short, recirculation controlled flames, (B) transformation flames, and (C) long, fuel jet dominated flames [75]. However, [63] reported that a more significant recirculation zone downstream of the bluff-body may higher stabilize a premixed flame. They stressed the very fact that in an exceedingly more significant recirculation zone, the reactants concerned will have longer continuance and therefore higher promote flame stabilization. It had been noted that the flame patterns were powerfully related to flame dynamics that were a gift [15]. They reportable that flame blowoff occurred as a sequence of events: initial extinction on the flame sheet, then giant scale wake disruption and at last flame blowoff. These flame behaviors were claimed to depend on wake cooling and shrinking. Additionally, vital variations between the iso-thermal and also the reacting flow structures were rumored.

2.10. Flame Instability Within a Bluff-Body Burner

As delineate within the literature once a bluff-body stabilised diffusion flame is stable, the flame root is usually found to be hooked up to the bluff-body. As fuel flow rate changes, holes begin to create within the flame sheet till no eternal flame is hooked up to the bluff-body, this finally resulting in a blowout. Consequently, there square measure two crucial conditions associated with flame stability: ascension and blowout. Numerous alternative researchers have additionally outlined the looks of holes in flame sheets as representing a 3rd state of the diffusion flame instability[69][70]. Additionally, bluff-body stabilised flame dynamics additionally as flame-area variations, which can be originated from oscillations within the shear layer and vortex merging, may be considered diffusion flame instabilities among the bluff-body burner [76].It was found that native extinctions triggered unstable diffusion flames at the neck region, once a painter range of fuel approached the unstable limit, during a bluff-body burner[73]. The unstable limit of a flame decided in no small extent by painter range of the doughnut-shaped air. Unstable flames corresponded to the incidence of flame rending or native flame extinguishing that was caused by the local strain rate extraordinary a crucial value [77]. [72] Reported there to be two different flame stability limits: indigenous flame extinction dominating the lifting of jet-like flames and therefore the partial extinguishing of blue-neck flame in jet-dominated flames. Stability of jet-like flames is ruled by local flame extinction at the position wherever the outer admixture layer of air vortex meets the central jet flame fronts. Over that fuel concentration within the recirculation zone compete for a significant role in deciding the flame stabilization [78]. They conjointly claimed that once the quantitative confinement relation was not up to 0.25, the confinement wouldn't have vital effects on diffusion flame stabilization or flame structures.

2.11. Interaction Between Flame and Flow Field Within A Bluff-Body Burner

The researcher reported that the rate magnitude relation of the central jet to the ring-shaped flow determined the number of stagnation points in conjunction with the scale and also the strength of the recirculation zones[78]. They applied to each reactive and non-reactive case at intervals completely different confinements. Whereas, [79] studied the reacting flow structures and distinguished them in terms of 4 completely different modes. It had been conjointly finished that the flow patterns were powerfully determined by the interaction between flow and combustion. A compared the iso-thermal case with the combusting case concerning the speed fields downstream of the bluff-body, once holding the speed quantitative relation of the central jet to the doughnut-shaped flow constant at U/U_a = 0.84 [80]. It was finished that the speed within the center line region was altered between one case and also the other; whereas the speed distributions within the remainder of the flows were quantitatively almost like each other. They conjointly according to that combustion would lead to a rise within the central jet penetration. However, according that the raised flames failed to affect the flow structures close to the bluff-body considerably[81]. Within the lifted flames, combustion within the recirculation bubble LED to a lower pressure domestically and therefore increased the reinforcement of the event of the central jet. It was found that the flow patterns and also the turbulent intensities might affect combustion byways that of fuel entrainment, diffusion and intermixture capabilities. They classified the flow structures into pre-penetration, penetration and tremendous shear flows in line with the speed ratios of the central jet to the doughnut-shaped flow.

2.12. Temperature on The Surface of A Bluff-Body

Considerable analysis has been applied on the premixed flames that were stable by a straightforward bluff-body while not a central jet[63][15][82][83]. However, there have been solely restricted quantities of analysis regarding the warmth load to the bluff-body. Utilised an exceptional wire thermocouple junction in learning the temperature fluctuations of the diffusion flame during a bluff-body burner [84]. The temperature distribution on the axial line of the burner, as well as temperature on the surface of the bluff-body, was given. [85] measured the temperature on the surface of the bluff-body of Cambridge/Sandia Stratified Swirl Burner exploitation optical maser iatrogenic Phosphor (LIP) measurement. Different premixed cases with and without swirl were tested. They all over that the general operation of the burner was adiabatic since the radiative and convective heat transfer by the bluff-body amounted to but 0.5% of thermal input of combustion. They conjointly noted that there had been few measurements of the temperature distribution of the flame holder, whereas that temperature had a robust impact on the flame stabilization. In fact, in practical applications in turbine combustors, the main challenge concerned in use of a bluff-body seems to be the severe heat load and therefore the extraordinarily extreme temperature on the surface of the bluff-body. The warmth load to the bluff-body may well be expected to powerfully affect the steadiness limits of the premixed flame [86]. Additionally, the temperature distribution on the surface of the bluff-body is vital about the lifespan of the combustion system [87]. A necessity of sensible methodologies that area unit ready to cut back the warmth load on the surface of the bluff-body.

2.13. Geometry of Bluff-Body Burner

Bluff-body stable diffusion flames area unit found in a very sort of applications, like turbine combustors, afterburners, heat recovery steam generators, and industrial furnaces [72]. To stabilize a diffusion flame, the bluff-body is usually designed to be placed on the axis of associate degree circular channel in such how that fuel jet passes through the middle of the bluff-body. Also, in bluff-body stable diffusion flames, the geometries of the burner are often altered by ever-changing the form and therefore the position of the bluff-body further because of the blockage quantitative relation. Researchers typically value more highly to place the bluff-body at the extent of the doughnut-shaped channel exit, as are often noted within the literature [88][73][72][89] and [79]. The bluff-body forms most typically used square measure disk-shape or round shape. varied alternative bluff-body burner geometries have additionally drawn the eye of investigators, like inserting the bluff-body downstream [74][29][90][91] or upstream [92] of the doughnut-shaped channel exit, or employing a rifled bluff-body [74].

The results of the scale of a disk-shape bluff-body on a liquefied crude gas (LPG)-H_2 jet diffusion flame was studied [92][93]. It was found that because the diameter of the bluff-body was magnified, the flame length became shorter. The recirculation zone downstream of the bluff-body performed higher in commixture the reactants, and then the reaction zone was seemingly to propagate toward the bluff body. However, the analysis involved with the results of the position of the bluff-body (especially whether or not it's at the extent to the centeral air channel exit or above it) on the recirculation zones and flame structures is rare . At constant time, as indicated higher than, analysers have already used burners with entirely different positions of the bluff-body in their research. Whether or not and to what extent the position of the bluff-body will affect the flame patterns remains a subject in would like of study. within the burner style method, additional data regarding the consequences of the position of the bluff-body on the flame behaviors is needed.

2.14. Comparison of Flame Stability by Swirl Flow and Bluff-Body

A compared of swirl and bluff-body stabilised diffusion flames, last that: if a bluff-body flame and a swirl flame were operated beneath conditions such they'd lose constant non-dimensional vortex strength (of air driven vortex) and therefore the same non-dimensional fuel jet momentum, the two flames would show similar flame properties and trends [95]. They additionally according that bluff-body flows had constant vortex rate as swirl flows did, with the swirl range being just about 0.5 (with associate accuracy of and or minus 0.1 in swirl number). They discovered two styles of flame structures (Type one, a fuel-jet dominated flame and sort two, a recirculating flame) each within the bluff-body and swirl stabilised flames. They additionally all over that flame behaviour was powerfully determined by the flow fields downstream of the bluff-body or the swirler. Additionally, for enormous powers and high inlet flow speeds, making a recirculation zone behind a bluff-body might not be enough to make sure that flame stabilization was maintained whereas pressure losses were reduced [96]. In such cases, swirl flow may be utilised in industrial burners to stabilize the diffusion flame [97]. Also, detected the advantage of the utilization swirl flow in flame stabilization is that the absence of a solid flame holder within the combustor avoids flame impingement on the surface of the flame holder, therefore making specific minimum maintenance and extended life for the combustion system[91]. There also are some analysis coping with the mixture of bluff-body and swirl stable flames, particularly diffusion flames. Used favorite laser-based diagnostic ways to review the mix of a bluff-body and swirl flow in helpful the diffusion flames[98]. Their experimental results may function careful knowledge validations of the numerical analysis that has been conducted by different researchers.

Examined through an experiment the results of adding a bluff-body to swirl stabilised flames, yet because the effects of adding a swirl to bluff-body stabilised flames[99]. A combustion characteristics of a blending methane-hydrogen diffusion flame stabilised by a mix of a bluff-body and swirl flow studied [67]. They tested their numerical model with experimental information from [49] they conjointly compared the everyday flow fields downstream of the bluff-body with and without whirling flow, as shown in figure 2.5.

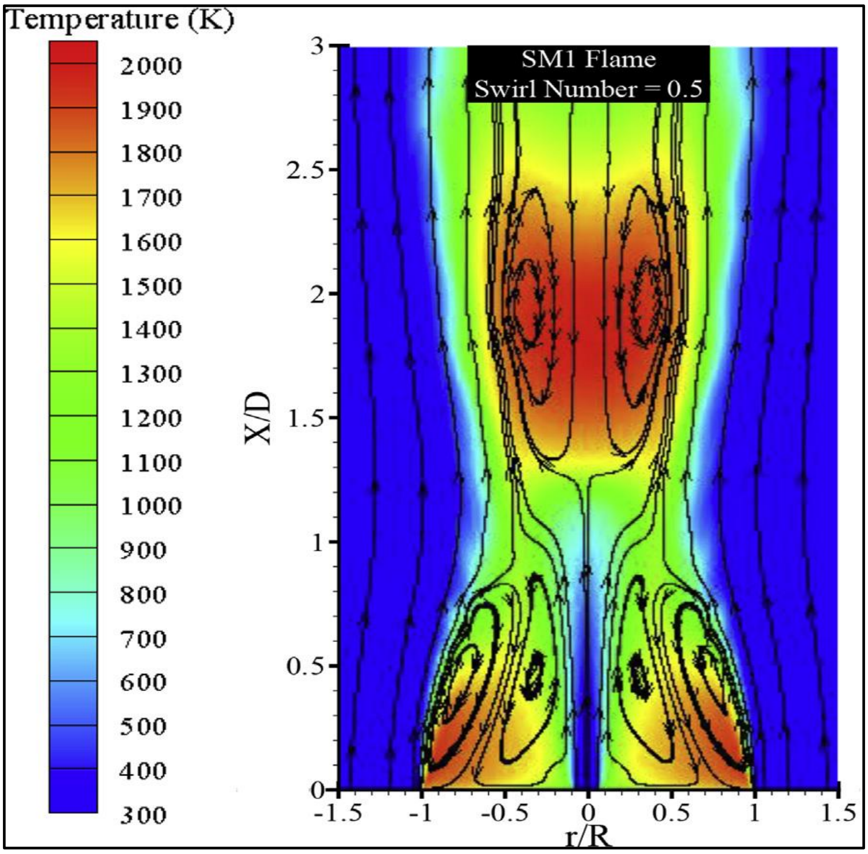


Fig.2 5. The predicted structure of the SM1 flame[46]

The central recirculation zone was driven by the central fuel jet, whereas the bluff-body created the outer recirculation zone and was inspired by the ring-shaped air flow. With a rise within the swirl range of the ring-shaped flow, more an extra} swirling flow induced 'secondary vortex' was shaped further downstream of the bluff-body. The flow fields appeared in Associate in nursing sandglass form [78] studied the flow structures of a turbulent jet, a bluff-body stable turbulent jet and a bluff-body stable whirling turbulent jet numerically during a co-flow setting. They all over that the mixture of the bluff body and swirl may considerably increase the blending of the central jet with the ring-shaped flow within the radial direction and therefore may cut back the axial extent of the high concentration zone.

However, the effect of the burner geometry is not fully understood, and the length of burner rim to burner diameter is not steady yet, in this study the focus to spot on the geometry effect on the stability and operation window of the burner using LPG as a fuel.

Table2. .1 Summary of literature review

Reaearcher	Type of study	purpose	Technician	Result
Chaudhuri, et al. [29]	Ex.	An experimental study of flame blowoff phenomenon in a bluff body stabilized flame confined in a cylindrical duct is presented.	The results were compared with those for the unconfined flame configuration as well. It is found that the blowoff equivalence ratios exhibit somewhat different trends for different approach velocities. For the uniform mixture profile, blowoff equivalence ratio first increases with increasing excitation frequency and then decreases at higher frequencies for the approach velocity of 5 m/s. For the 11 m/s approach velocity, the trend is different, and the blowoff equivalence ratio continuously increases with increasing excitation frequency	For the uniform mixture profile and 5 m/s approach velocity, blowoff equivalence ratio first increases with increasing excitation frequency by a maximum of about 6% and then diminishes at higher frequencies to values similar to that of the unforced case. For the 11 m/s approach velocity, the trend is different, and the blowoff equivalence ratio continuously increases with increasing excitation frequency by about 16%.
Sreenivasan et al. [33]	Ex.	The general implication is that different roughness geometries with the same ΔU^+ will have similar turbulence characteristics, at least at a sufficient distance from the roughness elements.	Measurements over two different surface geometries (a mesh roughness and spanwise circular rods regularly spaced in the streamwise direction) with nominally the same ΔU^+ indicate significant differences in the Reynolds stresses, especially those involving the wall-normal velocity uctuation, over the outer region.	The Clauser roughness function ΔU^+ is a useful descriptor of the effect the surface roughness has on the mean velocity distribution in the inner region of a boundary layer, there is as yet no adequate scheme which describes the effect the roughness has on the Reynolds stresses in the outer region of the layer.

Gordon, et al. [35]	Ex.	Simultaneous 10-kHz OH-PLIF and 20-kHz two-component PIV were made in conjunction with widefield 20-kHz flame luminescence imaging of an unconfined, swirling, lean premixed, bluff-body stabilized flame during flashback.	Analysis of the time-correlated flame history inside the exit nozzle during flashback and non-flashback flame events led to a new hypothesis for the flashback mechanism.	The phenomena of flashback were investigated using timecorrelated, simultaneously acquired PIV, OH-PLIF and FL data at kHz repetition rates. OH-PLIF at 10 kHz and PIV at 20 kHz were in fact reported. The results give insights into the mechanism of upstream propagation of the flame inside the annular slot of the burner.
James F. et al.[36]	Ex. and Th.	This paper first reviews recent ideas that explain why swirl has a strong stabilizing effect on a flame. Then some measurements are discussed that were obtained using a complex gas turbine fuel injector/mixer operated at realistic levels of swirl and multiple recirculation zones.	A precessing vortex core can be a source that drives a combustion instability. In addition, swirl affects the unsteady anchoring location of a flame, which also can lead to combustion instabilities, as are observed in our experiment	The combustion instability results in the flame motion and this indicates that flame stability plays an important role in creating the pressure oscillations associated with combustion instabilities. That is, if the base of the gas turbine flame can be securely anchored, then the periodic flow motions due to swirl and the precessing vortex core would not lead to the violent flame motions. More research is needed to determine if the motion of the flame base (associated with periodic liftoff and flashback) plays a dominant role in many types of combustion instabilities.
Lasky, . et al.[37]	Ex.	Flame extinction dynamics are investigated for highly turbulent premixed bluff-body stabilized flames within a blow-down combustion facility. Blowout is induced through the rapid reduction of fuel flow into the reactant mixture.	A novel turbulence generator is designed to modulate inflow turbulence levels. The turbulence generator implements both jet impingement and grid-based methods to vary turbulence across a wide range of intensities, including the thin reaction regime and pushing into the broken reaction regime.	Bluff body flame extinction has been investigated for various free stream turbulence conditions. A dynamic turbulence generator was utilized to modulate turbulence levels with a combined static grid and fluidic jet impingement design to achieve a range of turbulence conditions. As the free stream turbulence levels were increased, the recirculation zone length was decreased

				while the flame spanned farther away from the bluff body centerline. This effectively hinders the interaction between the shear layer and flame and delays the manifestation of high strain rate magnitudes along the flame boundary.
Yiheng Tong et al. [61]	Ex.	Flame structures, blowout limits and emissions of swirlstabilized premixed methane-air flames were studied experimentally in a small atmospheric combustor rig. Combustion sections with rectangular cross section (30mm by 40mm) and circular cross section (inner diameter = 39mm) were used to investigate effects of combustor geometry on the flame's performance.	It is found that the flame became longer and more unstable with decreasing equivalence ratio or increasing total mass flow rates. A strong high-amplitude and low-frequency oscillation was found to be the reason for the flame blowout. A possible reason for flame instability and blowout is presented in the paper. Within the parameters investigated in this study, the equivalence ratio had the strongest impact on flame stabilities and CO emission.	1. At high equivalence ratio, flame is short in vertical direction and stable with a small heat release zone. 2. With the decreasing of equivalence ratio, flame becomes longer and unstable with a high-amplitude oscillation and a larger heat release area. 3. Decreasing Φ further, both in the rectangular and circular combustors, L gets longer to a critical value (which is approximately the same for these two geometries) and then flame could not be sustained anymore and blowout occurs.
Babak Kashir et al . [67]	Th.	This study is conducted in two stages. Initially,a coupled flamelet /radiation approach along with two distinct turbulence models are employed to investigate the well-known SM1 flame of Sydney swirl burner. The k-u-SST and modified k-ε turbulence models are used to close the Reynolds stresses.	Comparison with experimental data revealed that both models provide reasonable results for the flow field, mixture fraction, temperature and carbon monoxide mass fraction. Nonetheless, the accuracy of predicted fields is better for the modified k-ε model in comparison with the other model. In the second part, the modified k-ε model is utilized for investigating the structure and combustion characteristics of blended CH_4-H_2 flames under distinct swirl numbers.	The hydrogen molar concentration is enhanced from 10% to 70%. By this enhancement, the non-dimensional flame length gets reduced about 40% for S_g = 0.3 flames which is the highest length decrease. Flames with S_g = 0.3 did not exhibit a secondary recirculation zone which was present in other swirl intensities. A radially converged tail at far-field is observed within S_g = 0.3 whilst others revealed an hourglass shape withopen tail at higher swirl intensities.

CHAPTER THREE

Specifications of LPG & Swirl Combustion

3.1. Introduction

Liquefied petroleum gas (LPG) is a hydrocarbon gas fuel that extracted from crude oil or natural gas. In the ambient temperature, LPG exists as gases but with applied moderate pressure, it is liquefied, therefore, it's called liquefied petroleum gas. LPG is a mixtures of petroleum gases mainly butane and propane. The mixtures ratio is differ in countries around the world that having LPG [100].

In Iraq, the commercial LPG might contain hydrocarbons mixture of propane, propylene, butane (normal-butane or iso-butane) and butylenes (including isomers) (Iraq Standard (IS) 830, 2003) [100].

3.2. Properties of LPG

This gas consisted of 0.8% ethane, 18.37% iso-butane, propane, 48.7%, and 32.45% N. Butane. The NG used in this research was produced by The North Gas Company, Iraq. The used NG consisted of: 84.23% methane, ethane 13.21%, 2.15% propane, isobutane 0.15%, 0.17% n. Butane, 0.03 Bentane. The Iraqi conventional gasoline which was produced from Al-Doura Refinery was used in this study. The Iraqi gasoline characterized by medium octane number (85 in the recent study), high lead and sulfur content (about 500 ppm) [101]. The fuels specifications were checked in their production sources. Table 3.1 lists the used fuels specifications and Table 3.2 showed General properties of commercial propane[102]. The ratio of the LPG mixtures depends on the LPG production in each country. Other country may refer LPG as propane for commercial purpose. Commercial LPG is a mixture of LPG products; with the primary component being propane at 70:30 with the other major component – butane (according to Petronas specification in Iraq at 2011). Ethyl mercaptan is added as an odourant to odourless LPG to detect it in case of leakage. LPG is a non-toxic, colorless and clean burning gas fuel that easily found available in the market. LPG has made the fuel for stoves in the restaurant, the fuel for heater and cooking appliances at homes, also used as a fuel in the transportations. LPG is a liquid under pressure but a gas at ambient conditions. Commercial LPG distributed to the customer in form of liquid. The ratio of LPG in liquid to gas phase is 1:270. Therefore, for the handler safety and easiness, the LPG liquefied at moderate temperature and stored in LPG storage tanks. LPG stored in liquid state, and used at the gaseous phase. To change LPG in liquid state into the gas state, the vaporizer needs to be installed. LPG is easily liquefied product (National Institute of Standards and Technology, 2010)[102].

Table 3 1. Fuel characteristics at pressure 1 atm and temperature 25°c properties[102]

Properties	unit	LPG	Gasoline
Density	Kg/m^3	505/1.85	730
Flammability limits	-	4.1-74.5	1.4-7.6
Auto ignition temperature for air	°C	588	550
LCV	KJ/Kg	42790	44790
Octane number	-	105+	86-92
Flame velocity	m/s	0.48	0.37-0.43
The adiabatic temperature of the flame	K	2263	2580
Quenching distance	(mm)	-	2
Fuel/air mass ratio	-	0.064	0.068
Heat of combustion	MJ/kg air	1.8-8.5	1.4-7.6
Flammability limits	Ø	3	2.83

Table 3. 2. General properties of commercial propane [102]

Properties	Value
Formula	C_3H_8
Boiling Point at 14.7 psia	-42°C -44°F
Freezing Point, at Atmospheric Pressure	-187.8°C -310°F
Specific Gravity of Liquid at 60°F	0.51
Specific Gravity of Vapour at 60°F (Air=1)	1.52
Mass per US Gallon of Liquid at 60°F (15.5°C)	4.20 lb
Mass per Imperial Gallon of Liquid at 60°F (15.5°C)	5.1 lb

3.3. LPG Supply Concept

LPG supplied to the consumers in two ways, piped gas system or from the actual storage of gas cylinders is used. LPG is stored using two methods, which are the manifold system and the bulk tank system (Gas Iraq, 2011)[100]. LPG storage tanks locate in isolated area from the building. There were also some instalments inside the building with certain mandatory requirement. The internal piping of LPG connected to the meter before used in the buildings appliances[100].

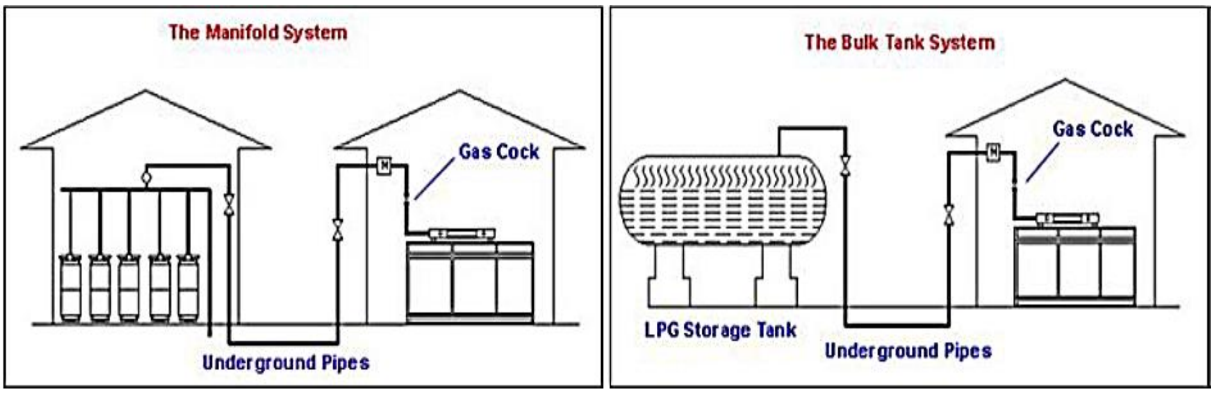


Fig.3 1LPG Manifold and Bulk Tank System Source: Gas Iraq, 2011 [100]

3.4. LPG Gas Cylinder

It is a cylinder of steel weights 13.5kgs and capacity 26.2 L provided with a regulator to control the quantity and pressure of the gas flowing. Table (3.3) below shows, the Characteristics of the cylinder is for the Iraq market[103].

Table 3 .3 Specifications of the cylinder in the Iraqi market [103]

Cylinder capacity of LPG	**26.5L**
The total height of the cylinder	**585mm**
Handle the diameter of the cylinder	**220mm**
Handle the height of the cylinder	**145mm**
Body the diameter of the cylinder	**300mm**
High body cylinder	**470mm**
The ring of the foot	**305mm X 63mm**
The thickness of the wall	**≥2.75mm**
Weight is empty	**13.5kg**
Working Pressure	**18 Bar**
Test Pressure	**34Bar**

3.5. Calculation of chemical formula for fuel

Knowledge of the chemical formula of the fuel used in the experiment is necessary to find the equivalence ratio according to mathematical relationships that will be explained later. The general chemical formula for any fuel is CnHm, where n and m are the numbers of carbon atoms and hydrogen atoms in the fuel respectively. Liquefied petroleum gas (LPG) does not have a constant chemical formula, so to find an approach formula it was taken the average percentages for the summation of the components as described in the following mathematical formula:

$$C_T = \Sigma X_i C_{ni} \quad (3.1)$$

Where:

C_T : The total number of carbon atoms

C_{ni} : Number of carbon atoms for each component

$$H_T = \Sigma X_i H_{ni} \quad (3.2)$$

Where: H_T The total number of hydrogen atoms, H_{ni} : Number of hydrogen atoms for each component and C_TH_T: The average chemical formula. The percentages of each ingredient for Iraqi light LPG have been. Using equation (3.2) and according to the rate of each gas, which is set in table (3.4), the average chemical formula will be $C_{3.624}$ $H_{9.248}$. The percentage of LPG fuel components has been adopted by laboratory tests conducted in The Gas Company of Al- Daura, Iraq. Gasoline used in the experimental analysis can be considered nearly ISO-Octane C_8H_{18}.

Table 3. 4 The composition of LPG fuel [103]

Composition	Vol.%	Gas constant (kJ/kg·K)
n-Butane	62.3	0.1432
Propane	36.3	0.1888
Ethane	0.9	0.2767
n-Pentane	0.5	0.1152

The ratio between the amount of air that can enter under ideal atmospheric conditions and the amount of air that is actually provided to the system is called volumetric efficiency.

$$\eta_v = \frac{\dot{m}_{aa}}{\dot{m}_{ath}} \times 100\% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.3)$$

Actual air mass flow rate can be determined using hand-Anemometers for given air velocity.

$$Q_{AIR} = V_{AIR} * A_{AIR} \quad m^3/sec \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.4)$$

$$\dot{m}_{AIR} = Q_{AIR} * \rho_{AIR} \quad Kg/sec \ldots\ldots\ldots\ldots\ldots\ldots (3.5)$$

Where V is air velocity measured using hand-Anemometers for specific air velocity, and $\dot{m}_{AIR}$ is the mass flow rate of air. The density of LPG fuel can be determined from the following relation [104].

$$\rho_{LPG} = (P/(R\,T)\ )_{LPG} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3.6)$$

The mass flow rate of LPG fuel is determined as follow:

$$\dot{m}_{LPG} = (\rho \times Q)_{LPG} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.7)$$

The gas constant for LPG fuel is calculated as follow:

$$R_{LPG} = \sum x_i\, R_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.8)$$

To determine the volume flow rate of LPG fuel, the molar mass is calculated from the relation:

$$Mm_{LPG} = \sum x_i\, Mm_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.9)$$

Introduction

In this chapter, the fundementals of swirl combustion will be introduced to clearfy the theoritical bases of the work. The swirl flow as used in combustion to generate swirl flame. As introduced in previous chapters, the swirl flame has more complete combustion, hence providing high power due the suficient residual time of the reactant in combustion zone. However, swirl flow has some stability issues as drawback. Blowoff and flashback are main stability issue of swirl flow. The strength of the swirl (swirl number) play a siginificant role in stability. The caculation of swirl number depends on the way of swirl generating. Swirl Flow flows are often generated by the following three routes[99-101].

1. Incidental entry (axial vortex generator)**,**

2. Rotating rotors (axial rotating rotors with flat or twisted blades),

3. Direct rotation (rotating tube).

3.6. Swirl Number

It is common to regulate and control moving flames through a variety of whirlpools. Any modification in its value has an effect on the dynamics of the flame [107][14]. The diversity of the vortex is often determined because the relation of the axial flow volume to the lateral momentum net the axial flux of the axial momentum multiplidby the radius of the equivalent nozzle [106] .

$$S = \frac{Axial\ flux\ of\ tangential\ momentum}{Axial\ flux\ of\ momentum\ X\ Exit\ radius} = \frac{G_\theta}{G_x R_o} \dots\dots\dots\dots (3.10)$$

Where:

$$G_\theta = \int_0^R (\rho uw + \rho \grave{u}\grave{w}) r^2 dr \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3.11)$$

$$G_x = \int_0^R (\rho u^2 + \rho \acute{u}^2 + (p - p_\infty r^2) dr \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.12)$$

u : axial velocity [m/s]

u' : fluctuating axial velocity [m/s]

w : tangential velocity [m/s]

w' : fluctuating tangential velocity [m/s]

ρ : density [kg/m^3]

r : Radius [m]

R_o : nozzle exit radius

However, setting the spiral set by using the equation above looks difficult as a result of it needs analysis of all rate and pressure profiles in different conditions. Which can provide a different spiral range for each object within the flow domain [108][5] .

Thus, [109] and [110] to ignore differences in pressure through flow (thermal conditions), you are likely to manage a swirl range from the pure geometry of a swirl burner as follows:

$$S_g = \frac{R_o \pi R_{eff}}{A_t} [\frac{Tangential\ flow\ rate}{Total\ flow\ rate}]^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.13)$$

Where:

R_o : the exit radius [m]

R_{eff} : the radius at which the tangential inlets are attached with respect to the central axis of the burner [m]

A_t : the total cross surface of the tangential inlets [m^2]

For tangential swirl burner

Tangential flow rate = Total flow rate

$$S_g = \frac{R_0 \pi R_{eff}}{A_t} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3.14)$$

However, the range of the above spiral of the equation has some disadvantages because it supports the ideal assumptions of good mixing between coaxial flows. Furthermore, the vortex can experience a major deterioration in the direction of swirl generation, because combustion conditions cause a thermal increase that leads to a significant increase in the axial rate. Therefore the combustion swirl numbers will be calculated according to the standard expected [109],

$$S_{g,comb} = S_{g,iso} \frac{T_{inlet}}{T_{outlet}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3.15)$$

Where:

$S_{g, comb}$ = the combustion swirl number [-]

$S_{g, iso}$ = swirl number at isothermal conditions [-]

T_{inlet} = the inlet temperature of the fluid [K]

T_{outlet} = the outlet temperature of the fluid [K]

Although there are difficulties in determining the number of vortices during combustion, some studies have used Doppler Laser Speedometer (Velocimetry) to measure speed field and velocity profiles to estimate the actual number of vortices [14][111]. It is clear that the number of calculated swirls was less than the estimated number of standard calculations based on the engineering parameters. The empirical analysis of vortex numbers changes to many vital determinants of heat release fluctuations and, as a result, there is much proper identification and instability of combustion dynamics[102].

Vortex numbers calculated by equation (3.6) can be difficult to flow the axial of the tangential momentum and axial flow of the axial momentum using Reynold-Navier-Stoke equations under the assumptions of the boundary layer. However, this technique is restricted in applications with weak vortex flow [112] . Vortex generating efficiency is a key feature that characterizes the performance of a combustion spiral, a performance from a spiral group. This is determined because the relationship between the size of the mechanical flow of energy by the flow of circulation through the throat reduces the static pressure energy between the air entrances and the burner of the burner. So it differs on the composition of spiral or pure geometry. The axial vortex generator are reduced to about 40% at S = 1, while their value is about 70-80% for the radial flow guide systems [105].

Swirl range is that the crucial issue for the onset of the vortex breakdown and thus the dimensions and form of the CRZ. Syred [109], Chigier [105] expliciting that the desired swirl range for the onset of the (CRZ) is $S<0.6$. Different studies [113][114] found that it's attainable to get (CRZ) even at low swirl numbers. However, the swirl degrees will be classified as follow[106]:

1- Extremely weak spiral ($S\leq 0.2$) In this case, the force of the vortex and the related velocities lead to rapid decay, so the number of pressure gradients produced by the pressure is not sufficient to generate axial reorientation.

2- Weak swirl ($S\leq 0.4$) up to the present swirl range the axial speed profiles area unit in Gaussian type, and also the most speed values area unit on the jet axis. However, these most values area unit displaced from the jet axis with swirl range larger than 0.5 with formation of the recirculation zone [105].

3- Strong swirl ($S\geq 0.6$) at this swirl variety the radial and axial pressure gradient reach higher values, and as a consequence the flow cannot be overcomed by fluid mechanical energy, allow the formation of the recirculation zone.

However, deciding the minimum swirl range or thus known as (Scr) that is needed for the formation of the vortex breakdown and therefore the swirl structures and set it as a universal worth for all whirling flows, looks to be a troublesome task. as a result of it depends on the actual flow options, that are completely different for all burner geometries [115]. So can calculate the equivalence ratio is:

$$\Phi = \frac{FAR_{act}}{FAR_{stoich}} \quad \text{(3.16)}$$

Equivalence ratio refers to the state of combustion whereas,

When ($\Phi = 1$) ideal state will be satisfied

($\Phi < 1$) Lean mixture conditions

($\Phi > 1$) Rich mixture conditions

Table 3.5 lists the used fuels specifications. However, some works use air access ratio ($\lambda = 1/\Phi$) to refer to the combustion status. Aerodynamically, moving flows yield each a vortex and axial-tangential movement at the same time. Moreover, recirculation phenomena in any swirl combustor are sophisticated because of their three-dimensional and time-dependent nature. So, the formation of the CRZ is ruled by several factors like swirl strength, burner configuration, equivalence ratio, flow field characteristics at the exit plane[116]. Moving flow may also result in the formation of three-dimensional unsteady vortex structures. These structures rotate around the moving central axis touching the blending and after the combustion method [117].

Table 3. 5 Fuel properties at 25°C and 1 atm [102]

Property	Gasoline	LPG	NG
Density (kg/m^3)	730	1.85/505	0.72
Flammability limits (volume % in air)	1.4-7.6	4.1-74.5	4.3-15
Flammability limits (Ø)	0.7-4	0.7-1.7	0.4-1.6
Autoignition temperature in air (K)	550	588	723
Minimum ignition energy (mJ)	0.24		0.28
Flame velocity (m/s)	0.37-0.43	0.48	0.38
Adiabatic flame temperature (K)	2580	2263	2215
Quenching distance (mm)	2		2.1
Stoichiometric fuel/air mass ratio	0.068	0.064	0.069
Stoichiometric volume fraction (%)	2		9,48
Lower heating value (MJ/kg)	44.79	42.79	45.8
Heat of combustion (MJ/kg air)	2.83	3	2.9

Moreover, the study conjointly indicates that the behavior of swirl structures, particularly the PVC, becomes additional complicated combustion conditions. Within the case of combustion, the tactic of fuel entry, the confinement level, and also the equivalence ratio play roles within the incidence and characteristics of coherent structures. For instance, axial fuel injection system will play a very important role within the suppression of the PVC amplitude, whereas the high level of confinement of the combustion chamber will alter the form and size of the CRZ significantly. This impact of confinement on the swirl structures has been conjointly tested [108][109][106] .

3.7. Swirl Flow Structure

All swirl combustion tools are designed to differentiate quickly, safely and safely with reasonable operating limits. This means that the burner must have the flexibility to carry the torch when a range of equivalence ratios, completely different fuels and different environmental conditions (stationary gas turbines or aerospace applications). However, most industrial combustion has been subjected to some operational issues which will cause a significant deterioration in its performance and as a result the overall system strength. The combined operability of the vortex combustion measurements is as follows:

Measure the level of extinction of flame, as a result of the mechanism of explosion. [16]Linked the level of disturbance with the stress rate. They found that the pressure rate doubled with increasing disturbance, resulting in localized extinction zones on the flame surface. [17] Simultaneously noted that the proportions of the blast equation are directly affected by the extinction of the upstream flow.

Due to the recent trends resulting from the use, pre-blended combustion and different fuels are introducing a high hydrogen or hydrogen mixture as a substitute fuel significantly. The surface explosion and flame extinction limit the unit area that directly corresponds to the percentage of hydrogen content of a given fuel. Many studies have shown that the ratio at the time of the explosion will be diluted by increasing the hydrogen ratio. Performance in these conditions results in the operation of burners at low flame temperatures and therefore low NO_x emissions [113][118][16] .

However, in addition to the effect of pressure and temperature, fuel composition plays a critical role in determining the automatic delay time [19]. Gas is the right fuel for stationary gas turbines and has a moderately weak ignition behavior at low temperatures. However, this behavior may be significantly affected by the addition of a higher hydrocarbon mixture [119] . Recently, hydrogen has been proven to be a clean energy carrier, and can be added to methane or natural gas to boost some of the operational demand due to delay time, wide flammability limits, high energy density, and high flame velocity. However, the hydrogen addition greatly affects self-appointment mechanisms. At the top of the hydrogen concentration, much of the hydrogen chemistry dominates the ignition of the mixture, while the nonlinear relationship between the ignition delay index and the ratio of the parity ratio becomes more pronounced with an increase in the hydrogen ratio [120].

The critical velocity gradient g_c, in general, depends on equivalence ratio, fuel-oxidiser kinetics, static pressure, static temperature, wall temperature, the state of the boundary layer and the geometry. A flashback will turn up once the rate gradients at a distance from the wall, becomes less of flame speed. The criterion of crucial speed gradient for laminar poiseuille flow in tubes showed [121].

This modulation flow speed undergoes a periodic drop below the time average, and enormous scales of vortices are going to be generated. If the frequency is low enough, there will be upstream flame propagation[122] . Another reason behind instabilities is equivalence ratio perturbations that have on the spot result on a reaction, flame speed and indirectly on the flame space that in turns control the amount of heat release response [123][124] .Inlet velocity fluctuation is also considered as one of heat release fluctuations, found that heat unharness becomes nonlinear after a certain level of inlet velocity amplitude[125].

Swirling flows and their coherent structures, particularly the processing vortex core (PVC), additionally represent another supply of unsteadiness or fluctuation. The (PVC) will trigger the formation of radial eddies and alter patterns of lean and rich combustion that successively consolidate combustions oscillations [10]. The method of development of those fluctuations within the combustor is ruled by a feedback cycle wherever heat unleash rate fluctuations add energy to the acoustic field. Consequently there will be acoustic pressure and speed fluctuations propagating throughout the combustion chamber. These fluctuations successively trigger coherent structures and equivalence magnitude relation oscillations resulting in additional heat fluctuations closing to the feedback loop [126].

Vortices transport equations are used by [127][128][129] to analyse the supply terms of source elements of flow field. They argued that the baroclinic force produces a substantial quantity of negative axial rate within the vortex core that successively leads to the CIVB flashback. They conjointly correlate the development of stagnation of the recirculation zone with the result of fixing the equivalence ratio of the axial position. Supported their investigations the upstream flame place and also the stagnation purpose play the dominant role within the onset of the CIVB. If the recirculation zone will pass the stagnation purpose within the upstream direction, the degree of enlargement upstream of the recirculation zone generates positive angle vorticity consequently positive axial rate. Therefore stable flame prevents the prevalence of the CIVB. However, upon additional upstream flame propagation (additional increase of equivalence ratio) baroclinic force can be increased, therefore the high chance of CIVB prevalence will increase also.

Swirl flow characteristics and native equivalence ratios directly have an effect on the interaction at the burner mouth and therefore the governing conditions of the CIVB flashback. There are some studies have investigated the impact of swirl strength and mixing degree, the flashback mechanism is altered from physical phenomenon flashback BLF to CIVB flashback with increasing equivalence ratios at low swirl intensities[130]. [131] found that CIVB flashback happens at higher swirl numbers than that of physical phenomenon flashback BLF. The impact of geometrical problems on CIVB flashback has additionally been investigated, and plenty of studies regarding the impact of adjusting geometries on the sweetening of CIVB flashback resistance have additionally been enforced. Central bluff bodies or lances are wide utilized in swirl burners to avoid upstream flame propagation or CIVB flashback.

It is value mentioning here that though functioning at leaner conditions is vital for lean premixed combustion systems, movement of flashback curves to the leaner region for the case of tiny injectors results in a substantial reduction of stability map (the blowoff and flashback curves became on the brink of every other) therefore additional seemingly to subject to blowoff and flashback[132]. This slender operation space is not favorable concerning the swirl combustors safe operation, any small change in equivalence ratio or mass rate may lead to one of the instability cases.

CHAPTER FOUR

Experimental Work

EXPERIMENTAL WORK

4.1. Introduction

The experimental rig in this work is a diesel burner used for domestic or commercial applications, and produces a capacity ranging from 12-14 kWh as shown in Figure 4.1 and Figure 4.2.An economic comparison was made when using LPG as fuel instead of diesel while maintaining the original design and dimensions.

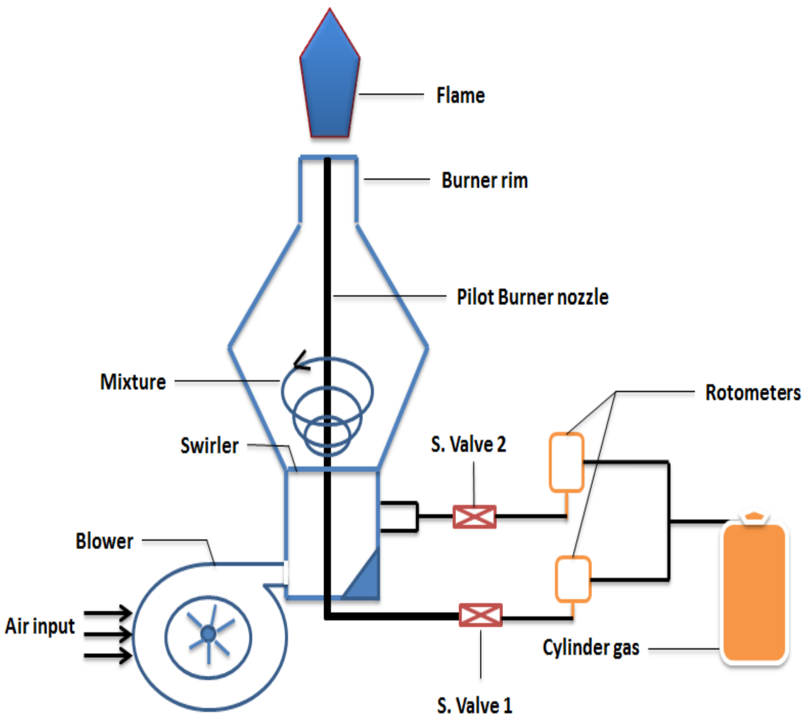


Fig.4. 1 Experimental rig sketch

All tests were conducted at the College of Technical Engineering in Najaf, AL-Furat AL-Awsat Technical University Najaf - Iraq. The main parts of the system are (small blower, cylindrical burner have different cross section areas, swirler vane guide , secondary fuel system work as bluff body and bank of rotometers and electrical control system) , which will be discussed in detail below.

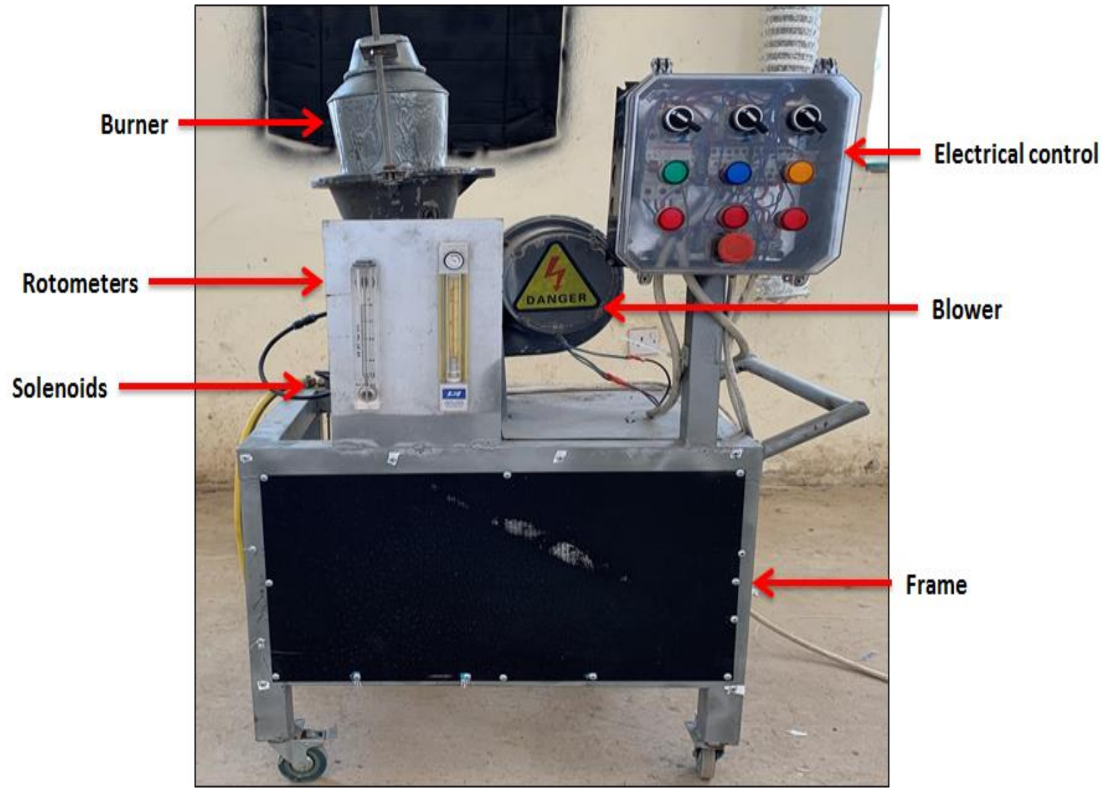


Fig.4. 2 Photograph experimental system

4.2. Blower

It is a small centerfuegal air blower that supplies the air to the combustion system at a flow rate ranging from 9.5 – 11 m^3/min. The delivered amount of air is controlled in two ways: first by a sliding gate fixed on the side of the blower on suction opening, which is marked to read the amount of air handled to the combustion system. Second using speed regulator (variac) to control the speed of the blower fan which enable the amount of air delivered to the system. This fan is connected to the body of the burner at the bottom by a rectangular opening with dimensions (8*7) cm as shown in Fig (4.3a and 4.3b). This blower is powered by a three-phase electric motor controlled by a switch on the control panel.

(a)

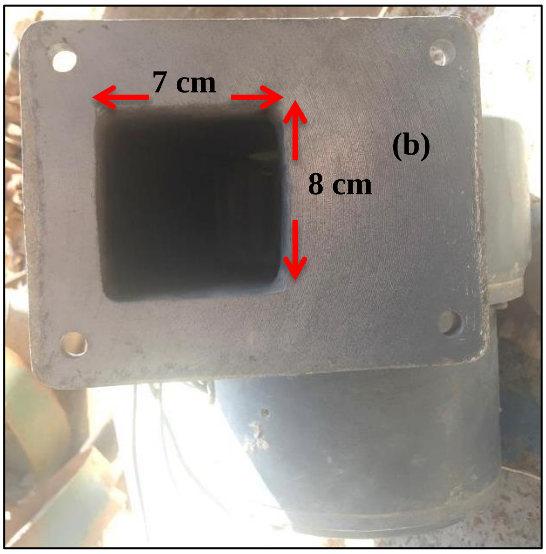


Fig.4. 3 (a) Blower (b) Air deliver opening

4.3. Burner

It is a cylindrical part with variable diameters can be divided into four regions:

4.3.1. First part (bottom)

It is a cylinder height (20 cm) and diameter (13 cm) connected from one side to the air emulator by a rectangular window with a distance (8 * 7) cm. The bottom of this part is closed with thin metal disc have 4 force adjustable bolts. The adjustable bolts are used as a last safety procedure where the bolts will lose with high pressure in case of flashback. In this section a small metal ramp placed in front of the window that changes the direction of air from the direction of the tangent to the vertical direction to avoid high recession. In the opposite direction of the drive and thus increase the reverse pressure on the drive, which reduces the flow rate . As shown in figure 4.4 the top of this part, a swirler vane guide is fitted to generate a swirl flow.

Fig.4. 4 The bottom part

4.3.2. Second part

It is a divergent cylindrical section extending above the bottom part and the lower part of it has a diameter (13 cm) and connected with the first part. As shown in figure 4.5The upper part is the diameter (16 cm) which is connected to the third section. In this section, the flow suffers from slowing due to increased flow area, which raises the pressure and increase the mixing between air and fuel.

Fig.4. 5 The second part

4.3.3. Third part

It is a convergence cylindrical section connected to the second part with a diameter (16 cm) and connect with rim burner with diameter (10 cm). As shown in figure 4.6 this section increases the flow speed while ensuring the continuation of the vortex to enter the last section of the burner nozzle.

Fig.4. 6 The third part

4.3.4. The burner nozzle

It is a cylindrical section of 5 cm diameter and the height is changed according to the model used. As shown in figure 4.7 the model (a) is 5 cm long, the second model is 10cm, the third model is 15cm and the ratio of l / d is 1, 2 and 3 respectively

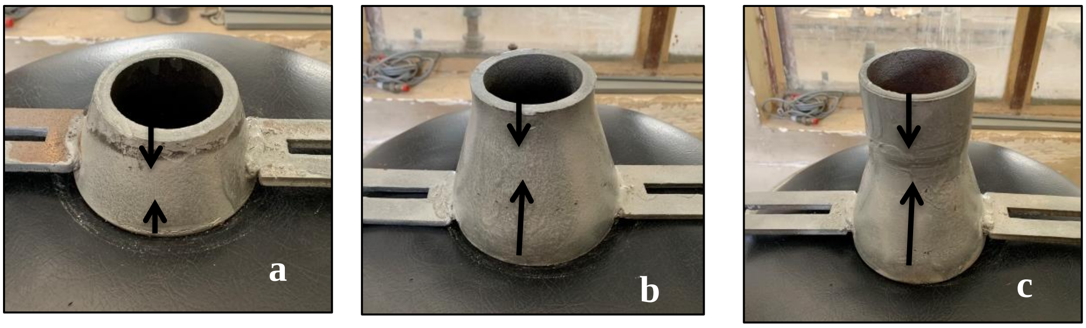


Fig.4. 7 Rim burner section

4.4. Swirler Vane Guide

To obtain swirl flow in diffusion or jet flow system a swirler vane guide is used. The swirler vane guide is a circular disc with a radial slot; these slots are inclined with the incoming flow in different angles. The number and angle of the swirler vane control how strength is. The vane guide used in this work has 16 slots and 30^0. The vortex is placed above the section where the bellows opening is located. As shown in Fig. 4-8, the vortex works to mix the air from the blower with the fuel from the fuel line and deliver the mixture to the next part, where the section is spaced to increase the pressure and reduce the flow velocity and give the mixing process time to completely complete.

Fig.4. 8 Swirler vane guide

4.5. Bluff Body

It is a sold object that is located in the central of the burner in swirl system. The bluff body used to stabilize the combustion. However, the bluff body has drawback represented by increase the law velocity region near walls, which is preferred to flame for boundary layer flashback. In some cases like this study the bluff body is used as pilot burner, where the flame or combustion is started and when the combustion maintained well the flow is turned off, or in some studies the bluff body is used to blow air to bush the flame bubble downstream and prevent the system from goes to CIVB flashback. However, in this study the bluff body is a pipe with a diameter of 0.62 cm and a lengths are (58, 63, and 68) cm of carbon steel penetrate the base of the burner and goes centrally and ends flashed with burner rim as shown in figure 4.9.

Fig.4. 9 Bluff body

4.6. Rotometers

Is a measuring instrument used to measure the flow rates of fuel equipped to the system to control the amount of fuel burned through a closed tube by allowing the fuel cross sectional area as the flow of fuel floating in a tapered tube, the higher the flow rates increased the area of the tube Pendulum rose to give reading the quantity supplied. For the burner, it is important to note the buoyancy position because it depends on the principle of gravity, so it is necessary to turn the device vertically (directed vertically) as shown in figure 4.10 .

Fig.4. 10 Rotometers

4.7. Electrical Control System

The system is composed of input and output processes in the form of electrical signals, where electrical switches and time intervals were used to open and close the electrical solenoid valve for fuel processing, as well as to operate the system fan. The rig is equipped with an Emergency shutdown push button in the event of any problem in the system which is extinguished completely from the source of electricity as shown in figure 4.11.

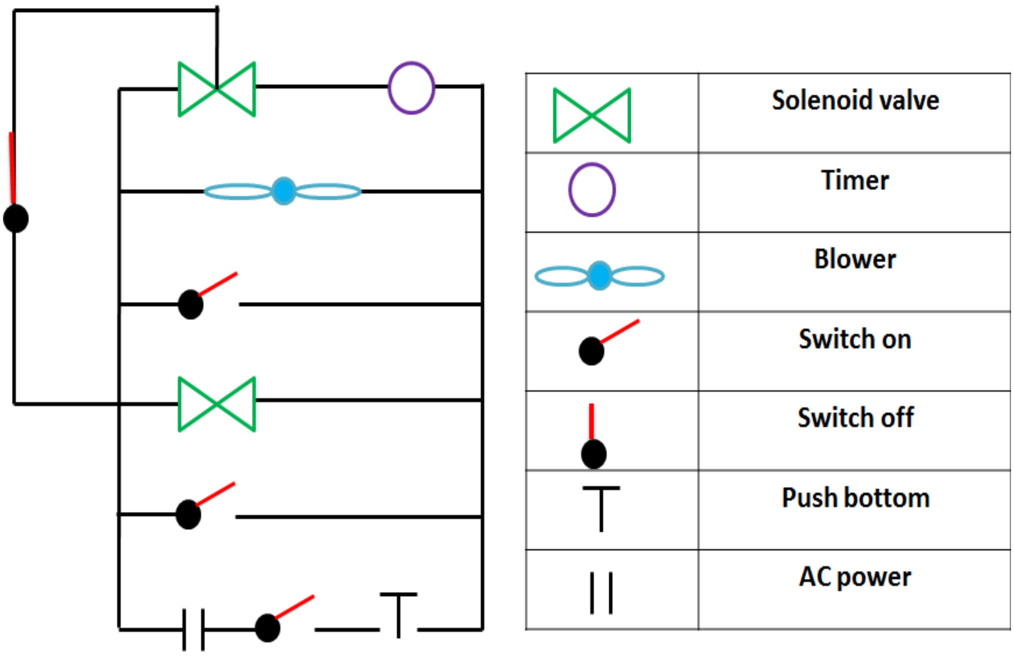


Fig.4. 11Electrical control Circle

4.8. Experiment Procedure

In the beginning of each experiment, the blower is started for 5 seconds to wash away any fuel accumulated or left in burner. Next, the blower is shut down and LPG fuel (liquefied petrol gas) is supplied to a pilot burner from the source through the first Solenoid valve. It is controlled by an electric switch installed in the electrical control panel to pass the fuel through a tube located in the central of the system or the body of the burner and end at the rim of the burner. The first ignition is done by using lighter, after the flame stable over the burner a mixture of air with the fuel (liquefied gas) to ensure a homogenous mixture exit through its button installed in the electrical control panel to operate the fan and the second solenoid and deliver air to burner and mixing it . Then the mixure passed through the swriler vane guide to spin the flow and generate a swirl flow, when the mixture leave the burner will ignite due the pilot flame. The burner ignite it with the primitive flame and end the role of the first work of the Solenoid (the first valve is switched off automatically). A separate swirl flame is generated from the rim of the burner that has a good stability and a blue color, due to the complete combustion due to homogeneous mixing. Finally, the flame is controlled by the amount of air and fuel fed to the system through the amount of air flow generated from the fan as well as the fuel flow rate through the fuel rotometer. Snapshots of the flame are taken using a high-speed camera to study flame behavior, stability, and separation from the rim of the burner. All previous steps were carried out for three different length of the burner neck 5 cm, 10 cm and 15 cm.

4.9. Instrumentation and measurement devices

4.9.1. Anemometer model DT-8894

Anemometer is a tool used to measure the speed or velocity of gases either in an isolated flow, such as airflow in a channel, or in non-confined flows, such as wind and the specification model in appendix A. To determine the wind speed, the anemometer detects the change in some physical characteristics . Where the device was placed in the flow to measure the speed of the air generated by the fan to determine the speed and take specific readings through the side hole of the fan according to specific gradations controlled by hand or by using a regulator (variac) that controls the current and voltages of the fan and take readings required as shown in figure 4.12.

Fig.4. 12 Anemometers

4.9.2. Infrared thermometer

Digital infrared thermometer gun with laser model (MASTECH-MS6520B) detects infrared connecting the object emitting degree; the instrument focuses the infrared energy of the component on the device through a lens, changes the surface temperature to an electrical signal, calculates and displays the activity temperature on LCD. With a range of (- 20- 500) °C and accuracy (1.5% +2) and emissivity is 0.95 as shown in figure 4.13.

Fig.4. 13 Infrared thermometer

4.9.3. Digital camera

It is a Sony Xperia Z-1 device with a special specification for taking very fast shots at 1000 frames per second. Where the camera was installed locally against the flame for the purpose of studying (the shape, height and diameter) of the flame generated from the burner, a flashback and blowoff.

The shot was taken of three models of the neck of the burner in the experimental test of this study, with different heights (5, 10 and 15) cm, respectively and the more details for camera showed in Appendix A.

CHAPTER FIVE

Result & Discussion

RESULTS & DISCUSSION

5.1. Introduction

In this chapter, review the most important results obtained from modulation the burner of a liquid fuel system (diesel) to a swirl burner using LPG as fuel and the effect of changing the neck length of the burner on the stability of the flame.

5.2. Effect of Fuel Type

The first objective of this study was to operate a commercial burner that uses liquid fuel (diesel) with alternative fuel (LPG). To achieve this goal, all parts of the original system, including fuel jet injector, have been maintained to serve as a bluff-body and a primary burner.

As described in the previous chapter, the burner capacity is 12.5 kWh and it was modified to burn LPG fuel. The burner was chosen to run over a wide range of the equivalent ratio of the equivalent ratio from the limits of the weak mixture at (Φ) 0.38 to an equivalence ratio 0.9, Where the values represent the operating window limits for this burner, at a mixing ratio below 0.38 separation the flame (blowoff) when increase the ratio more than 0.9 the flashback accrue.

from the economic point of view, the use of liquefied petroleum gas (LPG) led to an increase in the output heat energy of the burner to 120 kWh. The heat energy generated was calculated based on the maximum flow rate of the blower and an equivalence ratio of 0.9 as shown in the appendix (A).

The huge difference in heat capacity of the same geometry explained by recalling the fact that there is uncompleted combustion process. Especially, if the fuel in liquid phase as diesel in this case which drop down the efficiency of the burner. Using LPG and premixed it far away from combustion zone and deliver it as a fully premixed fuel will improve the combustion process. On the other hand, the swirling of the flow that be structured of the flow and the flame as a consequence. Such coherent will insure that the mixture will not be diluted by external fresh air and give the combustion process to consume the most of the mixture. Heat generated from such combustion be much more than generated when using diesel as a fuel.

5.3. Effect of Burner Geometry on Flame Structure

After conducting operating window experiments, setting limits for blow off and flashback, the effect of the length of the burner on the structure of the flame has been studied. As noted earlier, the mixture (air/fuel) comes out of the rim of the burner in a swirler form as a result of its passing through the vane guide, which leads to the acquisition of the fluid or mixture a strong, coherent structure that maintains the constant shape of the mixture when exiting burner rim and reduces the process of mixing with the outer region.

In practice, when combustion occurs, this ensures a greater period of time for the combustion process before interfering with the outer environment of the air, which increases the efficiency of the combustion process. This effect is clearly reflected by the blue color of flame, which shows signs of a near-complete combustion process.

From an aerodynamic point of view, the strength of the swirl structure depends on what is known as the swirl number (S), which represents the intensity of the tangential momentum to the intensity of the axial momentum, so the value of the swirl number is constant for the burner depending on swriler geometry as described by equation 3.10. However, the length of the burner neck will stimulate what is known as swirl decay, which is the amount of loss in momentum due to friction between the fluid and the walls of the burner.

This effect is reflected in the form of shrinking in the diameter of the flame as shown in Fig 5.1 that show stretch in lifted flame. To understand the effect of the neck length on the stretched flame the burner rim diameter as a basic quantity. In case of the 5cm neck, the flame diameter was around 1.75d (8.5cm), while it was around 7cm or 1.4d for the 10cm neck as shown in figure 5.2, with increase the neck length the flow turn to be diffusion like and the flame takes V shape and the flame diameter was around 6 cm as shown in figure 5.3.

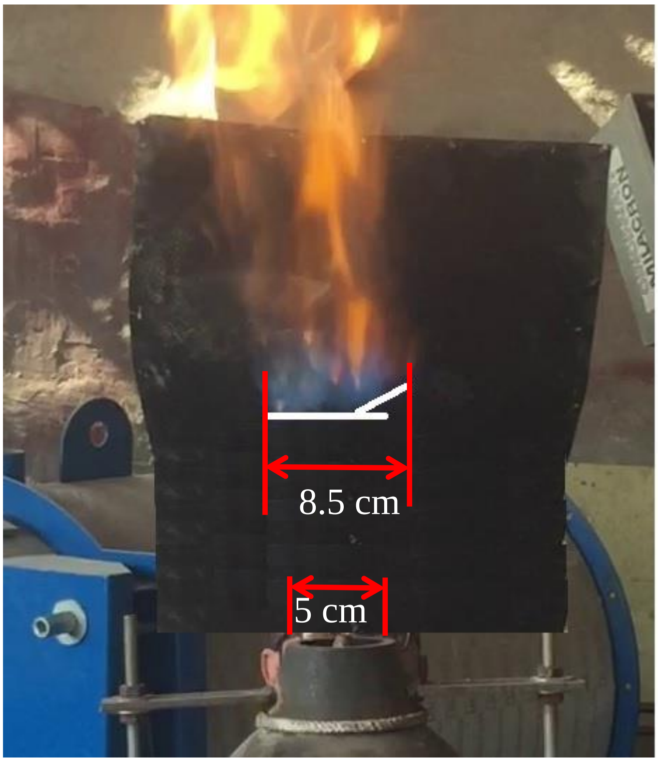


Fig.5. 1 flame stretch of (5cm) neck

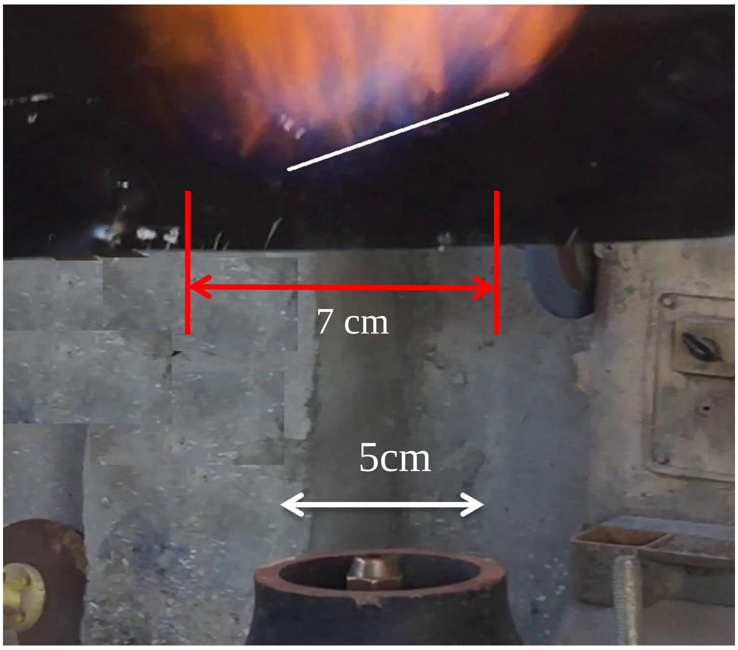


Fig.5. 2 flame stretch of (10cm) neck

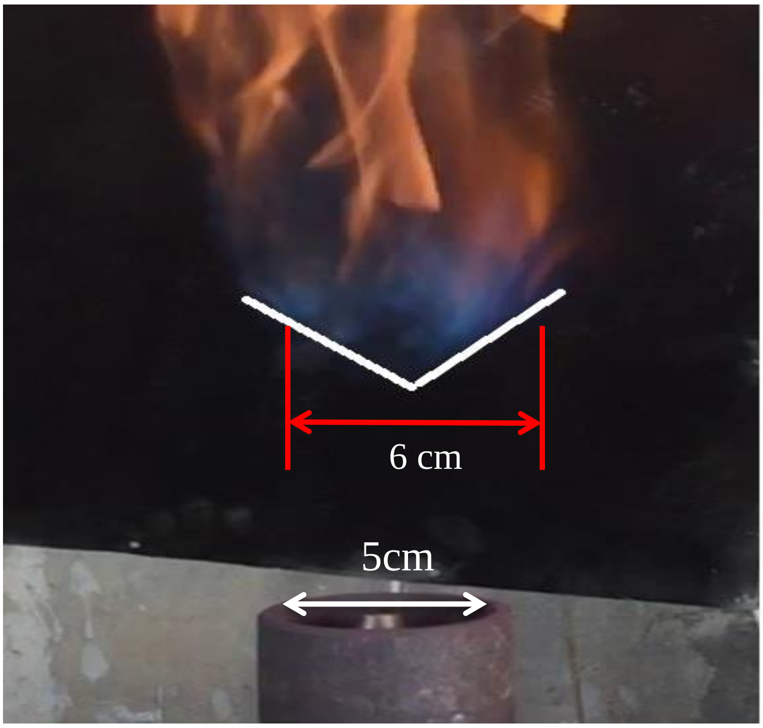


Fig.5. 3 flame stretch of (15cm) neck

This shrinking in diameter is due to the shifting flow from the swirl to the jet form, where the peripheral momentum that causes the flame-throwing state is reduced and is responsible for increasing the diameter of the flame base.

5.4. Effect of Neck Length on Flame Stagnation Point

Flame point of the stagnation is defined as the point at which the amount of the speed of the flame is equal to the speed of the coming fuel mixture in the opposite direction, so the point at which the velocity result is equal to zero represents the point of the stagnation of the flame.

Factors affecting the point of stagnation of the flame include:

* The equivalence ratio (Φ)

* swirl number (S).

* The type of fuel or mixture.

For the experiments conducted, the type of fuel and the equivalence ratio were preserved to study the effect is constant on how far the flame sits away from the edge of the burner or what is known as the point of the flame's stagnation.

Experiments have shown that increased neck length leads to the proximity of the stagnation point to the edge of the burner and as shown in Fig 5.4,5 and6.

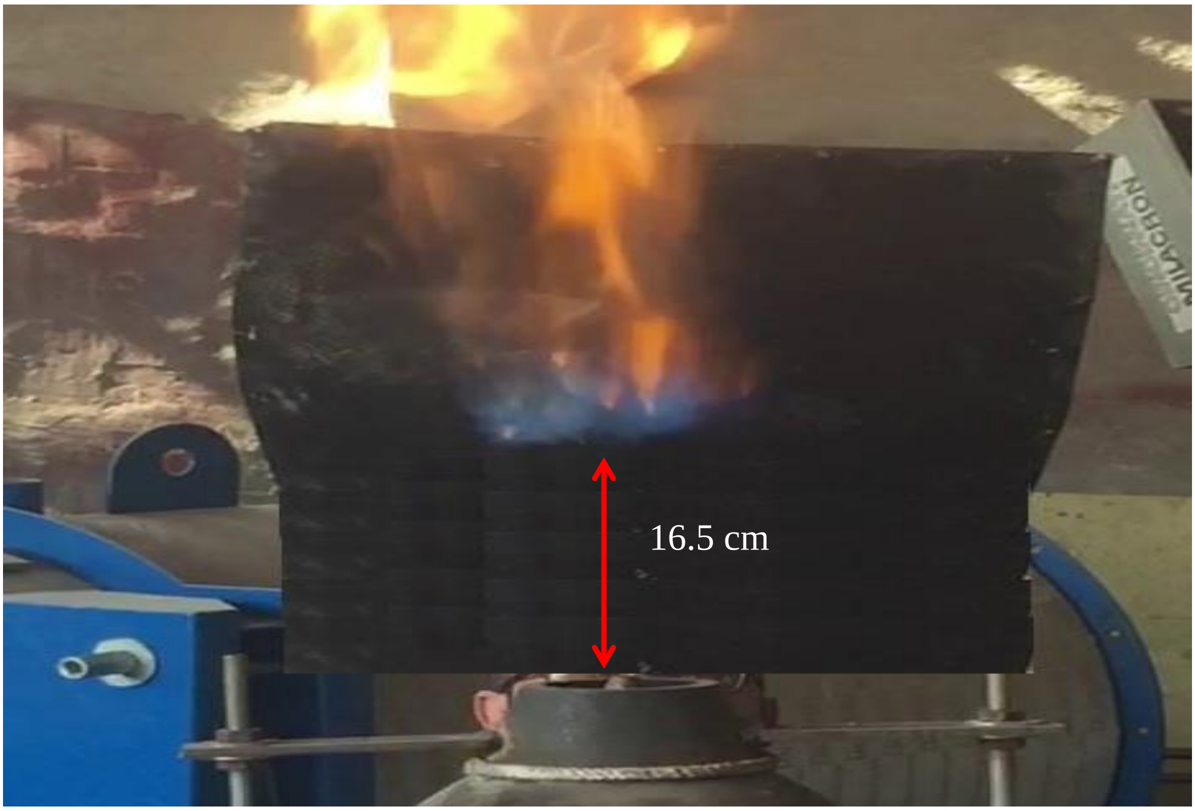


Fig.5. 4 Flame Stagnation point of (5cm) length neck

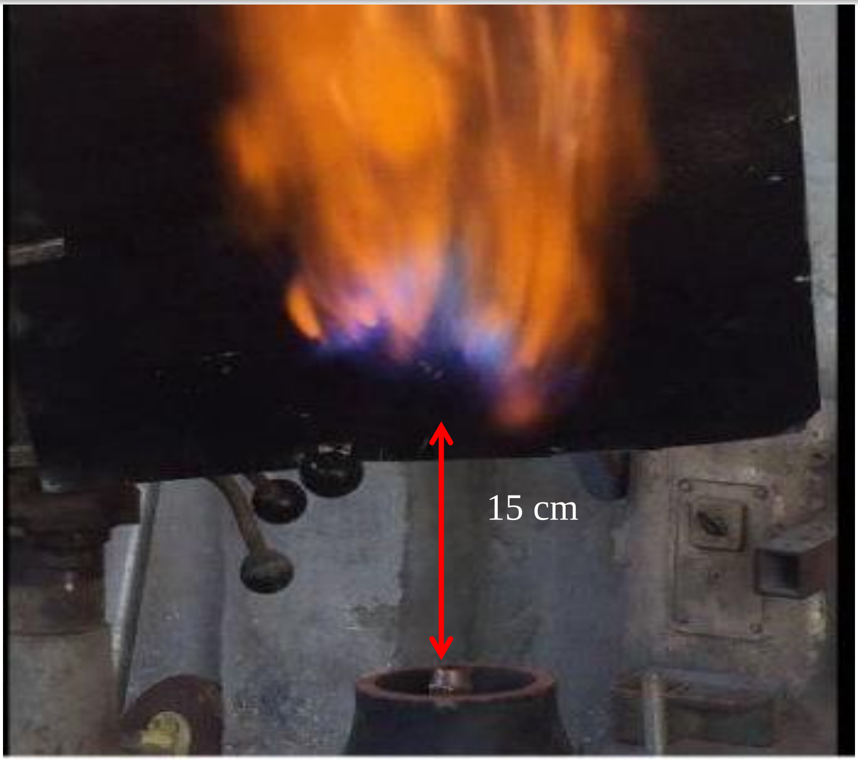


Fig.5. 5 Flame Stagnation point of (10cm) length neck .

Fig.5. 6 Flame Stagnation point of (15cm) length neck

The relationship between the length of the burner's neck and the distance of the flame's stagnation from the edge of the burner has been represented as shown in figure 5.7.Where (x) represented distance from base of the flame to edge of the burner while (D) is a diameter of the rim burner and (L) is length of the rim burner.

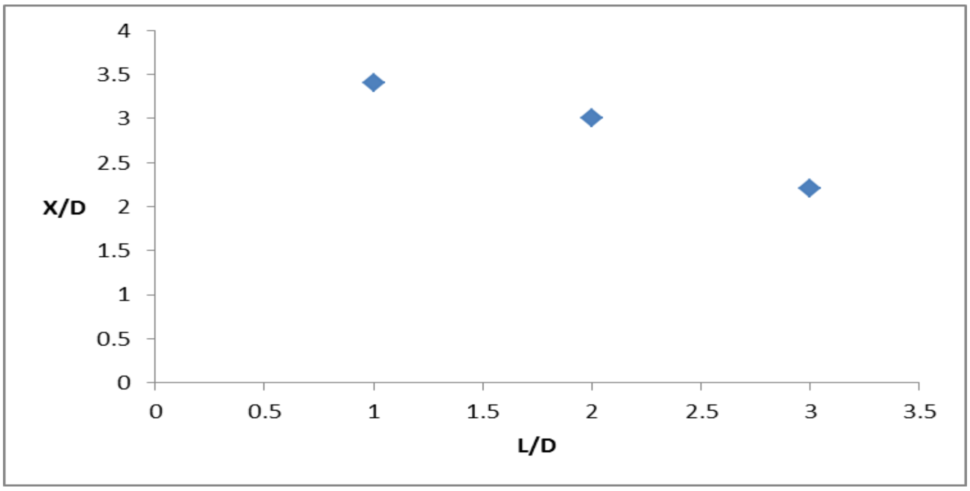


Fig.5. 7. Stagnation point of flame at different neck length

5.5. The Effect Length of Burner Neck on Operating Window

The efficiency of burners is measured by the stability provided by the incinerator at different operating conditions, for example in power plants the main criterion is the ability to maintain combustion stable when the demand for energy decreases, which leads to operates the burner within its maximum limits in both terms, poor and rich mixture status . When the burner is turned on within a low or no loads, the mixing rate of fuel is either very poor or very rich depending on the control system used at the station. In both cases, the range between the two should preferably be wide.

When the low mixing ratios (poor mixture) the flame tends to move away from burner rim and thus break off and extinguish what is known as the phenomenon of blow off. On the other hand, when the fuel or mixture is very rich in fuel, the flame tends to propagate upstream towards the fuel system which is known as flashback. Therefore, the burner, which has a wide range between the phenomenon of blow off and flashback, is preferable.

When examining the effect of the length of the burnt neck on the operating limits (operating window), it is noted that:

1) For the minimum (blow off) the effect of increasing the length of the neck of the burner leads to higher stability at an equal equivalence ratio. In other words, when installing the equivalent value, the burner with the longer neck showed higher stability than the other two models and to get the phenomenon of the blow off required an increase rate air flow in the mixture area thus getting a poorer mixture.
2) On the other hand, the increase in the length of the neck accelerates the occurrence of flashback phenomenon where the phenomenon of flashback occurred in a less equivalence ratio than it needs of the 5 cm burner as shown in table 5.1 below.

Table 5. -1 Varation length with velocity

		15cm		10cm		5cm	
		velocity (m/s)	Φ	velocity (m/s)	Φ	velocity (m/s)	Φ
Blowoff	1	2	0.4	2	0.39	2	0.38
	2	2.2	0.41	2.2	0.4	2.2	0.39
	3	2.4	0.41	2.4	0.41	2.4	0.39
	4	2.5	0.42	2.5	0.41	2.5	0.39
	5	2.6	0.41	2.6	0.4	2.6	0.4
	6	2.8	0.4	2.8	0.4	2.8	0.4
Flashback	1	2	0.82	2	0.8	2	0.78
	2	2.2	0.84	2.2	0.81	2.2	0.78
	3	2.4	0.85	2.4	0.82	2.4	0.8
	4	2.5	0.83	2.5	0.84	2.5	0.82
	5	2.6	-	2.6	-	2.6	0.81
	6	2.8	-	2.8	-	2.8	

5.6. Study of Operating Limits

As mentioned earlier, the basic measure of the success of any burning design in external combustion systems depends on the ability of the burner to operate under changing conditions in terms of temperature. Most designers aspire to find a burner capable of giving the greatest possible efficiency when using multiple types of fuel, which is more difficult because the stability of the burner is closely related to the type of fuel used, so the stability map of a single burner is very difficult to apply when using another type of fuel. In order to draw a stability map for any incinerator, it must be done according to the following steps, which is what has been followed in this research to find a map of the stability of the incendiary:

1) The burner is operated within an equivalence ratio ranged between 0.5 - 0.6. This ratio is considered to be secure for many of the designs currently used in incinerators when using non-hydrogen-boosted fuel[133]. When the flame stabilizes, we increase the percentage of fuel in the mixture while maintaining a steady amount of air in order to obtain a rich mixture, which stimulates the flame to move towards the nozzle of the burner and we continue to increase the ratio of fuel to where the flashback phenomenon occurs.
2) After the occurrence of the phenomenon of flashback and the entry of flame inside the burner and its stability at the border between the base of the neck and the body of the burner where many designers rely on setting a threshold for the purpose of installing the fire return and preventing it from attacking the source of fuel in the system except in case of excessive fuel rates in the mixture. Reduce the fuel to push the mixture towards the combustion zone, which leads to the lifting of the flame from inside the burning nozzle to the outside. By continuing to reduce the percentage of fuel the flame more and more pushed away from the nozzle of the burner until it reaches the state of

separation or fire (blow off). The equivalence ratio recorded at which the flashback and blow of phenomena occurred respectively.

3) Repeat the process above after increasing the air flow rate to a higher rate than before and recording the new flashback and blowoff points.
4) By repeating the process to more than one rate of air flow we get what is known as the stability map as shown in Figs (5.8-10) as showed in Appendix A.4.

Where the results for the operating window in Fig. 5.8 for the neck of the burner with a length of 5 cm indicate that the boundaries of the bluff regions (0.38 – 0.40), while the flashback areas (0.78 – 0.81), and that the limits of flame stability were between (0.38 – 0.81).

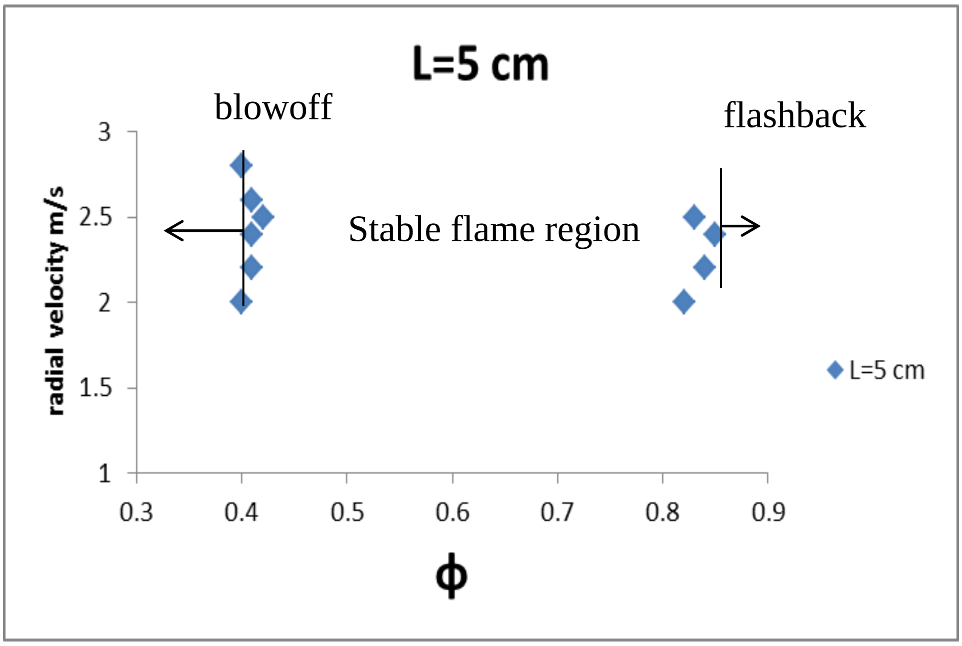


Fig.5. 8 Operation widow of the burner with 5 cm long neck

While the results for the operating window in Fig 5.9 for the neck of the burner with a length of 10 cm indicate that the boundaries of the bluffs regions (0.39 - 0.41) while the flashback occurrences (0.8 – 0.84), and the limits of flame stability It was between (0.39 – 0.84).

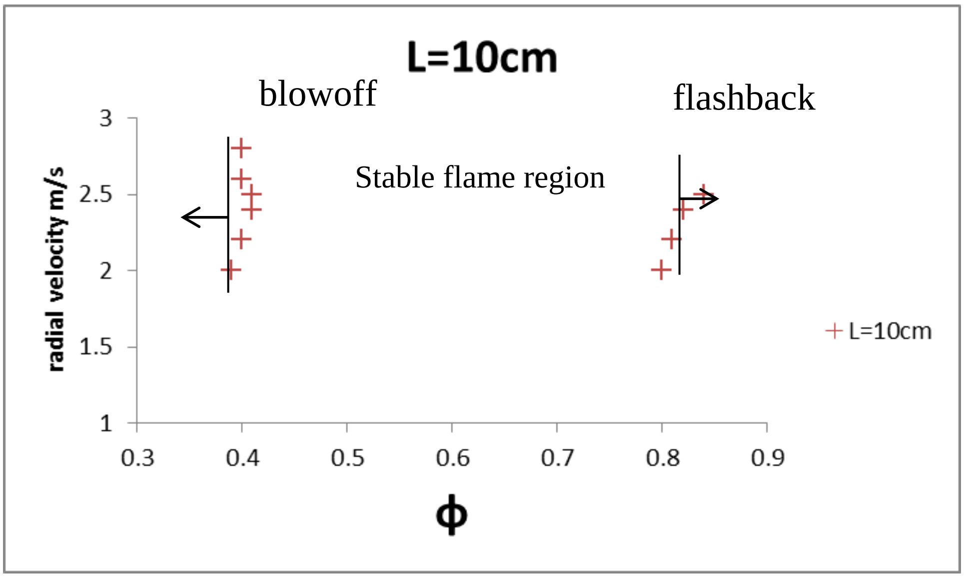


Fig.5. 9 Operation window of the burner with 10 cm long neck

Finally, for Fig.5.10 the results for the operating window for the neck of the burner with a length of 15 cm indicate that the boundaries of the bluffs regions (0.40 -0.42) while the flashback occurrences (0.82 – 0.85), and the limits of flame stability It was between (0.40 – 0.85).

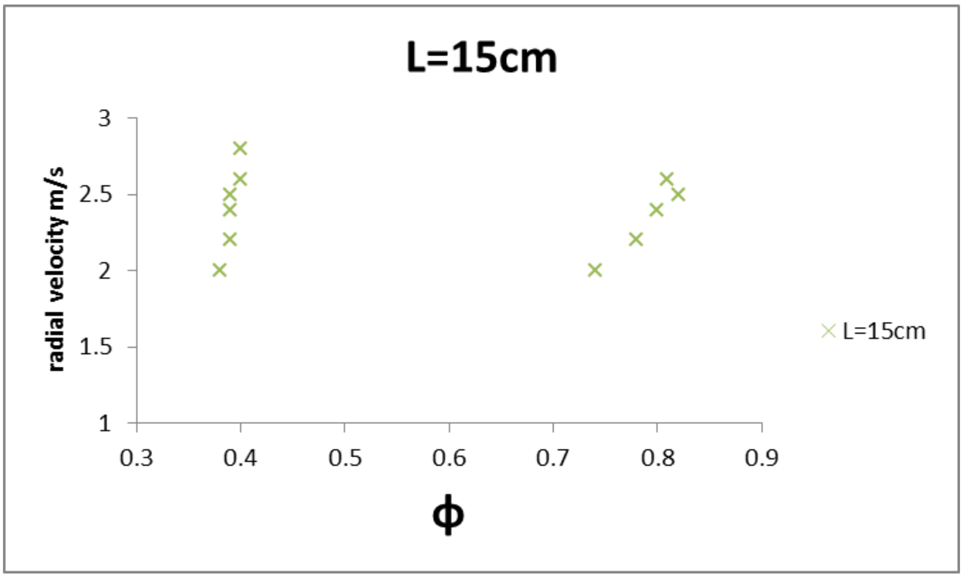


Fig.5. 10 Operation window of the burner with 15 cm long neck

The overall results of operation window for the three geometries is shown in figure 5.11.

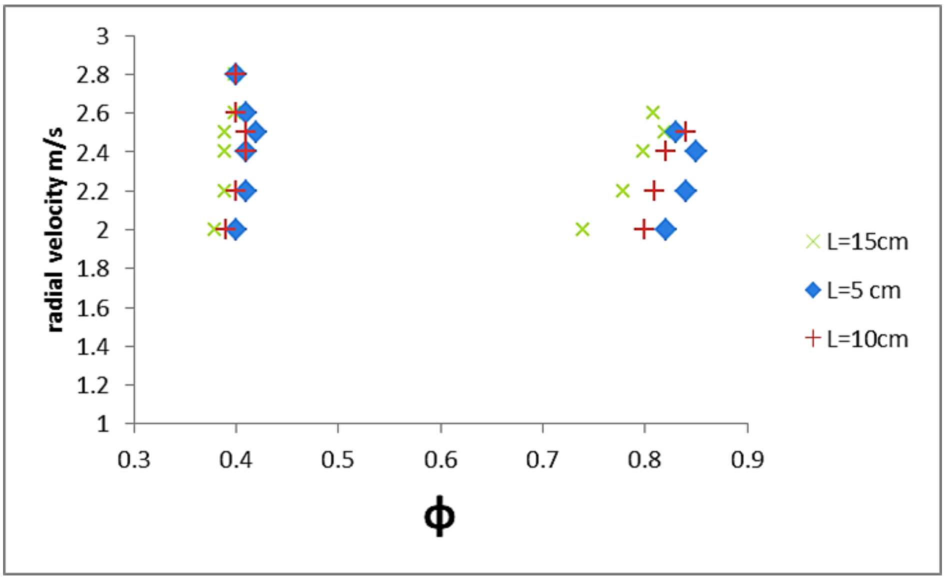


Fig.5. 11 Operation window for all cases

CHAPTER FOUR

Conclusions

&

Recommendations

CONCLUSIONS & RECOMMENDATIONS

6.1. Conclusions

The main conclusions that could be concluded from this work are :

1) The possibility of modifying any external combustion system (burner) powered by diesel fuel to use liquefied gas fuel (LPG), and without any distortion of the system while maintaining the basic parts of the system and thus not affecting the overall design of the system.
2) From the aerodynamic point of view, it is concluded that the strength of the vortex will decrease with increasing length due the friction with burner inner walls. As a consequence, the swirl flow will turn to jet or diffusion like flow.
3) Through practical experiments, it was shown that increase length of the burner's neck leads to move the stagnation point towards the edge of the burner where it was graphically represented.
4) Increasing the length of the neck of the burner leads to higher stability in term of the equivalent ratio. At constant equivalence value, long neck burner showed higher stability than the other two models . Therefore, in low load or no load the long neck is preferable.
5) Increasing the length of the burner neck has precipitated the flashback phenomenon.

6.2. Recommendations (future work)

The results of this study open up new horizons of flame stability techniques and thus obtain more stability and more work space, and therefore cannot be covered by this study and should be taken into account.

6) Studying the effect of the use of confinement in the combustion area on the stability of the flame and the operating window.
7) Studying the amount of emissions with a change in the length and shape of the burner neck.
8) Studying the effect of changing the shape of the burner neck from the cylindrical to other forms such as slot (rectangular), square, triangular or oval on the amount of the operating window.

REFERENCES

[1] J. A. Denev *et al.*, "Burner design for an industrial furnace for thermal post-combustion," *Energy Procedia*, vol. 120, pp. 484–491, 2017.

[2] A. Leiserowitz, "international public opinion, perception, and understanding of global climate change," 2003.

[3] J. T. Yang, C. C. Chang, K. L. Pan, Y. P. Kang, and Y. P. Lee, "Thermal analysis and PLIF imaging of reacting flow behind a disc stabilizer with a central fuel jet," *Combust. Sci. Technol.*, vol. 174, no. 3, pp. 71–92, 2002.

[4] A. S. Alsaegh, F. Amer Hatem, and A. Valera-Medina, "Visualisation of Turbulent Flows in a Swirl Burner under the effects of Axial Air Jets," *Energy Procedia*, vol. 142, pp. 1680–1685, 2017.

[5] M. Al-Hashimi, "Flashback and Blowoff Characteristics of Gas Turbine Swirl Combustor," 2011.

[6] F. Catapano, S. Di Iorio, A. Magno, P. Sementa, and B. M. Vaglieco, "A comprehensive analysis of the effect of ethanol, methane and methane-hydrogen blend on the combustion process in a PFI (port fuel injection) engine," *Energy*, vol. 88, pp. 101–110, 2015.

[7] M. Lo Faro, V. Antonucci, P. L. Antonucci, and A. S. Aricó, "Fuel flexibility: A key challenge for SOFC technology," *Fuel*, vol. 102, pp. 554–559, 2012.

[8] "EPA. (2015). Overview of Greenhouse Gases. Available: http://www.epa.gov/climatechange/EPAactivities/economics/nonco2mitigation.html." .

[9] J. Gurney and B. P. Company, *BP Statistical Review of World Energy*, vol.

4, no. 2. 2019.

[10] N. Syred, “A review of oscillation mechanisms and the role of the precessing vortex core (PVC) in swirl combustion systems,” *Prog. Energy Combust. Sci.*, vol. 32, no. 2, pp. 93–161, 2006.

[11] M. Stöhr, R. Sadanandan, and W. Meier, “Experimental study of unsteady flame structures of an oscillating swirl flame in a gas turbine model combustor,” *Proc. Combust. Inst.*, vol. 32 II, no. 2, pp. 2925–2932, 2009.

[12] T. Lieuwen, V. McDonell, D. Santavicca, and T. Sattelmayer, “Burner development and operability issues associated with steady flowing syngas fired combustors,” *Combust. Sci. Technol.*, vol. 180, no. 6, pp. 1169–1192, 2008.

[13] P. Sayad, A. Schönborn, and J. Klingmann, “Experimental investigations of the lean blowout limit of different syngas mixtures in an atmospheric, premixed, variable-swirl burner,” *Energy and Fuels*, vol. 27, no. 5, pp. 2783–2793, 2013.

[14] D. Durox *et al.*, “Flame dynamics of a variable swirl number system and instability control,” *Combust. Flame*, vol. 160, no. 9, pp. 1729–1742, 2013.

[15] S. J. Shanbhogue, S. Husain, and T. Lieuwen, “Lean blowoff of bluff body stabilized flames: Scaling and dynamics,” *Prog. Energy Combust. Sci.*, vol. 35, no. 1, pp. 98–120, 2009.

[16] B. Roy Chowdhury and B. M. Cetegen, “Experimental study of the effects of free stream turbulence on characteristics and flame structure of bluff-body stabilized conical lean premixed flames,” *Combust. Flame*, vol. 178, pp. 311–328, 2017.

[17] A. A. Chaparro and B. M. Cetegen, “Blowoff characteristics of bluff-body

stabilized conical premixed flames under upstream velocity modulation," *Combust. Flame*, vol. 144, no. 1–2, pp. 318–335, 2006.

[18] J. Lewis, A. Valera-Medina, R. Marsh, and S. Morris, "Augmenting the Structures in a Swirling Flame via Diffusive Injection," *J. Combust.*, vol. 2014, pp. 1–16, 2014.

[19] T. Lieuwen, V. McDonell, E. Petersen, and D. Santavicca, "Fuel Flexibility Influences on Premixed Combustor Blowout, Flashback, Autoignition, and Stability," *J. Eng. Gas Turbines Power*, vol. 130, no. 1, p. 011506, 2008.

[20] A. E. E. Khalil and A. K. Gupta, "Clean combustion in gas turbine engines using Butyl Nonanoate biofuel," *Fuel*, vol. 116, pp. 522–528, 2014.

[21] S. Rahm, "Addressing Gas Turbine Fuel Flexibility Authored by :," vol. 4601, 2009.

[22] L. Rye, S. Blakey, and C. W. Wilson, "Sustainability of supply or the planet: A review of potential drop-in alternative aviation fuels," *Energy Environ. Sci.*, vol. 3, no. 1, pp. 17–27, 2010.

[23] E. Ahmadi Moghaddam, S. Ahlgren, C. Hulteberg, and Å. Nordberg, "Energy balance and global warming potential of biogas-based fuels from a life cycle perspective," *Fuel Process. Technol.*, vol. 132, no. x, pp. 74–82, 2015.

[24] J. U. Nef, "An Early Energy Crisis and Its Consequences culminated some two centuries later in the Industrial Revolution," 1977.

[25] Wikipedia, "IEA. (2015). Renewable energy. Available: https://en.wikipedia.org/wiki/Renewable_energy." 2016.

[26] M. Braun-Unkhoff, J. Dembowski, J. Herzler, J. Karle, C. Naumann, and U. Riedel, "Alternative Fuels Based on Biomass: An Experimental and

Modeling Study of Ethanol Cofiring to Natural Gas," *J. Eng. Gas Turbines Power*, vol. 137, no. 9, p. 091503, 2015.

[27] K. F. Mustafa and H W GITANO, "effect of variation in liquefied petroleum gas (lpg) proportions in spark ignition engine emissions," in *International Conference on Environment 2008*, 2008, pp. 1–7.

[28] M. M. Sirdah, N. A. Al Laham, and R. A. El Madhoun, "Possible health effects of liquefied petroleum gas on workers at filling and distribution stations of Gaza governorates," *East. Mediterr. Heal. J.*, vol. 19, no. 03, pp. 289–294, 2013.

[29] S. Chaudhuri and B. M. Cetegen, "Blowoff characteristics of bluff-body stabilized conical premixed flames in a duct with upstream spatial mixture gradients and velocity oscillations," *Combust. Sci. Technol.*, vol. 181, no. 4, pp. 555–569, 2009.

[30] S. Taamallah, K. Vogiatzaki, F. M. Alzahrani, E. M. A. Mokheimer, M. A. Habib, and A. F. Ghoniem, "Fuel flexibility , stability and emissions in premixed hydrogen-rich gas turbine combustion : Technology , fundamentals , and numerical simulations," *Appl. Energy*, vol. 154, pp. 1020–1047, 2015.

[31] M. Gazzani, P. Chiesa, P. Milano, V. Lambrusctiini, and S. Sigalí, "Using Hydrogen as Gas Turbine Fuel : Premixed Versus Diffusive Flame Combustors," vol. 136, 2014.

[32] K. R. Sreenivasan and S. Raghu, "The control of combustion instability: A perspective," *Curr. Sci.*, vol. 79, no. 6, pp. 867–883, 2000.

[33] R. A. Antonia and P. A. Krogstad, "Turbulence structure in boundary layers over di erent types of surface roughness," *Fluid Dyn. Res.*, vol. 28, pp. 139–157, 2001.

[34] N. Syred, M. Abdulsada, A. Griffiths, T. O. Doherty, and P. Bowen, "The effect of hydrogen containing fuel blends upon flashback in swirl burners," *Appl. Energy*, vol. 89, no. 1, pp. 106–110, 2012.

[35] R. L. Gordon and M. J. Tummers, "Experimental analysis of flashback in lean premixed swirling flames : Upstream flame propagation," *Exp Fluids 49853–863*, no. February 2014, pp. 854–863, 2010.

[36] J. F. Driscoll and J. Temme, "Role of Swirl in Flame Stabilization," in *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, 2011, no. January, pp. 1–11.

[37] I. M. Lasky, A. J. Morales, J. Reyes, K. A. Ahmed, and I. G. Boxx, "The Characteristics of Flame Stability at High Turbulence Conditions in a Bluff-Body Stabilized Combustor," no. January, pp. 1–7, 2019.

[38] Y. Xiao, Z. Cao, and C. Wang, "Flame stability limits of premixed low-swirl combustion," *Adv. Mech. Eng.*, vol. 10, no. 9, pp. 1–11, 2018.

[39] N. Karimi, S. McGrath, P. Brown, J. Weinkauff, and A. Dreizler, "Generation of Adverse Pressure Gradient in the Circumferential Flashback of a Premixed Flame," *Flow, Turbul. Combust.*, vol. 97, no. 2, pp. 663–687, 2016.

[40] Y. M. Al-Abdeli and A. R. Masri, "Stability characteristics and flowfields of turbulent non-premixed swirling flames," *Combust. Theory Model.*, vol. 7, no. 4, pp. 731–766, 2003.

[41] W. Malalasekera, K. K. J. Ranga-Dinesh, S. S. Ibrahim, and A. R. Masri, "LES of recirculation and vortex breakdown in swirling flames," *Combust. Sci. Technol.*, vol. 180, no. 5, pp. 809–832, 2008.

[42] R. Santhosh and S. Basu, "Transitions and blowoff of unconfined non-premixed swirling flame," *Combust. Flame*, vol. 164, pp. 35–52, 2016.

[43] M. E. Loretero and R. F. Huang, "Effects of Acoustic Excitation on a Swirling Diffusion Flame," *J. Eng. Gas Turbines Power*, vol. 132, no. 12, p. 121501, 2010.

[44] P. Kalt, Y. Al-Abdeli, A. Masri, and R. Barlow, "Swirling turbulent non-premixed flames of methane: Flow field and compositional structure," *Proc. Combust. Inst.*, vol. 29, no. 2, pp. 1913–1919, 2002.

[45] A. R. Masri, P. A. M. Kalt, Y. M. Al-Abdeli, and R. S. Barlow, "Turbulence-chemistry interactions in non-premixed swirling flames," *Combust. Theory Model.*, vol. 11, no. 5, pp. 653–673, 2007.

[46] Y. M. Al-Abdeli and A. R. Masri, "Turbulent swirling natural gas flames: Stability characteristics, unsteady behavior and vortex breakdown," *Combust. Sci. Technol.*, vol. 179, no. 1–2, pp. 207–225, 2007.

[47] "Valdez, N., et al. Turbulent bluff-body flames close to stability limits revealed by coupling of high speed optical diagnostics. 2019."

[48] P. Schmittel, B. Günther, B. Lenze, W. Leuckel, and H. Bockhorn, "Turbulent swirling flames: Experimental investigation of the flow field and formation of nitrogen oxide," *Proc. Combust. Inst.*, vol. 28, no. 1, pp. 303–309, 2000.

[49] A. R. Masri, P. A. M. Kalt, and R. S. Barlow, "The compositional structure of swirl-stabilised turbulent nonpremixed flames," *Combust. Flame*, vol. 137, no. 1–2, pp. 1–37, 2004.

[50] O. Stein and A. Kempf, "LES of the Sydney swirl flame series: A study of vortex breakdown in isothermal and reacting flows," *Proc. Combust. Inst.*, vol. 31 II, pp. 1755–1763, 2007.

[51] M. Malanoski, M. Aguilar, J. O. Connor, D. Shin, B. Noble, and T. Lieuwen, "Flame Leading Edge and Flow Dynamics in a Swirling , Lifted

Flame," pp. 1–11, 2012.

[52] X. Liu, H. Zheng, J. Yang, and Y. Li, "LES-PDF Modeling of Blowout Analysis in Slit Bluff-Body Stabilized Flames," *Int. J. Spray Combust. Dyn.*, vol. 7, no. 2, pp. 131–150, 2015.

[53] L. Y. M. Gicquel, G. Staffelbach, and T. Poinsot, "Large Eddy Simulations of gaseous flames in gas turbine combustion chambers," *Prog. Energy Combust. Sci.*, vol. 38, no. 6, pp. 782–817, 2012.

[54] A. Kempf, R. P. Lindstedt, and J. Janicka, "Large-eddy simulation of a bluff-body stabilized nonpremixed flame," *Combust. Flame*, vol. 144, no. 1–2, pp. 170–189, 2006.

[55] M. Engineering, E. Studies, and N. Road, "the effect of swirl burner aerodynamics formation," *Exp. Tech.*, 1981.

[56] R. W. Schefer, M. Namazian, J. Kelly, and M. Perrin, "Effect of confinement on bluff-body burner recirculation zone characteristics and flame stability," *Combust. Sci. Technol.*, vol. 120, no. 1–6, pp. 185–211, 1996.

[57] S. Flames, A. J. De Rosa, S. J. Peluso, B. D. Quay, and D. A. Santavicca, "the effect of confinement on the structure and dynamic response of lean-premixed, swirl-stabilized flames," *Proc. ASME Turbo Expo 2015 Turbine Tech. Conf. Expo. GT2015*, pp. 1–12, 2015.

[58] Y. Tong, "influence of combustor geometry on swirl stabilized premixed methane-air flame," *Proc. ASME Turbo Expo 2016 Turbomach. Tech. Conf. Expo.*, pp. 1–10, 2016.

[59] V. Bellucci, F. Guethe, F. Meili, P. Flohr, and C. O. Paschereit, "Detailed Analysis of Thermoacoustic Interaction Mechanisms in," *Combustion*, 2004.

[60] D. C. Haworth, “Progress in probability density function methods for turbulent reacting flows,” *Prog. Energy Combust. Sci.*, vol. 36, no. 2, pp. 168–259, 2010.

[61] M. Li, Y. Tong, M. Thern, and J. Klingmann, “Investigation of methane oxy-fuel combustion in a swirl-stabilised gas turbine model combustor,” *Energies*, vol. 10, no. 5, 2017.

[62] W. P. Jones and V. N. Prasad, “Large Eddy Simulation of the Sandia Flame Series (D-F) using the Eulerian stochastic field method,” *Combust. Flame*, vol. 157, no. 9, pp. 1621–1636, 2010.

[63] M. D. S. Giovangigli, “Premixed and nonpremixed test problem results,” *Reduc. Kinet. Mech. Asymptot. Approx. Methane-Air Flames*, no. c, pp. 29–47, 2005.

[64] P. Sayad, A. Schönborn, and J. Klingmann, “Experimental investigation of the stability limits of premixed syngas-air flames at two moderate swirl numbers,” *Combust. Flame*, vol. 164, pp. 270–282, 2016.

[65] M. G. Mungal, “Approved for Public Release Approved for Public Release,” vol. 486, no. 0704, 2004.

[66] “The open source CFD toolbox web site:< http://openfoam.com>,” 2017. .

[67] B. Kashir, S. Tabejamaat, and N. Jalalatian, “A numerical study on combustion characteristics of blended methane-hydrogen bluff-body stabilized swirl diffusion flames,” *Int. J. Hydrogen Energy*, vol. 40, no. 18, pp. 6243–6258, 2015.

[68] J. Yoon, M. K. Kim, J. Hwang, J. Lee, and Y. Yoon, “Effect of fuel-air mixture velocity on combustion instability of a model gas turbine combustor,” *Appl. Therm. Eng.*, vol. 54, no. 1, pp. 92–101, 2013.

[69] W. M. Roquemore, R. S. Tankin, H. H. Chiu, and S. A. Lottes, “A study of

a bluff-body combustor using laser sheet lighting," *Exp. Fluids*, vol. 4, no. 4, pp. 205–213, 1986.

[70] B. B. Dally, D. F. Fletcher, and A. R. Masri, "Flow and mixing fields of turbulent bluff-body jets and flames," *Combust. Theory Model.*, vol. 2, no. 2, pp. 193–219, 1998.

[71] H. K. Ma and J. S. Harn, "The jet mixing effect on reaction flow in a bluff-body burner," *Int. J. Heat Mass Transf.*, vol. 37, no. 18, pp. 2957–2967, 1994.

[72] Y. C. Chen, C. C. Chang, K. L. Pan, and J. T. Yang, "Flame lift-off and stabilization mechanisms of nonpremixed jet flames on a bluff-body burner," *Combust. Flame*, vol. 115, no. 1–2, pp. 51–65, 1998.

[73] H. Tang, D. Yang, T. Zhang, and M. Zhu, "Characteristics of Flame Modes for a Conical Bluff Body Burner With a Central Fuel Jet," *J. Eng. Gas Turbines Power*, vol. 135, no. 9, p. 091507, 2013.

[74] K. C. San, Y. Z. Huang, and S. C. Yen, "Flame Patterns and Combustion Intensity Behind Rifled Bluff-Body Frustums," *J. Eng. Gas Turbines Power*, vol. 135, no. 12, p. 121502, 2013.

[75] A. R. Masri and R. W. Bilger, "Turbulent diffusion flames of hydrocarbon fuels stabilized on a bluff body," *Symp. Combust.*, vol. 20, no. 1, pp. 319–326, 1985.

[76] A. Ayache and M. Birouk, "Experimental Study of Turbulent Burning Velocity of Premixed Biogas Flame," *J. Energy Resour. Technol.*, vol. 141, no. 3, p. 032202, 2018.

[77] M. G.P. Smith, D.M. Golden, M. Frenklach, N.W. Moriarty, B. Eiteneer and W. J. G. Goldenberg, C.T. Bowman, R.K. Hanson, S. Song, "Gas Research Institute, Chicago, IL, http://www. me. berkeley.

edu/gri_mech.," 2000.

[78] K. K. J. R. Dinesh, K. W. Jenkins, A. M. Savill, and M. P. Kirkpatrick, "Influence of Bluff-body and Swirl on Mixing and Intermittency of Jets," *Eng. Appl. Comput. Fluid Mech.*, vol. 4, no. 3, pp. 374–386, 2010.

[79] J. T. Yang, C. C. Chang, and K. L. Pan, *Flow structures and mixing mechanisms behind a disc stabilizer with a central fuel jet*, vol. 174, no. 3. 2002.

[80] R. W. Schefer, M. Namazian, and J. Kelly, "Velocity measurements in turbulent bluff-body stabilized flows," *AIAA J.*, vol. 32, no. 9, pp. 1844–1851, 2008.

[81] R. F. Huang and C. L. Lin, "Velocity Fields of Nonpremixed Bluff-Body Stabilized Flames," *J. Energy Resour. Technol.*, vol. 122, no. 2, p. 88, 2002.

[82] P. Eriksson, "the Zimont Tfc Model Applied To Premixed Bluff Body Stabilized," pp. 1–9, 2007.

[83] C. Y. Lee, L. K. B. Li, M. P. Juniper, and R. S. Cant, "Nonlinear hydrodynamic and thermoacoustic oscillations of a bluff-body stabilised turbulent premixed flame," *Combust. Theory Model.*, vol. 20, no. 1, pp. 131–153, 2016.

[84] J. Nishimura, T., Kaga, T., Shirotani, K., Kadowaki, "Vortex Structures and Temperature Fluctuation in a Bluff-body Burner," *J. Vis.*, vol. 1, no. 3, pp. 271–281, 1999.

[85] M. Euler, R. Zhou, S. Hochgreb, and A. Dreizler, "Temperature measurements of the bluff body surface of a swirl burner using phosphor thermometry," *Combust. Flame*, vol. 161, no. 11, pp. 2842–2848, 2014.

[86] M. J. Russi, M. A. Com-, and V. Nuys, "The influence of flame holder

temperature on flame stabilization," *Influ. FLAME Hold. Temp. FLAME Stab.*, pp. 743–748, 1993.

[87] C.-X. Lin and R. J. Holder, "Reacting turbulent flow and thermal field in a channel with inclined bluff body flame holders," *J. Heat Transfer*, vol. 132, no. 9, p. 091203, 2010.

[88] I. Esquiva-Dano, H. T. Nguyen, and D. Escudie, "Influence of a bluff-body's shape on the stabilization regime of non-premixed flames," *Combust. Flame*, vol. 127, no. 4, pp. 2167–2180, 2001.

[89] R. F. Huang and C. L. Lin, "Characteristic Modes and Thermal Structure of Nonpremixed Circular-Disc Stabilized Flames," *Combust. Sci. Technol.*, vol. 100, no. 1–6, pp. 123–139, 1994.

[90] P. Guo, S. Zang, and B. Ge, "Technical brief: predictions of flow field for circular-disk bluff-body stabilized flame investigated by large eddy simulation and experiments," *J. Eng. Gas Turbines Power*, vol. 132, no. 5, p. 054503, 2010.

[91] P. Guo, S. Zang, and B. Ge, "LES and Experimental Study of Flow Features in Humid-Air Combustion Chamber With Non-Premixed Circular-Disc Stabilized Flames," pp. 709–718, 2009.

[92] N. R. Caetano and L. F. Figueira da Silva, "A comparative experimental study of turbulent non premixed flames stabilized by a bluff-body burner," *Exp. Therm. Fluid Sci.*, vol. 63, pp. 20–33, 2015.

[93] P. Kumar and D. P. Mishra, "Effects of bluff-body shape on LPG-H2 jet diffusion flame," *Int. J. Hydrogen Energy*, vol. 33, no. 10, pp. 2578–2585, 2008.

[94] D. P. Mishra and P. Kumar, "Experimental study of bluff-body stabilized LPG-H2 jet diffusion flame with preheated reactant," *Fuel*, vol. 89, no. 1,

pp. 212–218, 2010.

[95] R. W. Schefer and M. Namazian, “A comparison of bluff-body and swirl-stabilized flames,” *Combust. Sci. Technol.*, vol. 71, no. 4–6, pp. 197–217, 1990.

[96] B. DALLY and R. MASRI, “Instantaneous and mean compositional structure of bluff-body stabilized nonpremixed flames,” *Combust. Flame*, vol. 114, no. 1–2, pp. 119–148, 1998.

[97] N. S. A.K. Gupta, D.G. Lilley, “Swirl flows, Tunbridge Wells, Kent(1984).,” *England, Abacus Press*, p. 488 p, 1984.

[98] A. Mestre and A. Benoit, “Combustion in swirling flow,” *Symp. Combust.*, vol. 14, no. 1, pp. 719–725, 1973.

[99] B. Ge and S. S. Zang, “Experimental study on the interactions for bluff-body and swirl in stabilized flame process,” *J. Therm. Sci.*, vol. 21, no. 1, pp. 88–96, 2012.

[100] M. T. Chaichan, “Study of performance of S . I . E . Fueled with supplementary hydrogen to gasoline,” vol. 13, no. December, 2006.

[101] M. Farrugia, A. Briffa, and M. Farrugia, “Liquid State LPG Conversion of an Older Vehicle,” *SAE Int.*, vol. 26, no. 13, pp. 1–8, 2014.

[102] M. T. Chaichan and K. S. Reza, “Spark Ignition Engine Performance When Fueled with NG , LPG and Gasoline Spark Ignition Engine Performance When Fueled with NG , LPG and Gasolin,” *Saudi J. Eng. Technol.*, vol. 21, no. January, pp. 105–116, 2017.

[103] C. E. S. M. L.C.F. TianLong, Household, http://www.tianlongcylinder.com/china/12.5kg-lpg-cylinder-for-household, “No Title,” 2012. .

[104] G. H. Choi, J. H. Kim, and C. Homeyer, "Effects of Different LPG Fuel Systems on Performances of Variable Compression Ratio Single Cylinder Engine," in *Proceedings of ICEF2002 2002 Fall Technical Conference of the ASME Internal Combustion Engine Division*, 2002, vol. 7, no. 11, pp. 369–375.

[105] "J. M. Beer and N. A. Chigier, Combustion Aerodynamics. London: Applied Science Publishers LTD, 1972."

[106] A. K. Gupta, D. G. Lilley, and N. Syred, "Book Review," *Combust. Flame*, vol. 63, p. 311, 1986.

[107] S. Candel, D. Durox, T. Schuller, J.-F. Bourgouin, and J. P. Moeck, "Dynamics of Swirling Flames," *Annu. Rev. Fluid Mech.*, 2014.

[108] A. Valera-Medina, "Coherent Structure and Their Effects on Process Occuring in Swirl Combustors," no. May, 2009.

[109] N. Gupta, K., Lilley, D.G., Syred and J. M. Beer, "Combustion in swirling flows: A review," *Combust. Flame*, vol. 23, 1974.

[110] "W. Fick, 'Characterisation and Effects of the Precessing Vortex Core.,' PhD, Cardiff University: Wales, UK., Cardiff University: Wales, UK, Cardiff University: Wales, UK., 1998."

[111] P. Palies, D. Durox, T. Schuller, and S. Candel, "The combined dynamics of swirler and turbulent premixed swirling flames," *Combust. Flame*, vol. 157, no. 9, pp. 1698–1717, 2010.

[112] D. Galley, S. Ducruix, F. Lacas, and D. Veynante, "Mixing and stabilization study of a partially premixed swirling flame using laser induced fluorescence," *Combust. Flame*, vol. 158, no. 1, pp. 155–171, 2011.

[113] P. Sayad, A. Schönborn, and J. Klingmann, "Experimental investigations

of the lean blowout limit of different syngas mixtures in an atmospheric, premixed, variable-swirl burner," *Energy and Fuels*, vol. 27, no. 5, pp. 2783–2793, 2013.

[114] Y. M. Al-Abdeli and A. R. Masri, "Recirculation and flowfield regimes of unconfined non-reacting swirling flows," *Exp. Therm. Fluid Sci.*, vol. 27, no. 5, pp. 655–665, 2003.

[115] A. C. Benim and K. J. Syed, *Flashback Mechanisms in Lean Premixed Gas Turbine Combustion*. 2014.

[116] N. Syred, P. Kay, and A. Griffiths, "Central recirculation zone analysis in an unconfined tangential swirl burner with varying degrees of premixing," pp. 1611–1623, 2011.

[117] A. M. Steinberg, C. M. Arndt, and W. Meier, "Parametric study of vortex structures and their dynamics in swirl-stabilized combustion," *Proc. Combust. Inst.*, vol. 34, no. 2, pp. 3117–3125, 2013.

[118] Q. Zhang, D. Noble, S. Shanbhogue, and T. Lieuwen, "PIV measurements in H2/CH4 swirling flames under near blowoff conditions," vol. 4, pp. 2304–2317, Jan. 2007.

[119] J. De Vries and E. L. Petersen, "Autoignition of methane-based fuel blends under gas turbine conditions," *Proc. Combust. Inst.*, vol. 31 II, no. 2, pp. 3163–3171, 2007.

[120] Y. Zhang, X. Jiang, L. Wei, J. Zhang, C. Tang, and Z. Huang, "Experimental and modeling study on auto-ignition characteristics of methane/hydrogen blends under engine relevant pressure," *Int. J. Hydrogen Energy*, vol. 37, no. 24, pp. 19168–19176, 2012.

[121] B. Lewis and G. Von Elbe, "Stability and Structure of Burner Flames," vol. 75, 1943.

[122] T. Lieuwen, V. McDonell, D. Santavicca, and T. Sattelmayer, "Burner development and operability issues associated with steady flowing syngas fired combustors," *Combust. Sci. Technol.*, vol. 180, no. 6, pp. 1169–1192, 2008.

[123] J. H. Cho and T. Lieuwen, "Laminar premixed flame response to equivalence ratio oscillations," vol. 140, pp. 116–129, 2005.

[124] R. Balachandran, A. P. Dowling, and E. Mastorakos, "Dynamics of bluff-body stabilised flames subjected to equivalence ratio oscillations," no. i, pp. 1–6.

[125] R. Balachandran, B. O. Ayoola, C. F. Kaminski, A. P. Dowling, and E. Mastorakos, "Experimental investigation of the nonlinear response of turbulent premixed flames to imposed inlet velocity oscillations," vol. 143, pp. 37–55, 2005.

[126] J. O'Connor, V. Acharya, and T. Lieuwen, "Transverse combustion instabilities: Acoustic, fluid mechanic, and flame processes," *Prog. Energy Combust. Sci.*, vol. 49, pp. 1–39, 2015.

[127] F. Kiesewetter and M. Konle, "Analysis of Combustion Induced Vortex Breakdown Driven Flame Flashback in a Premix Burner With Cylindrical Mixing Zone," vol. 129, no. October 2007, 2013.

[128] M. Konle, A. Winkler, F. Kiesewetter, J. Wäsle, and T. Sattelmayer, "CIVB Flashback Analysis with Simultaneous and Time Resolved PIV-LIF Measurements," in *13th Int Symp on Applications of Laser Techniques to Fluid Mechanics Lisbon, Portugal, 26-29 June, 2006 CIVB*, 2006, pp. 26–29.

[129] M. Konle and Æ. T. Sattelmayer, "Interaction of heat release and vortex breakdown during flame flashback driven by combustion induced vortex

breakdown," pp. 627–635, 2009.

[130] G. Baumgartner and T. Sattelmayer, "experimental investigation of the flashback limits and flame propagation mechanisms for premixed hydrogen-air flames in non-swirling and swirling flow," *Proc. ASME Turbo Expo 2013 Turbine Tech. Conf. Expo. GT2013*, pp. 1–10, 2017.

[131] P. Sayad, A. Schönborn, M. Li, and J. Klingmann, " Visualization of Different Flashback Mechanisms for H 2 /CH 4 Mixtures in a Variable-Swirl Burner ," *J. Eng. Gas Turbines Power*, vol. 137, no. 3, p. 031507, 2014.

[132] F. A. Hatem, "flashback analysis and avoidance in swirl burners," CARDIFF UNIVERSITY SCHOOL OF ENGINEERING, 2017.

[133] C. Zamfirescu and I. Dincer, "Ammonia as a green fuel and hydrogen source for vehicular applications," *Fuel Process. Technol.*, vol. 90, no. 5, pp. 729–737, 2009.

[134] I. Staffell, "The Energy and Fuel Data Sheet, W1P1 - Revision 1," no. March, pp. 1–11, 2011.

Appendix (A)

A.1. Calculation Heat Amount Generation for Diesel

$$Q = \dot{m} \,. LHV \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (A.1)$$

$$\text{Q} = \frac{3.5}{3600}\left(\frac{kg}{s}\right) * \ 43300\left(\frac{\text{kJ}}{\text{kg}}\right) = 42.097 \ \text{kW}$$

A.2. Calculation Heat Amount Generation for LPG

$$\text{Q} = \frac{10}{3600}\left(\frac{kg}{s}\right) * \ 46600\left(\frac{\text{kj}}{\text{kg}}\right) = 129.44 \ \text{kW}$$

Where LHV is net heat value taken from REF.[134].

A.3. Camera Specifications for Sony xperia Z-1

Video camera settings

Full HD (500 fps)

1920×1080(16:9)

Full HD (Full High Definition) format with 500 fps and 16:9 aspect ratio.

Full HD (1000 fps)

1920×1080(16:9)

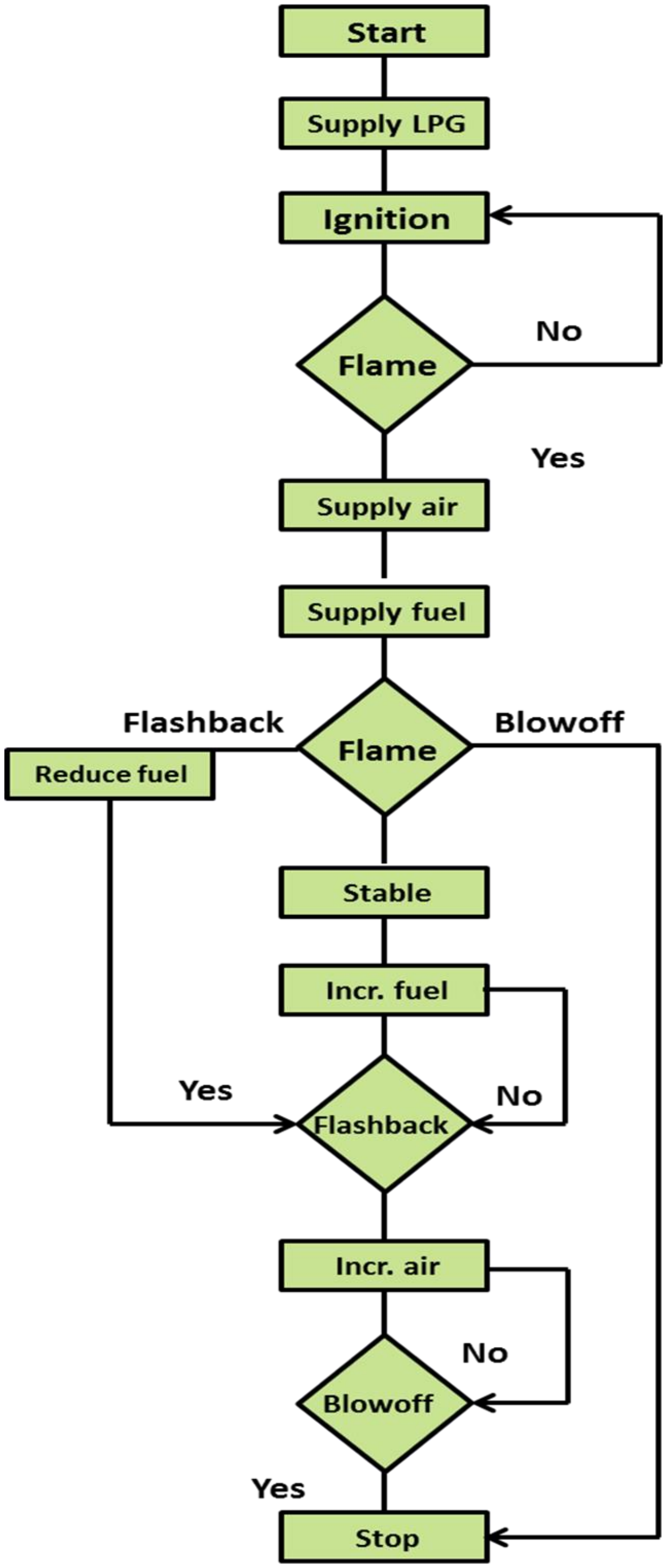
Full HD (Full High Definition) format with 1000 fps and 16:9 aspect ratio.

HD

1280×720(16:9)

HD (High Definition) format with 16:9 aspect ratio.

A.4. Procedure blocks diagram



A.5. Infrared Thermometer Specification and Calibration


QUALITY MANAGEMENT SYSTEM

ISO 9001

CERTIFIED TO MEET ISO 9001

CERTIFICATE OF CONFORMITY

We hereby certify that our quality management system is certified to meet ISO 9001 (Quality Management System), and that this product was produced in conformity to the system which assures that the product meets its published specifications

We further certify that this product was tested and calibrated in accordance with the MASTECH calibration process during the manufacturing process .These calibration procedures are also based on the standard of ISO 9001 .

It is certified that the standards and devices used for the test and calibration are traceable in accordance with National Standard in China.

The test results obtained during the manufacturing process for this product is as follows :

Quality Assurance Manager

Holly Liu

MASTECH®

DONGGUAN HUAYI MASTECH COMPANY LIMITED
Yuliangwei Industrial Area, Qingxi, Dongguan,
Guangdong, China
http://www.p-mastech.com

Fig. A. 1 Certificate of conformity IR thermometer

MASTECH® | CALIBRATION CERTIFICATE | Page 1 of 1

MODEL NO.	MS6520B Non-contact Infrared Thermometer
TEST DEPT.	QA Department
STANDARD	Operation Manual
EQUIPMENT	Fluke 5520A
CONDITION	TEMPERATURE: 25℃ HUMIDITY: 50%
SERIES NO.	

TEST RECORD

RANGE	INPUT	STANDARD REQUIREMENT	MAX DEVIATION		MEASURED DATA	RESULT
			HIGH	LOW		
℃	-20℃	±1.5%+2℃	-19.8℃	-20.2℃	-19.9℃	PASSED
	0℃	±1.5%+2℃	-0.2℃	+0.2℃	0.0℃	PASSED
	20℃	±1.5%+2℃	+19.8℃	+20.2℃	20.1℃	PASSED
	100℃	±1.5%+2℃	+98.3℃	+101.7℃	100.5℃	PASSED
	500℃	±1.5%+2℃	+495.3℃	+504.7℃	500.2℃	PASSED

TEST RESULT: ■PASSED □PENDING □FAIL

Xiong Ying

INSPECTOR: Xiong Ying

DONGGUAN HUAYI MASTECH CO.,LTD
东莞华仪仪表科技有限公司

Fig. A. 2 Calibration Certificate IR thermometer

A.6. Anemometer Model DT-8894 (Specification & Calibration)

Technical Specifications

Air Velocity	Range	Resolution	Accuracy
m/s	0.40 - 30.00	0.01	±3% ±0.20 m/s
ft/min	80 - 5900	1	±3% ±40 ft/min
km/h	1.4 - 108.0	0.1	±3% ±0.8 km/h
MPH	0.9 - 67.0	0.1	±3% ±0.4 MPH
Knots	0.8 - 58.0	0.1	±3% ±0.4 knots
Air Flow	Range	Resolution	Area
CFM	0-999900	0.001	0-999.9 ft^2
CMM	0-999900	0.001	0-999.9 m^2
Air Temperature	Range	Resolution	Accuracy
	14-140°F (-10-60°C)	0.1°F/C	±4.0°F (2.0°C)
InfraRed Temperature	Range	Resolution	Accuracy
	-58 to -4°F (-50 to -20°C)	0.1°F/C	±9.0°F (5.0°C)
	-4 to 932°F (-20 to 500°C)	0.1°F/C	±2% reading or ±4°F (2°C)

CFM(ft^3/min)=Air Velocity(ft/min)XArea(ft^2)
CMM(m^3/min)=Air Velocity(m/s)XArea(m^2)X60
CFM : cubic feet per minute
CMM : cubic meters per minute

	m/s	ft/min	km/h	MPH	knot
1 m/s	1	196.87	3.60	2.24	1.944
1 ft/min	0.00508	1	0.01829	0.01138	0.00987
1 km/h	0.2778	54.69	1	0.6222	0.54
1 MPH	0.4464	87.89	1.6071	1	0.8679
1 knot	0.5144	101.27	1.8519	1.1523	1

Fig. A. 3 Technical Specifications for A.M DT-8894.

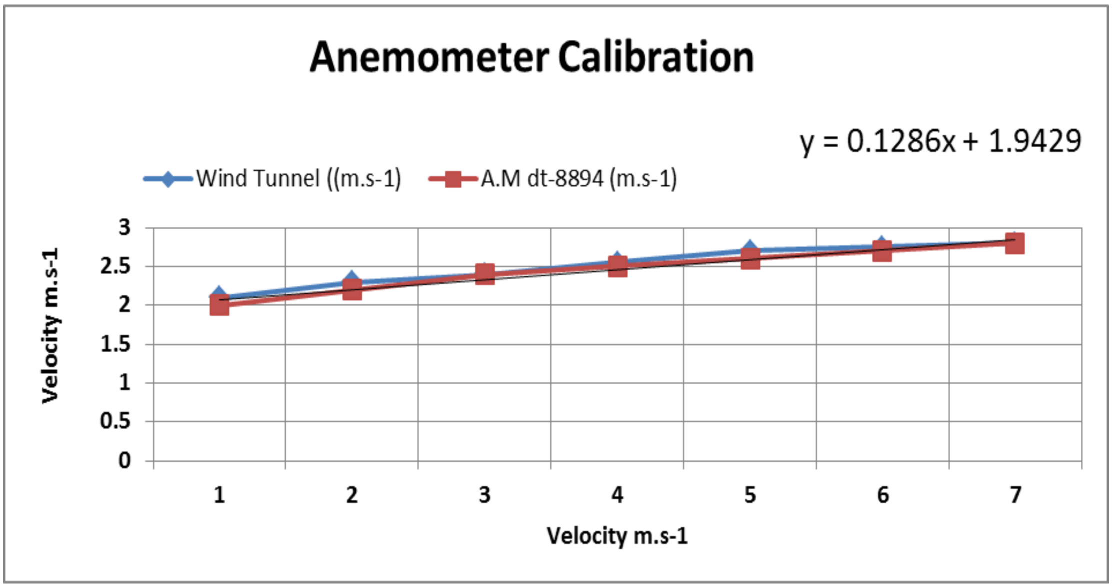


Fig. A. 4 Calibration A.M DT-8894

الخلاصة

ان الاحتراق والسيطرة عليه ضروريان لوجودنا على هذا الكوكب منذ علمنا به. في الوقت الحاضر ، حيث يعتمد عليه تشغيل الحصة الأكبر من الكهرباء في العالم ومعظم أنظمة النقل الخاصة بنا. بالإضافة إلى ذلك ، تعتمد العمليات الصناعية أيضًا بشكل كبير على الاحتراق. في معظم أنظمة الاحتراق الصناعي ، يحدث الاحتراق في ظل ظروف مضطربة والتي يمكن أن تنتج عدم استقرار للاحتراق. هذه هي إشكالية لأنها يمكن أن تؤدي إلى تذبذبات في التشغيل أو التشغيل المنخفض أو المرتفع لدورة مكونات النظام ، والاشتعال باللهب أو اللمظة الراجعة ، والتذبذبات في كفاءة الاحتراق مع مستويات انبعاث عالية أو حتى تلف أنظمة الاحتراق. وبالتالي ، فإن تثبيت اللهب له أهمية أساسية في التصميم والأداء الفعال والتشغيل الموثوق لأنظمة الاحتراق.

تمت دراسة تأثير هندسة المحرق على نافذة التشغيل من محرق تجاري صغير(13 كيلو واط في الساعة) . وكان المحرق في الأصل يستخدم الديزل كوقود وتم التعديل عليه من قبل الباحث للعمل مع غاز البترول المسال. تمت دراسة طول حافة المحرق من خلال اخذ ثلاث اطوال لرقبة المحرق هي (5 سم، 10سم و 15سم) ،حيث ان نسبة طول الرقبة الى القطر بالنسبة للمحرق هي (1، 2، و 3) على التوالي. ان التعديلات التي اجريت لغرض عمل المنظومة على نوعين من الوقود (الغاز المسال او الديزل) هي ممكنه ، مع اضافه بعض التكاليف البسيطة من اجل السيطرة والتحكم الامن بالمنظومة. لتعزيز استقرار الاحتراق تم استخدام موجهات دوامة للحصول على تدفق دوامي وتحسين هيكلية اللهب. وتظهر النتيجة أن الزيادة في طول الرقبة للمحرق سوف تقلل من هيكلية الدوامة وتحويل التدفق الدوامي إلى تدفق انتشاري الذي يزيد من امكانية حدوث الومضة الراجعة في الطبقة المتاخمة. ولكن مع استخدام الحد الاقصى من المحرق ، فان زيادة طول رقبة المحرق تعطي نتيجة جيدة من جانب انفصال الشعلة عند زيادة طول رقبة المحرق المستخدم، من خلال دفعها الى منطقة الخليط الضعيف $\Phi = 0.38$ ، ولكن في حالة الومضة الراجعة فإنه سيؤدي إلى حدود أصغر حجمًا وهو أمر غير مفضل . في فترة قوة المحرق ، يعمل وقود غاز البترول المسال (LPG) مع تدفق الدوامة على زيادة طاقة المحرق إلى حوالي 130 كيلوواط في الساعة. على الرغم من ذلك ، يرتبط هذا التحسن بنوع الوقود في المقام الأول ولكن بنية التدفق لها تأثير كبير على استقرار اللهب.

جمهورية الـعـراق

وزارة التعليم العالي والبحث العلمي

جامعة الفرات الاوسط التقنية

الكليـة التقنية الهندسيـة ـ النجف

دراسة تجريبية لتأثير شكل المحرق على استقرار اللهب

رسـالة

مقدمة الى الكلية التقنية الهندسية – النجف / جامعه الفرات الأوسط كجزء من متطلبات نيل درجة الماجستير التقني
في هندسة الميكانيك – تخصص حراريات

من قبل

جميل توفيق جميل النفاخ

إشـراف

الأستاذ المساعد الدكتور

قحطان عدنان عبد

الدكتور المدرس

محمد عبد الرضا الفحام

2019-Najaf

النجف-**1439 هـ**