2.1 Introduction

A gas turbine combustor having a fuel injection nozzle for diffusion combustion disposed in a central portion of the combustor and an annular premixed nozzle disposed in an outer peripheral portion of the fuel injection nozzle for injecting a mixed gas of fuel and air. The annular premixed nozzle includes an annular premixing chamber and a plurality of premixed fuel nozzles for injecting fuel into the annular premixing chamber. The annular premix nozzle is divided by a partition (108) to form a plurality of premixing chambers each adjacent to the fuel injection nozzle for diffusion combustion. Each of the premixing chambers includes at least one of the premixed fuel nozzles. A mechanism is provided for supplying fuel to a predetermined number of the premixing chambers in a low load operation of the gas turbine and for supplying fuel to all of the premixing chambers in a high load operation.
2.2 Combustion Fundamentals

Combustion perhaps describe most simply as an exothermic reaction of a fuel and an oxidant. In gas turbine application the fuel may be gaseous or liquid, but the oxidant is always air. Combustion occurs in many forms, not all of which are accompanied by flame or luminescence. The following regimes of combustion can be distinguished. (A.B Wassel, 1977)

2.3 Pre-Flame Combustion

This is a slow process that normally requires from 1 to 100 second reaching 80% completion. The reaction occurs throughout an extended volume at temperatures ranging from 600 to 800 K. The products of combustion contain high concentrations of oxygenated organic species; hence, only part of the latent heat of combustion is released.

2.4 Deflagration

This is a fast process that requires less than 1 ms for 80% completion. It is characterized by the presence of flame that propagates through the unburned mixture. A flame may be defined as a rapid chemical change occurring in a very thin layer, involving steep gradients of temperature and species concentrations, and accompanied by luminescence. From a macroscopic viewpoint the flame front can be viewed as an interface between the burned gases and the unburned mixture. Compared with the unburned mixture, the burned gases are much higher in volume and temperature, and much lower density. Deflagration waves normally propagate at velocities below 1m/s. All the flame processes occurring in gas turbine combustors fall within this category.
Damage to buildings, equipment and people can result from a large-scale short-duration deflagration. The nature of the damage is primarily a function of the total amount of fuel burned in the event (total energy available), the maximum flame velocity that is achieved, and the manner in which the expansion of the combustion gases is contained.

Figure 2.1: Damaging deflagration events

In free-air deflagrations, there is a continuous variation in deflagration effects relative to maximum flame velocity. When flame velocities are low, the effect of a deflagration is the release of heat. Some authors use the term flash fire to describe these low-speed deflagrations. At flame velocities near the speed of sound, the energy released is in the form of pressure and the results resemble a detonation. Between these extremes both heat and pressure are released.

2.5 Detonation

The characteristic feature of detonation is a shock wave that is connected with and supported by a zone of chemical reaction. Detonation wave proceed at supersonic velocities, ranging from 1 to 4 km/s. Their propagation velocities can be computed from general equation for gas dynamics and thermodynamics, without any consideration of reaction kinetics. Detonation waves cannot occur in the conventional fuel-air mixture employed in gas turbine combustors, but the possibility could a rise situation where oxygen injection is employed to facilities ignition and engine acceleration.
2.6 Gas Turbine Combustor

Gas turbine engines are widely used in aircraft, marine, power generation and industrial application due to largely tremendous advantages in term of range, speed, fuel economy, passenger comfort, compactness and high power output. Conventional gas turbine combustion chamber essentially consists of three main sections. These are primary, intermediate and dilution zones. The most vital section for the combustion chamber designer is the primary zone since combustion of fuel is initiated in this section (Al-Kabie, H.S., 1989). The achievement of complete combustion in the primary zone is the aim of the present work which reduces the need for other sections of the combustors fulfilling the requirement of small size and light weight of gas turbines.

2.7 Theory of Operation

Gas turbines are described thermodynamically by the Brayton cycle, in which air is compressed isentropically, combustion occurs at constant pressure, and expansion over the turbine occurs isentropically back to the starting pressure.

In practice, friction, and turbulence cause:

- a) non-isentropic compression: for a given overall pressure ratio, the compressor delivery temperature is higher than ideal.
- b) non-isentropic expansion: although the turbine temperature drop necessary to drive the compressor is unaffected, the associated pressure ratio is greater, which decreases the expansion available to provide useful work.
- c) pressure losses in the air intake, combustor and exhaust: reduces the expansion available to provide useful work.
As with all cyclic heat engines, higher combustion temperature means greater efficiency. The limiting factor is the ability of the steel, nickel, ceramic, or other materials that make up the engine to withstand heat and pressure. Considerable engineering goes into keeping the turbine parts cool. Most turbines also try to recover exhaust heat, which otherwise is wasted energy. Recuperators are heat exchangers that pass exhaust heat to the compressed air, prior to combustion. Combined cycle designs pass waste heat to steam turbine systems. Then, combined (co-generation) uses waste heat for hot water production.

Mechanically, gas turbines can be considerably less complex than internal combustion piston engines. Simple turbines might have one moving part: the shaft/compressor/turbine/alternative-rotor assembly (see image above), not counting the fuel system.

More sophisticated turbines (such as those found in modern jet engines) may have multiple shafts (spools), hundreds of turbine blades, movable stator blades, and a vast system of complex piping, combustors and heat exchangers.

As a general rule, the smaller the engine the higher the rotation rate of the shaft(s) needs to be to maintain tip speed. Turbine blade tip speed determines the maximum pressure that can be gained, independent of the size of the engine. Jet engines operate around 10,000 rpm and micro turbines around 100,000 rpm.
Thrust bearings and journal bearings are a critical part of design. Traditionally, they have been hydrodynamic oil bearings, or oil-cooled ball bearings. This is giving way to foil bearings, which have been successfully used in micro turbines and auxiliary power units.

2.8 Operation of a Gas Turbine Combustor

The combustor is divided into three separate regions; those are primary zone, intermediate zone and dilution zone. If all the air and fuel supplied to the gas turbine engine were supplied into the combustor directly, the resulting mixture would have a fuel-air ratio lower than the lean flammability limits. Thus the combustion is initiated and stabilized by the controlled mixing of fuel and air in the primary zone and the exact fuel-air ratio of the mixture will depend on the approach to emission reduction that is adopted, either lean, stoichiometric or rich. Stoichiometry refers to the amount of air required theoretically to combust completely a particular amount of fuel.

The role of the primary zone in the combustor is to ensure complete combustion of the fuel by providing sufficient time, temperature and turbulence. The intermediate zone serves as an extension to the primary zone providing an increased residence time at high temperature prior to cooling and virtual freezing of reaction in the dilution zone. Meanwhile, the role of the dilution zone is to admit the air remaining after the combustion and wall cooling requirement have been met, and to provide an outlet
stream with a mean temperature and a temperature distribution that are acceptable to the turbine.

2.8.1 Combustor Arrangement

There are three common combustor arrangement; tubular, annular and tub annular type combustors. Tubular combustor is also known as can-type combustor.

2.8.1.1 Tubular Combustor

![Figure 2.4: Tubular Combustor (Treager, I.E, 1995)](image)

Tubular combustor as shown in Figure 2.2 has one combustor on a central axis or several combustors arranged equidistant on the same pitched circle diameter. Each combustor consists of an inner flame tube or liner cylinder mounted on the same axis inside an outer casing cylinder. Tubular combustor is mainly used in industries, marine, vehicular and aircraft application. However modern aircraft applications are more concerned with the engines weight-thrust ratio and so combustors that have a larger combustion volume, hence more thrust, are preferred. The advantages and disadvantages of tubular combustor are shown below.
Advantages

i. Mechanically Robust.

ii. Small variation between individual combustor in combustion and aerodynamic performance.

iii. Rig testing can be performed with just one combustor using a fraction of the total engine air and fuel mass flow.

iv. Problems associated with the initiation in combustion in all combustors except for single combustor.

v. High pressure loss.

Disadvantages

I. Bulk and weight.

ii. Igniter for each combustor increases complexity of design except for single combustor.

iii. Interconnection tubes between combustors for the air flow except for single combustor.
2.8.1.2 Annular Combustor

Annular combustor as shown in Figure 2.3 consists of an inner annulus mounted on the same axis inside an outer casing annulus. Annular combustor is widely used in modern aircraft application particularly in military aero engines. The advantages and disadvantages of annular combustor are shown below.
Advantages

i. Minimum length and weight.

ii. Minimum pressure loss.

iii. Minimal problems with light around.

Disadvantages

i. Buckling problems on outer liner leading to disruption of cooling air flow and variation in outlet gas temperature creating possible thermal stresses in the turbine blades.

ii. Rig testing requires use of total engine air and fuel mass flow.

iii. Even distribution of fuel and air is difficult to achieve around the annular.
2.8.1.3 Tuboannular Combustor

Tubo-annular combustor as shown in Figure 2.6 is a hybrid of the previous two types of combustors. This combustor consists of several cylindrical liners arranged equidistant on the same pitched circle diameter are mounted inside a single outer casing annulus. The advantages and disadvantages of tubo-annular combustor are shown below.

![Figure 2.6: Tubo-annular Combustor (Treager, I.E., 1995)](image-url)
Advantages

i. Mechanically robust.

ii. Low pressure loss.

iii. Shorter and lighter than tubular combustor.

iv. Rig testing requires use of just one combustor, using fraction of total engine air and fuel flow.

Disadvantages

i. Suffers from the problem of light around.

ii. Less compact than annular combustor.

iii. Even distribution of air is difficult to achieve around the annulus.

iii. Igniter for each combustor increases the complexity of design.
2.8.2 Combustor Design Requirement

The basic function of a combustor is to convert admitted fuel and air mixture to a temperature rise for the turbine stage. However there are wide varieties of criteria that also need to be considered in order to achieve the best combustor design. The criteria are (Fricker,N. and Leuckel,W., 1976):

i. The combustor must be capable of reliable and smooth ignition over a wide range of ambient conditions.

ii. After ignition, the flame must stay alight over wide range of inlet temperature, pressure and equivalent ratio.

iii. The fuel should be completely burned so that all of its chemical energy is liberated as heat; typically modern combustors achieve combustion efficiencies of 99.9 percent over a wide range of equivalent ratios.

iv. The pressure loss of the combustor should be low, between 2-7 percent of the combustor inlet pressure. Higher pressure loss would result in higher compressor pressures.

v. The temperature distribution at the exit of the combustor often needs to be altered in order to increase the life of turbine blades.

vi. Low emissions of carbon monoxide, unburned hydrocarbons, oxides of nitrogen, oxides of sulphur and soot will be necessary to pass ever more stringent emission limits.

vii. All combustor types must be designed to be durable and safe.

viii. Aero engine requires short combustor length to keep the engine light weight.
2.9 Air Swirler

The main problem in the combustion system is to stabilize the flame in various situations. This situation is totally difficult to archive mainly in the aircraft usage. It cause by the variation of pressure in the combustion area. These problems will effect the uncompleted combustion that create an emission that will impure the environment that create air pollution such as black smoke and nitrogen dioxide.

In term of stabilizing the combustion flame, the common solution is to consider the shape of air flow in main area. To built the turn back flow shape, a gadget known as air swirler is use to create this kind of air flow shape. Basically, the injector is surrounded by the air swirler. The air swirler will support at the air flow and the result of whirling combustion that create vortecs. The low pressure area in the middle of the vortecs will influence the circulation as shown in figure 2.5. There is various type of air swirler is use for this purpose. Most of the combustor uses the air swirler to stabilize the flame including the gas turbine.

![Circulation created by air swirler (Mellor, 1990)](image)

Figure 2.7: Circulation created by air swirler (Mellor, 1990)
2.9.1 Swirler Type

Various type of swirler is regularly use until this moment. Determination of air swirler, pressure and pressure drop is an important aspect that visualize the characteristic of all type of air swirler that have been use either in gas turbine or in combustion.

![Figure 2.8: Type of air swirler (Mellor, 1990)](image)
2.10 Injection System

Fuel injection system also plays a major role in gas turbine combustion performance. Most combustion chambers employ high pressure fuel system in which the liquid fuel is forced through a small orifice to form a conical spray of fine droplets (atomization) in the primary zone. This is to produce a high ratio of surface to mass in the liquid phase, resulting in very high evaporation rates. The most obvious requirement in fuel injection is that the time required for burning of the spray (vaporize) must be kept short. The injector is also referred to as atomizer as its main function is to atomize the fuel.
2.10.1 Injectors Requirement

Ideal fuel injectors would possess all the following characteristics (Lefebvre, A.H., 1983) and (Bent, R.D. and McKinlay, J.L., 1985):

i. Good atomization over the entire range of fuel flows.

ii. Rapid response to changes in throttle settings.

iii. Freedom from flow instabilities.

iv. Low susceptibility blockage by contamination and carbon deposition on the nozzle.

v. Low susceptibility to gum formation by heat soakage.

vi. Capability for scaling, to provide design flexibility.

vii. Low cost, lightweight, ease of manufacture and ease of removal for servicing.

viii. Low susceptibility to damage during manufacture and installation.

ix. Freedom from vaporization icing, thus making it unnecessary to use carburetor heat except under the most severe atmospheric conditions.

x. More uniform delivery of the fuel-air mixture.

xi. Improved control of the fuel-air ratio.

xii. Reduction of maintenance problems.

xiii. Instant acceleration of the engine after idling, with no tendency to stall.

xiv. Increase engine efficiency.

xv. An easy ignitable mixture.

xvi. A ratio of maximum to minimum fuel flow that exceeds the ratio of maximum to minimum combustor airflow.

xvii. Controlled dispersion of the fuel throughout the primary combustion zone.

xviii. An exit gas temperature distribution that is insensitive to variations in fuel flow rate.
2.10.2 Atomization Process

In gas turbine combustion chambers, atomization is normally accomplished by spreading the fuel into a thin sheet to induce instability and promote disintegration of the sheet into drops. Thin sheets could be obtained by discharging the fuel through orifice with specially shaped approach passage by forcing it through narrow slots, by spreading it over a metal surface or by feeding it to the centre of a rotating disk. The function of the atomizer is to attenuate the fuel into a fine jet or thin sheet from which ligaments and ultimately drops will be produced and distribute the resulting drops throughout the combustion zone in a controlled pattern and direction.

2.10.2.1 Jet Break Up

Several modes of jet disintegration have been identified, but in all cases the final mechanism involves the break up of unstable threads of liquid into rows of drops conforming to the classical mechanism postulated by Rayleigh (Lefebvre, A.H., 1983). According to Rayleigh’s theory, liquid becomes unstable and breaks into drops when the amplitude of a small disturbance, symmetrical about the axis of the jet, grows to one half the diameter of the undisturbed liquid jet. This occurs when \( \pi \frac{d}{d\lambda} = 4.5 \), where \( \lambda \) is the wavelength of the disturbance and is the initial jet diameter. For this value of 4.5, the average drop diameter of break up is 1.89, which is almost double of the diameter of initial jet diameter. In Rayleigh’s theory, liquid viscosity is not considered. This theory later extended by Weber to include the effect of liquid viscosity effect on the break up (Lefebvre, A.H., 1983). According to Weber, the ratio \( \pi \frac{d}{d\lambda} \) of required to produce maximum instability for viscous jets is given by:

\[
\frac{\lambda}{d_o} = \left[ \pi \sqrt{2 T_1} + \frac{3 \mu_0}{\sqrt{\rho_0 c o_{d_o}}} \right]^{-0.5}
\]

When \( \mu = 0 \), the value of \( \pi \frac{d}{d\lambda} = 4.44 \), which is almost the same as the value of Rayleigh’s prediction. However, when a liquid with viscosity of 0.86 kg/ms s experimented, the ratio of \( \pi \frac{d}{d\lambda} \) for maximum instability ranged form 30 to 40. This clearly differs from Rayleigh’s prediction.
In the case of liquid jet disintegration due to the influence of the surrounding air, the drop size obtained is governed by the ratio of disruptive aerodynamic force $2ARU/p$ to the consolidating surface tension force $\sigma/d$. This dimensionless ratio is also known as Weber number. od

\[
  We = \frac{\rho U^2 d}{\sigma}
\]

In the case of liquid jet disintegration without the influence of the surrounding air, the atomization quality is dependent on jet diameter, liquid properties density, surface tension and viscosity. This break up mechanism is dependent to Z number.

\[
  Z = \frac{We^{\frac{3}{2}}}{Re} = \frac{\mu_k}{\sqrt{\sigma \rho d s}}
\]

### 2.10.2.2 Sheet Break Up

Fraser and Eisenklam, has identified three modes of sheet disintegration, described as rim, wave and perforated sheet disintegration (Bent, R.D. and Mckinlay, J.L., 1985).

In the rim disintegration mode, forces were created by surface tension causes the free edge of a liquid sheet to contract into a thick rim, which then breaks up by a mechanism corresponding to the disintegration of a free jet. When this occurs, the resulting drops continue to move in the original flow direction, but they remain attached to the receding surface by thin threads that also rapidly break up into rows of drops. This mode of disintegration is most prominent where the viscosity and surface tension of the liquid are both high. It tends to produce large drops, together with numerous small satellite droplets.
In perforated sheet disintegration, holes appear in the sheet at a certain distance from the orifice. The holes are delineated by rims formed from the liquid that was initially included inside. These holes grow rapidly in size until the rims of adjacent holes coalesce to produce ligaments of irregular shape that finally break up into drops of varying size.

Atomizers that discharge the fuel in the form of sheet are usually capable of exhibiting all three modes of sheet disintegration. Sometimes two different modes occur simultaneously, and their relative importance can greatly influence both the mean drop size and the drop size distribution.

### 2.10.3 Spray Characteristics

Combustion performance is also dependence on spray characteristic such as mean drop size, drop size distribution, spray pattern, cone angle, dispersion and penetration. Mean drop size and drop size distribution are important in designing the atomizer meanwhile spray pattern, cone angle, dispersion and penetration are governed partly by atomizer design and partly by the aerodynamics influence to which the spray is subjected after atomization is completed.

#### 2.10.3.1 Mean Drop Size

Mean diameter plays an important role in determining the evaporation rate and atomization qualities of various sprays. The general idea of the mean diameter is to replace the given spray with imaginary drops which have the same diameter while retaining certain criteria of the original spray. The sauter mean diameter (SMD) is the one which is most common and widely used. It is defined as the diameter of a drop having the same volume/surface ratio as the entire spray (Hoe, Y.M., 2000). Table 2.5 shows some mathematical definitions of mean drop size.

\[
SMD = \frac{\sum nD^3}{\sum nD^2}
\]


2.10.3.2 Spray Pattern And Cone Angle

The uniformity of the distribution of fuel in a conical spray is referred as spray pattern. Poor spray pattern adversely affects many important aspects such as combustion performance, pattern factor and pollutant emissions. The spray cone has a strong influence on ignition, stability limits and exhausts emission. In plain orifice atomizer, the cone angle is narrow and fuel drops is fair evenly dispersed throughout the entire spray volume. It is possible to produce solid cones with swirl atomizers, but, for gas turbine applications, the spray is usually in the form of a hollow cone of wide angle with most of the drops at the periphery.

As plain orifice atomizers produce a narrow and compact spray in which only small proportion of the drops are subjected to the effects of air resistance, the distribution of the spray as a whole is dictated mainly by the magnitude and direction of the velocity imparted to it on exiting from the atomizers orifice. With swirl atomizers however the hollow conical structure of the spray incurs appreciable exposure to the influence of the surrounding air. Normally, an increase in spray cone angle increases the extent of this exposure, leading to improve atomization and an increase in the proportion of drops whose distribution is dictated by the aerodynamics of the primary zone.

![Figure 2.10: Spray Pattern (Hoe, Y.M., 2000)]
Figure 2.11: Cone Angle (Hoe, Y.M., 2000)
2.10.3.3 Dispersion and Penetration

Dispersion could be expressed as the ratio of the volume of the spray to the volume of the fuel contained within it. The advantage of a good dispersion is that the fuel mixes rapidly with the surrounding gas. This could increase the evaporation rate and heat release. Dispersion is small in narrow spray angle and high in wide spray angle (Hoe, Y.M., 2000). In swirl atomizers, dispersion are governed mainly by mean drop size, drop size distribution, cone angle, surrounding medium and fuel properties. However, those factors that increase the spray cone angle also tends to improve the spray dispersion.

Meanwhile, penetration of a spray may be defined as the maximum distance of fuel reaches when injected into stagnant air. It is governed by the relative magnitudes of two opposing forces: (1) the kinetic energy of the fuel jet and (2) the aerodynamic resistance of the surrounding gas. The initial jet velocity is high, but as atomization proceeds and the surface area of the spray increases, the kinetic energy of the fuel is gradually dissipated by frictional losses to the gas. When, the drop has finally exhausted their kinetic energy, mainly gravity and the movements of the surrounding gas dictate their trajectory (Hoe, Y.M., 2000). In general, a compact, narrow spray will have high penetration, while a well atomized spray of wide cone angle, incurring more air resistance, will tend to have low penetration. In all cases, the penetration of a spray is much greater than that of a single drop. The first drop to be formed impart their energy to the surrounding gas, which begins to move with the spray; the gas therefore offers less resistance to the following drops that consequently penetrate further.
2.10.4 Types of Atomizers

There are several atomizers that are used for combustion applications. Several types of atomizers are briefly described in this section. Relative merits of these atomizers were simplified and accessible.

2.10.4.1 Plain Orifice Atomizer

Plain orifice atomizer is widely used in afterburners, where the fuel injection system normally consists of one or more circular manifolds. The spray produced by plain orifice atomizer usually has a cone angle between 5° and 15°. The narrow spray angle exhibited by plain orifice atomizer makes it impractical for most application.

![Figure 2.12: Plain Orifice Atomizer (Hoe, Y.M., 2000)](image)

2.10.4.2 Simplex Atomizer

Simplex atomizer has a wider cone spray angle than plain orifice atomizer. Swirling motion is imparted to the fuel so that, under the action of centrifugal force, spread out in the form of hollow cone as soon as it leaves the orifice. Simplex atomizer is the simplest form of pressure swirl atomizer. A major drawback of the simplex atomizer is that its flow rate varies as the square root of the fuel injection pressure (Hoe, Y.M., 2000).
Figure 2.13: Simplex Atomizer (Hoe, Y.M., 2000)
2.10.4.3 Wide Range Atomizer

The major drawback in simplex atomizer has led to the development of wide range atomizer such as duplex, dual orifice and spill atomizer. These atomizers have ratio of maximum to minimum fuel output about 20 with fuel injection pressure not exceeding 7 MPa. There are two types of wide range atomizers that are duplex atomizer and dual orifice atomizer (Hoe, Y.M., 2000).

The different between duplex atomizer and simplex atomizer is that its swirl chamber employs two sets of tangential swirl port. One set is the pilot or primary ports for the low flows encountered when the engine is idling or at high altitudes and the other set comprises the main passage for the large flow required under normal operating condition. This atomizer is widely used in aircraft engine application.

Dual orifice atomizer is also known as duplex atomizer. It is comprised of two simplex atomizer that are fitted concentrically, one inside the other. At a low fuel flows all the fuel is supplied from pilot atomizer. When the fuel pressure reaches a predetermine value, the pressuring valve open and admits fuel to the main atomizer (Hoe, Y.M., 2000).

![Figure 2.14: Duplex Orifice Atomizer (Hoe, Y.M., 2000)](image)

![Figure 2.15: Dual Orifice Atomizer (Hoe, Y.M., 2000)](image)
2.10.4.4 Spill Return Atomizer

Basically, spill return atomizer is almost similar to simplex atomizer. Spill return atomizer differs from simplex atomizer such that the rear wall of the swirl chamber instead of being solid, it contains an annular passage which fuel can be spilled away from the atomizer. Fuel is supplied to the swirl chamber at high pressure and high flow rate (Hoe, Y.M., 2000).

![Figure 2.16: Spill Return Atomizer (Hoe, Y.M., 2000)](image)

2.10.4.5 Fan Spray Atomizer

Fan spray atomizer is usually obtained by cutting slots into plane or cylindrical surfaces and arranging for the fuel into each slot from two opposite directions. In the single hole fan spray atomizer, there is only one single orifice; this orifice forces the liquid into two opposite streams within itself, so that a fan spray issues from the orifice and spreads out in the shape of a sector of a circle of about 75° angle. An air shroud is usually fitted around the atomizer tip, using the pressure differential across the linear wall (Hoe, Y.M., 2000).

![Figure 2.17: Fan Spray Atomizer (Hoe, Y.M., 2000)](image)
2.10.4.6 Air Assist Atomizer

An example of this atomizer is the use of shroud air on fan spray and simplex atomizer. This atomizer’s swirl port is sized to pass the maximum fuel flow at the maximum fuel injection pressure, then the fuel pressure differential is too low to give good atomization at the lowest fuel flow. Internal mixing air assist atomizer is very suitable for highly viscous fuels and good atomization can be obtained (Hoe, Y.M., 2000).

![Air Assist Atomizer](image)

**Figure 2.18:** Air Assist Atomizer (Hoe, Y.M., 2000)

2.10.4.7 Air Blast Atomizer

In principle, the air blast atomizer functions in exactly the same manner as the air assist atomizer because both employ the kinetic energy of a flow airstreams to shatter the fuel jet or sheet into ligaments and then drops. The main difference between these two systems lies in the quantity of air employed and its atomizing velocity (Hoe, Y.M., 2000).

2.10.5 Slinger System

In slinger system, fuel is supplied at low pressure along the hollow main shaft and is discharged radially outwards through holes drilled in the shaft. These injection holes vary in number from 9 to 18 and in diameter from 2.0 to 3.2 mm. The holes may be drilled in the same plane as a single row but some installations feature a double row holes. The holes never run full; they have a capacity that is many times greater than the required flow rate. They are made large to obviate blockage. However, it is important that the holes be accurately machined and finished, since experience shown that
uniformity of flow among injection holes depends on their dimensional accuracy and surface finish. If one injection holes supplies more fuel than others, a rotating hot spot will be formed in the exhaust gases, with disastrous consequence for the particular turbine blade on which the hot spot happens to impinge.

The advantage of the slinger system is that it is low in cost and simple. Only low pressure fuel pump is needed and atomization quality depends on engine speed. The influence of fuel viscosity is small, so the system has a potential multifuel capability. One drawback of the slinger system is its slow response to changes in fuel flow. A more serious problem is that of high altitude relighting performance. With the engine wind milling, the rotational speed is quite low and consequently the atomization quality is relatively poor. This system is suitable for small engines. The problems of wall cooling could arise if the system were applied to engines with high pressure ratios (Hoe, Y.M., 2000).

2.10.6 Flame Stabilizer

One of the main basic requirements of the combustor is to support combustion over a wide range of operating conditions. This could be achieved by an appropriately designed flame stabilizer. Flame stabilization could be achieved if a sheltered region is provided to entrain and recirculates some of the hot combustion burnt gases with the fresh incoming fuel and air mixture. There are several types of flame stabilizer such as bluff bodies, opposed jets, jet mix and grid mix, axial swirler and radial swirler.
2.10.6.1 Bluff Body

The bluff body flame stabilizer causes a flow recirculation by creating a low pressure zone in its near wake region.

![Bluff Body Flame Stabilizers](image)

**Figure 2.19:** Bluff Body Flame Stabilizers

2.10.6.2 Axial and Radial Air Swirler

Axial and radial swirlers stabilize the flame through the generation of central recirculation zone that is formed when the vortex breakdown occur. Both of these swirlers attempt to inject the fuel into the base of the swirling shear layer to increase flame stability.

![Axial or Radial Air Swirlers](image)

**Figure 2.20:** Axial or Radial Air Swirlers
CHAPTER 3

SWIRLER DESIGN CONCEPT

3.1  Swirler Design

Swirling jets were used for stabilization and control of flame and to achieve high intensity combustion. The common method of generating swirl is by using angled vanes in the passages of air.

Most conventional combustors employ the axial flow type swirlers. The swirler vanes were usually flat for ease of manufacture, but curved vane was sometimes used for their better aerodynamics properties (Lefebvre, 1983). Ahmad, et al. (1986) found problems in the achievement of adequate combustion efficiency and stability with lean primary zones using large air flow axial swirler with central fuel injection (Kim, 1995). Alkabie, et al. (1988) showed that these problems could be overcome by the use of radial swirler followed by a dump expansion with their quite different near swirler aerodynamic.

For large air flow, the axial swirler has disadvantages for accommodating more air because the expansion from the swirler is reduced by the requirement to increase the swirler diameter. Increasing the air flow would reduce the flow expansion to the combustor diameter. The expansion ratio should be more than 1.5 to create a corner recirculation zone. However, this problem not encountered with radial swirlers since the radial swirler outlet can be maintained constant and the vane depth increased to accommodate more air to achieve the pressure loss required. Alkabie (1989) found the noticeable improvement in performance and NOx emission of the radial swirler over the axial swirler due to the immediate contact of fuel with the turbulent swirled air as it leaves the central fuel injector. So, in this research, the axial swirlers would be used.
Figure 3.1 Isometric drawing of 60° Flat Vane Axial Air Swirler

Figure 3.2 Isometric drawing of 20° Flat Vane Axial Air Swirler
3.1.1 Swirler Aerodynamics

A basic requirement of all gas turbine is that the flame stay lighted over a wide range of operating conditions. This is especially arduous for the aircraft combustor, which has to cope with the adverse conditions of low pressure and temperature and occasionally the ingestion of rain or ice. The primary-zone airflow pattern is of prime importance to flame stability. Many different types of airflow pattern are employed, but one feature common to all is the creation of a torroidal flow reversal that entrains and recirculates a portion of the hot combustion product to mix with the incoming air and fuel. These vortices are continually refreshed by air admitted through holes pierced in the liner walls, supplemented in most cases by air flowing through swirlers and flare-cooling slots, and sometimes by air employed in atomization.

One of the most effective ways of inducing flow recirculation in the primary zone is to fit a swirler in the dome around the fuel injector. Vortex breakdown is a well-known phenomenon in swirling flows; it causes recirculation in the core region when the amount of rotation imparted to the flow is high. This type of recirculation provides better mixing than is normally obtained by other means, such as bluff bodies, because swirl components produce strong shear regions, high turbulence and rapid mixing rates. These characteristics of swirling flows have long been recognized and have been used in many practical combustion devices to control the stability an intensity of combustion and the size and shape of the flame region.
3.1.2 Rapid Mixing

There are number of ways of producing better mixing between air and fuel. One of the ways is by creating rapid mixing combustion system. Rapid fuel and air mixing are best produced by using swirlers.

To achieve rapid fuel and air mixing, turbulence must be generated to promote the mixing. Turbulence energy is created from pressure energy dissipated downstream of the stabilizer. In swirlers, increasing the blockage or pressure drop of the swirler can generate turbulence. Swirler pressure drop could be done in number of ways:

i. Increasing the swirler vane angle.

ii. Decreasing the swirler outlet diameter (d/D) or increasing the swirler hub diameter, both of which increase the swirler flow blockage.

iii. Increasing the number of vanes.

Besides the effect of rapid fuel and air mixing, all of these factors also increase the size of the recirculation zone. An increase in the size of the recirculation zone together with the turbulence generated in the shear layer region can increase fuel and air mixing significantly.
3.1.3 Swirl Flow

Swirl flow is a main flow produced by air swirled in burner system. Such flow is the combination of swirling motion and vortex breakdown. Swirling flow is widely used to stabilize the flame in combustion chamber. Swirling flow induces a highly turbulent recirculation zone that stabilizes the flame resulting in better mixing and combustion. An advantage of swirling flow is the fact that a centrifugal force field, present in swirling, tends to accelerate the mixing of two flows having different densities and thus increase the reaction rate in the combustion process (Fricker, N. and Leuckel, W., 1976).

The primary function of this flow is to achieve a mixture that can sustain continuous, and to maintain or stabilize combustion over a wide range of operating conditions. Air is introduced tangentially into the combustion chamber and forced to change its path, which contributes to the formation of swirling flow. The strength of the flow is dependent on the swirler vane angle and the air pressure supplied.

Swirl is widely used in industrial application ranging from gas turbine combustors to diesel engines. It is often dictates that the supported flame must be short and intense in continuous combustion system such as gas turbine combustor in order to achieve the maximum heat release quickly. Long flames are generally less well mixed, this can be gauged by the apparent of yellow flame and contribute more to pollutant formation as the residence time is higher. Additionally yellow flames, as there are more rich regions, the temperature is less uniform across the flame and fluctuations in temperature can have a profound increasing effect on the NOx emissions (Escott, N.H., 1993).
3.1.4 Effect of Swirl

The introduction of swirl has been applied extensively in industrial furnace and combustion chambers in order to improve flame stabilization (Wu, H. L. and Fricker, N., 1976). Swirl also has been used as a mean of controlling flame shape and combustion intensity in furnace flames. The effect of swirl is to decrease the velocity gradient at the exit of burner thus causing a faster decay of the velocities in the flow field with increase of swirl flow (Chervinskey, A. and Manheimertiment, Y., 1968).

One of the main effects of the application of swirl into a flow is the central reverse flow zone that is formed and a highly complex turbulent flow field creates the reverse flow zone or recirculation zone, as shown in Figure 3.1, has traditionally been regarded as a reservoir or store of heat and active chemical species. It cyclically transports hot combustion products from downstream regions into the flame region. The high temperature products, despite the dilution effect, serve as an energy source for preheating and ignition assistance. Between the forward flow and the reverse flow zone boundary is a region of steep velocity gradients and high intensity turbulence, which promotes high entrainment rates and rapid mixing between the fuel and air.

As a result of the high entrainment and homogeneous mixing, swirl reduces both flame lengths and flame attachment lengths and consequently shortens the combustion chamber length necessary for complete combustion (Kim, M.N., 1995). Swirl also promotes high combustion efficiency, easy ignition, reactant recirculation zone residence time, pollutant optimization potential, widened stability and blow off limits.
Geometry of the combustor also affects the reverse flow zone. The precise effect of swirl on a flow field is found to be depending on many factors as well as on the swirl number. For example:

**Nozzle Geometry**: The presence of a central hub encourages a larger recirculation zone.

**Size of Enclosure**: Central recirculation zone can be more pronounced in enclosures than those of comparable free jets.

**Exit Velocity Profile**: Recirculation zones tend to be longer when the flow is produced via swirl vanes as opposed to an axial and tangential entry swirl generators.

The location and the shape of the recirculation zone are a function of the various inlets and swirl generator configurations, enclosure size, extent of reaction and any other factor that manipulates the imposed pressure gradient. Syred and Dahman (1965) suggest that smaller chamber diameters reduce the interference between the flow field and furnace enclosure, thus providing a recirculation zone that is longer and more advantageous for flame stabilization.
3.1.5 Swirl Stabilized Flame

The primary zone airflow pattern of gas turbine combustors is of major importance of flame stability. Various types of airflow pattern are employed, but one feature common to all is the creation of a torroidal reverse flow. This torroidal vortex system plays an important role in flame stabilization since it entrains and recirculates a portion of the hot combustion product to mix with the incoming air and fuel. One of the most effective ways to induce recirculation flow in the primary zone is by fitting a swirler around the fuel injector. This type of recirculation zone may provide better mixing than that obtained by other means such as bluff body. This is because of the strong shear regions, high turbulence and rapid mixing rates produced by the swirling action. Besides that, the presence of a solid surface exposed to the high temperature is reduced and the deposition of coke such as occur on bluff bodies in heterogeneous combustion is also reduced.

Swirl increases the production of turbulence above that generated by non-swirling flows because the presence of the tangential velocity component provides additional velocity gradient. Swirling also increases the turbulence burning velocity to ensure blow off does not occur. Besides that, recirculation vortex produced by swirl acts as a heat source forcing combustion product to move upstream and mix with the partially premixed reactant. This increases the amount of contact between fuel, air and hot combustion products (Syred, N. and Beer, J.M., 1974). An additional factor that explains why swirl has a stabilizing effect is that stagnation points are found at upstream and / or downstream positions of central recirculation zone. This stagnation point would act as a bluff body with the flame attaching in the sheltered downstream near wake region.
3.1.6 Swirler Pressure Drop

Swirler pressure drop is equal to the difference in pressure between the plenum chamber and the combustor. The swirler pressure drop was calculated as follows (Escott, N.H., 1993).

\[ \Delta P = P_{1T} - P_{3T} = (h_{1T} - h_{3T}) \rho_w g \]  \hspace{1cm} (3.1)

where \[ P_{1T} = P_{1S} + P_{1D} + \rho_1 g \Delta h_1 + P_a \] \hspace{1cm} (3.2)

and \[ P_{3T} = P_{3S} + P_{3D} + \rho_3 g \Delta h_3 + P_a \] \hspace{1cm} (3.3)

\( P_{ns} \) and \( P_{nD} \) are the static and dynamic pressure in the \( n \) region. \( P_a \) is the atmospheric pressure. As the combustor is placed horizontally, it was assumed that \( \Delta h_1 \approx \Delta h_3 \approx 0 \) and \( \rho_1 = \rho_3 \). Thus, the equations (3.2) and (3.3) can be combined to yield:

\[ \Delta P = (P_{1S} + P_{1D}) - (P_{3S} + P_{3D}) \] \hspace{1cm} (3.4)

Values of pressure loss in a typical gas turbine combustor lie between 2 percent to 7 percent at reference Mach number of 0.047 (Clements, T.R., 1976). The pressure loss can be calculated by using the following equation:

\[ \Delta P / P = \left( \frac{\gamma}{2} \left( \frac{M}{C_D} \cdot \frac{A_1}{A_2} \right) \right)^2 \] \hspace{1cm} (3.5)
Where,

\[ \Delta P/p \quad = \text{Swirler pressure loss.} \]
\[ C_D \quad = \text{Swirler discharge co efficiency.} \]
\[ \gamma \quad = \text{Ratio of specific heat.} \]
\[ A_1 \quad A_2 \quad = \text{Combustor and swirler open area.} \]
\[ M \quad = \text{Airflow Mach number.} \]
3.1.7 Swirl Number

The previous experimental studies have shown that the flame size, shape, stability and combustion intensity are affected by the degree of swirl imposed on the flow. This degree of swirl is denoted by the swirl number $S$, which is a non-dimensional number characterizing the amount of rotation imposed to the flow. An advantage of swirling flow combustion is the fact that a centrifugal force field, present in swirling or vortex flow, tends to accelerate the mixing of two flows having different densities and thus increase the reaction rate in the combustion process.

The common method of generating swirl is by using angled vanes in the passages of air. The characteristic of the swirling flow depends on the swirler vane angle. Basically there are two types of swirler design; axial swirler and radial swirler. Most conventional combustor employs the axial flow type of swirler. The swirler vane is usually flat for ease of manufacture, but curved vane is sometimes performed for their better aerodynamic properties.

Alkabie, et al (1988) found problems in the achievement of adequate combustion efficiency and stability with lean primary zones using large air flow axial swirler with central fuel injection. Alkabie, et al (1988) showed that these problems could be overcome by the use of radial swirler followed by dump expansion with their quite different near swirler aerodynamic. Flat vane swirler is inefficient because they run under stalled condition.

Swirl number represents the axial flux of swirl momentum divided by the axial flux of axial momentum and is widely used for characterizing the intensity of swirl in enclosed and fully separated flow. That is (Kim, M.N., 1995).
\[ S = \frac{G \Theta}{G_x x D/2} \]  

(3.6)

Where:

- \( G\theta \) = Axial flux of angular momentum.
- \( G_x \) = Axial flux of axial momentum.
- \( D/2 \) = Nozzle radius.

This is a very basic calculation of a swirl number. There is better suggestion on the calculation for the swirl number. Claypole and Syred (1981) proposed a geometrical swirl number, \( gS \) which was taken as non-dimensional measure of the tangential momentum supplied to the flow and if perfect mixing and conservation of momentum is assumed, then the swirl number can be defined in terms of the geometry of the combustor.

\[ S_g = r_o \pi r/A_t \text{ (Tangential flow / total flow)}^2 \]  

(3.7)

Where:

- \( A_t \) = Area of tangential inlet.
- \( r_e \) = Radius of the exit of the combustor.
- \( r_o \) = Radius of the tangential inlets from the centre of the combustor.

In the present work, swirls number calculation based on Leuckel method would be employed. This method would not much represent the real situation. However, Leuckel method was a basic method used to simulate the effectiveness of fuel and air mixture for a particular swirler vane angle. Past researchers agree that there is an optimum value of swirl number, where above that value, the emissions will begin to increase. Kim (1995) proposed that swirl number higher that 3.25 would raise the emissions.
From the Leuckel method swirl number calculation, swirl vane angle of 70° and above were not recommended. Swirl number, $\sigma$ calculation based on Leuckel method was as followed (Appendix C):

\begin{align}
\psi &= \frac{n \cdot s}{2 \pi r_1 \cdot \cos \alpha} \\
\sigma &= \frac{\tan \alpha}{1 - \psi}
\end{align}

Where:-

$n$ = Number of vane.
$s$ = Thickness of vane.
$r_1$ = Swirler outlet vane.
$\alpha$ = Swirler vane angle.