OPTIMIZATION OF FLAMELESS CYCLONE COMBUSTION CHAMBER FOR THE COMBUSTION OF BIOMASS PRODUCER GAS

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DECLARATION

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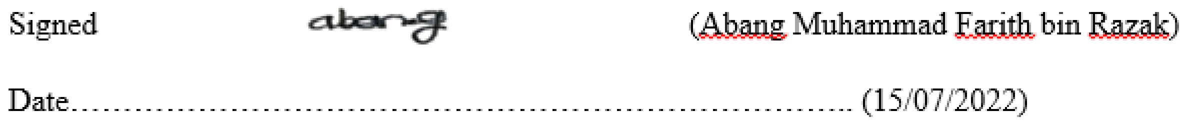

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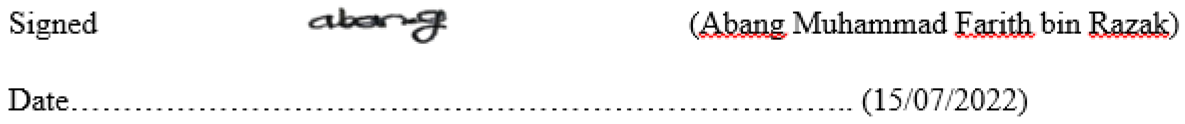

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d	Nozzle diameter (Inlet tube diameter)
dh	Hydraulic diameter
Da	Damköhler number
Dn	Mass diffusivity of n species
Dt	Turbulence diffusivity
h	Combustor height
Ka	Karlovitz number
Kv	Recirculation factor
lo	Integral length scale
l	Thermal conductivity
Jin	Initial jet momentum rate
ma	Mass flow rate of combustion air
mA/F	Mass flow rate of premixed air/fuel
meg	Mass flow rate of exhaust gas
mF	Mass flow rate of fuel
n	Number of species

P	Pressure
Pr	Turbulent Prandtl number
ui/j	Velocity in vector component
μt	Turbulent viscosity
Sct	Schimidt number
SL	Laminar flame speed
Sn	Swirl number
Tave	Average combustor temperature
Ti	Temperature at location i = 1,2,3….
Tn	Normalized temperature uniformity
Tu	Temperature uniformity
λ	Thermal conductivity
S	Standard deviation
Vin	Inlet reactants velocity
Vrms	Root-mean-squared fluctuating velocity
Yn	Mass fraction of species
~	Favre averaging
ρ	Density
Φ	Equivalence ratio
ε	Turbulent dissipation rate
α	Thermal diffusivity
τ	Residence time
τflow	Characteristic flow time
τchem	Characteristic chemical time
τk	Characteristic Kolmogorov time
ξ	Fine structure scale of Eddy Dissipation Concept Model
Rdil	Reactants dilution ratio

LIST OF ABBREAVATION

AIC	Akaike Information Criterion
CAD	Computer Aided Design
CDC	Colorless Distributed Combustion
CFD	Computational Fluid Dynamics
CHBR	Closed Homogenous Batch Reactor
CHP	Combined Heat and Power generation system
COSTAIR	Continuous air Staging combustor
DOE	Design of Experiment
EDM	Eddy Dissipation Model
EDC	Eddy Dissipation Concept Model
FC	Flameless Combustion
FLOX	FLameless Oxidation
FR/ED	Finite Rate/Eddy Dissipation Model
HiTAC	High Temperature Air Combustion
IEA	International Energy Agency
LHV	Lower heating value
LPG	Liquefied Petroleum Gas
MILD	Moderate or Intense Low-oxygen Dilution
PG	Producer Gas
RNG	ReNormalization Group turbulent model
RSM	Reynolds Stress turbulent model

OPTIMIZATION OF FLAMELESS CYCLONE COMBUSTION CHAMBER FOR THE COMBUSTION OF BIOMASS PRODUCER GAS

ABSTRACT

Due to its low heating component, producer gas (PG) combustion results in flame instability, a slow burning rate, and a decrease in power production. A possible combustion method for enhancing combustion performance is flameless combustion. Its use with PG is still far less widespread, though. This work uses the data gathered from the existing experiment and numerical analyzation to study the reaction of the PG in Premixed Flameless Combustion. The Flameless Combustion produced with dilution ratio, R dil > 0.6 of the reactant. Multiple combustor with different nozzle air inlet diameter and combustor were created using SOLIDWORK software. The value for the parameter (air inlet nozzle diameter & combustor height) are 30 mm, 40 mm, 50 mm and 500 mm, 600 mm, 700 mm respectively. The purposed was to study the effect of the combustor parameter which combination will produce most optimum and efficient based from the Nitrogen Oxide (NOx) emissions also presence of the complete combustion. The data gathered from the Computational Fluid Dynamic (CFD) simulation by utilizing ANSYS Fluent software. Then, for the optimization of the cyclone combustor parameter, Minitab software were used by using Design of Experiment (DOE) concept which Full Factorial concept. Full factorial optimization using two factors—nozzle diameter and combustor height—and three stages produced a total of 9 data sets to analyze in the DOE concept. Based on the optimization's results, the data sets that have the most optimum results will be achieved.

PENGOPTIMALAN KEBUK PEMBAKARAN SIKLON BAGI PEMBAKARAN TANPA API UNTUK PEMBAKARAN GAS PENGELUAR BIOMASS

ABSTRAK

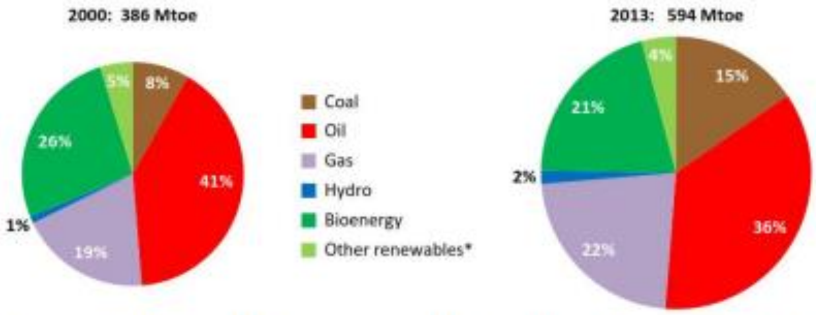
Pembakaran gas pengeluar (PG) menghasilkan ketidakstabilan api kerana ia mempunyai komponen pemanasan yang rendah, kadar pembakaran yang perlahan, dan penurunan pengeluaran kuasa. Kaedah pembakaran yang mungkin akan meningkatkan prestasi pembakaran adalah pembakaran tanpa api (Flameless Combustion). Namun, penggunaan kaedah pembakaran ini dengan PG masih belum diperluas. Kajian ini menggunakan data yang diperoleh daripada ekperimental dan menjalankan analisa berangka untuk melihat reaksi gas pengeluar dalam pracampuran pembakaran tanpa api. Penghasilan pembakaran ini dibantu dengan ratio pencairan bahan tindak balas semasa pembakaran R dil > 0.6. Pelbagai pembakar dengan diameter muncung salur masuk udara serta ketinggian yang berlainan dihasilkan menggunakan perisian SOLIDWORK. Nilai-nilai bagi parameter muncung salur masuk udara adalah 30 mm, 40 mm dan 50 mm manakala bagi ketinggian adalah 500 mm, 600 mm dan 700 mm. Ini bertujuan untuk mengkaji parameter pembakar yang mana lebih efisien dan optimum dalam penghasilan gas nitrogen oxida (NOx) yang rendah. Data ini diperoleh semasa simulasi CFD yang dilakukan menggunakan perisian ANSYS Fluent. Bagi proses pengoptimunan parameter pembakar , perisian Minitab digunakan dengan mengamalkan konsep Rekaan Cubaan iaitu Pemfaktoran Penuh. Konsep ini dilakukan dengan menggunakan 2 faktor (diameter muncung salur masuk udara & ketinggian pembakar) serta 3 tahap yang akan menghasilkan 9 set data dimana set-set data ini akan dianalisa. Berdasarkan analisa data, set data yang paling mempengaruhi dalam penghasilan keputusan yang paling optimum akan berjaya diperoleh.

CHAPTER 1: INTRODUCTION

1.1 Overview of the Biomass Combustion

In terms of power generation, combustion is a basic requirement for fuel to energy conversion. However, burning causes environmental issues, particularly greenhouse gas emissions (Hosseini and Wahid 2014). Alternative fuels produced from renewable energy sources are categorized as one of the viable approaches to alleviate these difficulties (Herbert and Krishnan 2016) (Hosseini and Wahid 2013) (Muench 2015). Combustion of alternative fuels with low hydrocarbon content (and hence low heating value) results in less greenhouse gas emissions as compared to fossil fuels. Biomass has been identified as one of the most significant renewable energy sources that may be primarily used to produce alternative fuels in order to reduce reliance on fossil fuel use (Demirbas 2005) (Herbert and Krishnan 2016) (Muench 2015) (Panwar, Kothari and Tyagi 2012) (Ruiz and Juarez, 2013)). Furthermore, biomass energy has a low carbon footprint, which helps to reduce the negative consequences of environmental concerns, particularly net CO2 emissions, which may be reduced throughout the bio-cycle (Yeoh,, et al. 2018).

The ongoing population and economic expansion, the globe uses more energy on a consistent basis. Particularly in Southeast Asia, the demand for energy surged by more than 50% between 2000 and 2013 and would grow by up to 80% by 2040 ((IEA) 2015). As illustrated in Figure 1.1, it is clearly seen that the largest portion of power generation is produced mostly from the use of fossil fuels like coal, gas, and oil.



* includes solar PV, wind, and geothermal; Note: Mtoe = million tonnes of oil equivalent by 1 toe = 41.87 GJ (Giga Joules)

Figure 1.1: Southeast Asia's power generating share between 2000 and 2013 *((IEA) 2015)*

1.2 Producer Gas as an Alternative Fuel

Figure 1.2 depicts an outline of common processes for converting biomass to energy, from gasification through downstream applications. Essentially, biomass may be burned directly to create heat and power. It may, however, be transformed into a more usable form of energy in the form of gaseous fuel known as producer gas (PG) or synthesis gas, which can be used to fire and operate the engines. PG is produced by partial burning of any biomass, followed by a gasification process that produces a mixture of combustible and non-combustible gases (Belgiorno. V 2003) (Dudyński 2012) (Sansaniwal 2017) (Widjaya 2018).

Carbon monoxide (CO), hydrogen (H2), methane (CH4), and inert species (N2, H2O, and CO2), as well as minor oxygen concentrations (O2), are produced by an air-blown gasification process at temperatures below 1200° (K. A. Al-Attab 2015) (K. A. Al-Attab 2011) (Z. A. Zainal 2002) (Z. A. Zainal 2010). The concentration of these species varies depending on the gasification method, gasifier, biomass feedstock, and gasifying agent (Couto 2013) (Lapuerta 2008) (Rafidah 2011) (Weerachanchai 2009) (Z. A. Zainal 2010). (Huynh 2013) proved that employing oxygen-enriched air/steam gasification may greatly improve the H2/CO ratio of a PG mixture. Increased H2/CO ratio is excellent for improving PG quality by boosting its heating value (Basu 2010).

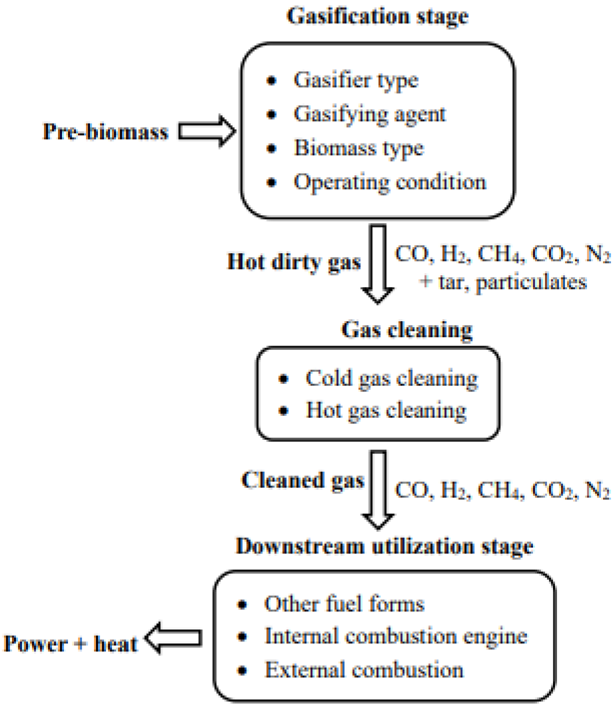


Figure 1.2: A typical overview of the use of producer gas as an alternative fuel.

According to Figure 1.2, the final stage of downstream usage, the combustion process, is critical in the conversion of PG to power and energy. From an economic standpoint, firing in a combustion chamber and utilising it in conjunction with external combustion engines is a great choice for small-scale applications of the combined heat and power generation (CHP) system (de Mena 2017) (Rentizelas 2009) (Rokni 2014). Due to the firing in a combustion chamber is not as sensitive to contaminates in raw PG as in internal combustion engine applications, this technique eliminates the requirement for specialised gas cleaning/cooling systems (de Mena 2017).

1.3 Flameless Combustion Definition

Combustion with an invisible flame, often known as "Flameless Combustion," is a new combustion technique that may meet the demands of high thermal efficiency and minimal pollutant emissions (Xing, 2017). Flameless combustion is also known as "High Temperature Air Combustion (HiTAC)" (Tsuji 2003), "Flameless Oxidation (FLOX) combustion" (Wünning 1997), "Moderate or Intense Low-oxygen Dilution (MILD) combustion" (Cavaliere 2004), and "Colorless Distributed Combustion" (CDC) (Arghode 2011). These combustion methods, however, are based on the same principle: the 5 combustion process operates in a low oxygen reactive environment by preheating and diluting fresh reactants prior to reaction, and the combustion process is carried out by completely distributed auto-ignition of fuel/air mixture. As a result, flameless combustion is achieved through high preheating with dilution of fresh reactants, where:

1. The temperature of the fresh reactants must be higher than the auto-ignition temperature of the fuel (Cavaliere 2004) (Wünning 1997).
2. The local reactants mixture must be diluted by inert species to less than 15% oxygen concentration (Khalil 2014) (Lezcano Benitez 2012) (Mancini 2007).

The combustion volume is occupied by a dispersed reaction and uniform temperature field throughout the flameless combustion process, resulting in an invisible flame with a fading flame front and the merger of the primary reaction zone and the post-flame zone. Although the flameless combustion mode functions in a high temperature environment (greater than the auto-ignition point of the fuel), its peak combustion temperature is suppressed, resulting in a far lower peak combustion temperature than the traditional combustion mode. This is due to the reactants being significantly diluted by hot combustion products, resulting in slower reaction rates and, thus, reduced combustion temperature.

The definition of flameless combustion settings is that the reactants must be hotter than the self-ignition temperature and must have pulled in sufficient inert combustion products to considerably lower the reaction's end temperature. This prevents flame front stabilisation. One of the most evident advantages of flameless combustion is the use of hot, warmed air in contemporary technology to reduce uncontrolled NOx formation and thermal stress on materials. There is no audible or visible evidence of the flames typically associated with burning; the fuel is oxidised spontaneously in a low oxygen environment with a significant amount of inert (flue) gases; the chemical reaction zone is quite diffuse, resulting in almost uniform heat release and a smooth temperature profile like:

- Avoiding the design problems caused by the many kinds of flames that different fuels create.
- Decreased the development of harmful chemicals and toxins.

Around thirty years ago, a breakthrough technique known as flameless combustion arose in this context. However, for energy-efficient combustion in steel furnaces, is currently a consolidated element of multiple advanced combustion research initiatives. A strange phenomena was noticed during testing with a self-recuperative burner in the domains of in 1991: at furnace temperatures of 1000°C and roughly 650°C air preheated temperature, no flame could be seen, but the fuel was totally burned. Furthermore, the furnace's CO and NOx emissions were quite low (Hossaini 2014) . To define the conditions of flameless combustion, the reactants must be hotter than self-ignition temperature and have entrained enough inert combustion products to lower the end reaction temperature much below adiabatic flame temperature, such that a flame front cannot be stabilised (Cavaliere A. n.d.). Figure 1.3 depicts conventional and flameless heavy oil burning with warmed, vitiated air. The observable variances are the consequence of divergent reaction steps that take various chemical pathways, resulting in significantly variable pollutant generation and heat flux distribution of hot combustion products. The mixing of 2-4 recirculating volumes (low Damköhler number) aims to warm while also reducing the output temperature peaks. All of these elements result in an incredibly efficient process with lower emissions; moreover, flame supervision may be dispensed with according to safety requirements because there is no danger of the reaction extinguishing and hence no risk of explosion.

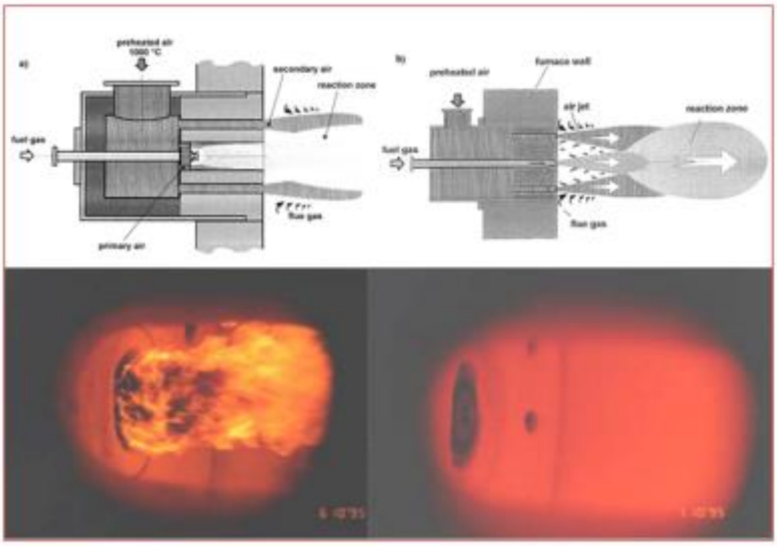


Figure 1.3: Heavy fuel oil fire with flame and without flame (left: flame mode – right: flameless)

In typical combustion systems, a stable flame front is achieved, and the local temperature approaches adiabatic. The front is distinguished by a steep gradient in temperature and composition as a result of radical reactions and convectional quenching. Hot peak temperatures stabilise the flame while also causing the development of thermal NO. In contrast, the flame front is avoided in a flameless burner, and combustion reactions occur at the mixing of fuel, air, and recirculated combustion products; the mixing is also a regulating mechanism for heat transmission and, as a result, the temperature profile. The temperature peak regime in flameless combustion is characterised by (Oberlack M 2000) and shown in Figure 1.4.

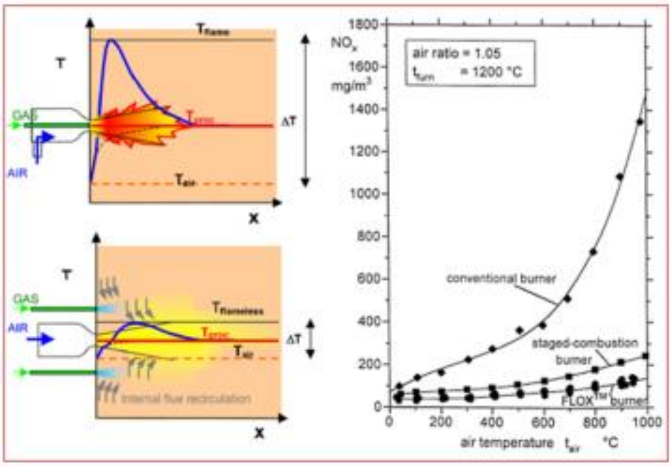
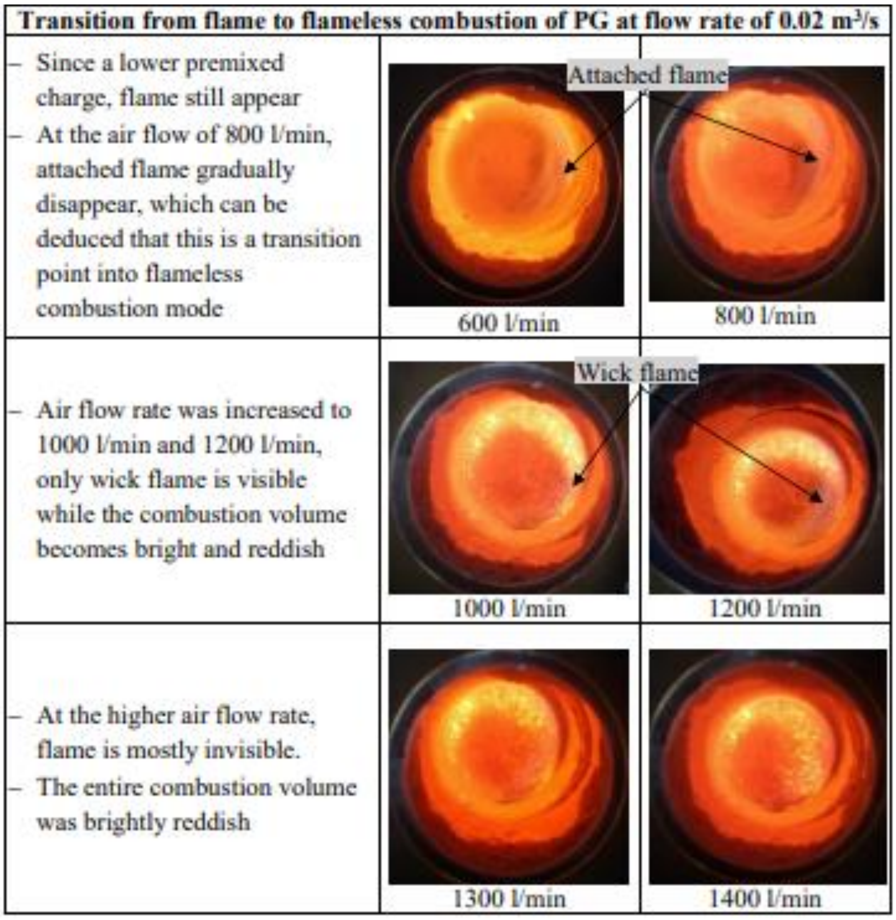


Figure 1.4: Typical flameless and conventional temperature profile *(M.K. 2014)* (left) and NOx concentration in conventional and flameless burners (right) *(al. 2001)*.

Experimentally, PG combustion mode with high combustion air flow resulted in visible flame disappearance and the chamber being filled with light radiation from the refractory cement liner. As stated from (Chanphavong 2017), for nozzle diameter 50 mm, a decreased flow rate of combustion air less than 800 l/min resulted in less exhaust gas recirculation to dilute the fresh air/PG mixture, although visible flame (attached flame combustion) still existed at the flame zone. When the combustion air flow was increased to more than 800 l/min, the visible flame virtually vanished, leaving only the wick flame. This type of wick flame combustion is referred to as a partly flameless combustion (Reddy 2013). The entire combustion volume turned visibly crimson with dazzling radiation from the refractory cement liner when the combustion air flow was more than 1200 l/min, indicating that flameless mode combustion had been accomplished at this point. This explains why air flow rate for the simulation is 1200 l/min since the air flow rate suggest that flameless combustion regime are achieved.



Transition from flame to flameless combustion of PG at flow rate of 0.02 m^3/s		
– Since a lower premixed charge, flame still appear – At the air flow of 800 l/min, attached flame gradually disappear, which can be deduced that this is a transition point into flameless combustion mode	600 l/min	800 l/min
– Air flow rate was increased to 1000 l/min and 1200 l/min, only wick flame is visible while the combustion volume becomes bright and reddish	1000 l/min	1200 l/min
– At the higher air flow rate, flame is mostly invisible. – The entire combustion volume was brightly reddish	1300 l/min	1400 l/min

Figure 1.5: Flame photos show the preheating process with LPG combustion and the transition from flame to flameless combustion mode for a 50 mm nozzle (L. A.-A. Chanphavong 2019).

1.4 Benefits and Application Status of Flameless Combustion

Flameless combustion was originally employed in industrial furnaces to minimise NOx emissions and improve combustion system performance, with regenerative heat exchangers utilised to capture waste heat from combustion products and transmit it back to the combustion zone. On the basis of the link between fuel use, CO2 generation, and fuel saving, tests (Katsuki 1998, Tsuji 2003) indicated that fuel saving may be enhanced up to 30%, equating to the same amount of CO2 reduction. NOx emissions from flameless combustion modes can be reduced by up to 80% when compared to typical modes (Abuelnuor 2014). Meantime, application of flameless combustion in an industrial boiler can be found in investigation of (Kawai 2002). Currently, flameless combustion has been focussed to gas turbine combustors (Khidr 2017) (Perpignan 2018). Flameless combustion presents a successful combustion technology to improve flame stability with high thermal field uniformity. This can be considered as a promising combustion method for low heating value fuel. Flame instability and low burnt-out rate combustions due to low heating value of the fuel can be mitigated by the high thermal field uniformity of flameless combustion technique. In particular, for PG fuel, high levels of preheating and dilution are already present in the PG through the gasification process. This will comply with the principle of flameless combustion. The raw PG generated in an air-blown gasifier has an exit temperature higher than 700°C (K. D. Kwiatkowski 2013) and consists of N2 and CO2 as inert gases of over 50% in its mixture (K. A. Al-Attab, Design and performance of a pressurized cyclone combustor (PCC) for high and low heating value gas combustion. 2011) making PG a suitable fuel for fuelling flameless combustion.

The combination of a high degree of preheating and huge temperature dispersion allows for a fully oxidised fuel/air mixture, resulting in complete combustion (low CO emission). In addition, thermal efficiency and flame stability are significantly increased over typical combustion modes (A. Gupta 2004). Furthermore, lower peak combustion temperatures result in decreased NOx emissions due to NO thermal formation suppression (Abuelnuor 2014).

1.5 Nitrogen Oxide

When fuel is burned at high temperatures, nitrogen in the diluting air of the combustion chamber is "fixed" into nitrogen oxide (NO). Nitrogen oxides are classified as nitric oxide (NO), nitrous oxide (N2O), nitrogen dioxide (NO2), nitrogen trioxide (NO3), nitric anhydride (N2O5), and nitrous anhydride (N2O3). Only NO and NO2 are important constituents of nitrogen oxides, which are frequently referred to as NOx (pronounced "NOx"). The oxidation of atmospheric (molecular) nitrogen is the primary source of nitric oxide, NO. If a considerable fraction of the fuel utilised in combustor contains nitrogen containing compounds, the oxidation of this component will be an additional source of NO. Numerous nitrogen oxides lack both colour and smell. However, a reddish-brown coating of air may frequently be visible above metropolitan areas due to one prevalent NOx, nitrogen dioxide (NO2). One of the key components in the creation of ground-level ozone, which can lead to major respiratory issues, is NOx. Additionally, it interacts to produce nitrate particles and acidic aerosols, which aid in the development of acid rain. NOx-derived particulate nitrates contribute to fine atmospheric particles that can reduce visibility. NOx emissions also have a role in the issue of global warming.

1.6 Project Objectives

- To identify if the design of the cyclone combustor are able to achieve flameless combustion criterion using ANSYS Fluent workbench.
- To create an optimum design of the cyclone combustor chamber that are able to achieve complete combustion and flameless combustion regime by design optimization using Design of Experiment (DOE) software.

1.7 Problem Statement

Flameless combustion is one of the possible combustion techniques for low heating value fuels. The utilization of heat recirculation in the flameless combustion process provides for increased fuel flexibility, higher thermal efficiency, and lower hazardous emissions when compared to traditional combustion. Aside from that, the problems in flameless combustion, particularly in premixed PG flameless combustion employing a cyclone combustor, have yet to be studied. High dilution of inert species (N2 and CO2) and numerous combustible species (CO, H2, and CH4) occurs during the combustion process of PG, making it difficult to optimize burner layouts and determine combustion conditions. The total procedure will become more challenging due to a lack of references. Premixed combustion strategy allows for good mixing result with a certain ratio of fuel/air mixture, which is better to control operating combustion conditions and to achieve low polluting emissions. If those systems can operate in flameless combustion mode with PG fuel, performance of the combustion system could be considerably improved with an outstanding reduction of polluting emissions. Hence, further investigation on this regard is needed.

1.8 Scope & Limitation

The point of the project is to create a cyclone combustion chamber that will run on producer gas from the gasification process. Due to the benefits of flameless combustion technology, the issue also strives to produce flameless combustion in the combustion chamber. The most significant characteristics to measure or determine in the design of the combustion chamber are fuel flow rate, air-fuel ratio or equivalence ratio, nozzle diameter, combustion chamber height & diameter, and fuel composition. Complete combustion is predicted from a well-fabricated combustion chamber after an acceptable design is produced from these amounts. The temperature of the incoming reactants (fuel + air) must be higher than the auto-ignition temperature in the combustion chamber to accomplish flameless combustion. This can be accomplished by preheating the entering reactants with external hot flue gas via a heat exchanger or internal flue gas recirculation. In a low oxygen atmosphere, flameless may also be accomplished by lowering the oxygen content in the combustible mixture. During the combustion process, the flameless combustion approach is distinguished by spontaneous ignition with no visual or aural indicators of flame.

Optimization of combustion chamber design is a strategy for choosing the optimal method/design from a set of multiple methods/designs gained via experimentation. Before the flameless cyclone combustion chamber can be optimized for the combustion of biomass producer gas, the cyclone combustion chamber must first be designed using the characteristics mentioned. The design might be carried out using any normal design of experiment (DOE) approach, which entails laying out the sequence in which the experiment will be carried out, taking into account both the dependent and independent variables as well as the results. The best design is then chosen from the data sets acquired; the best design may be based on a design that has a high combustion/thermal efficiency while using less energy with less NOx pollutant.

CHAPTER 2: LITERATURE REVIEW

2.1 PG Combustion in the Staged Combustor

As a combustor, a staged combustion chamber with axial and radial reactant injections was employed to power a single shaft micro-gas turbine employing a dual-fuel mode of PG and LPG (Sadig 2015). The combustor's performance was assessed in terms of LPG fuel replacement and emission characteristics. The study found that radial air injection had a higher LPG replacement ratio than axial air injection. When LPG is replaced for producing gas, NOx emissions decrease, while CO emissions increase for both injection types. (Mandl 2011) devised an air staged combustion chamber with a fuel-rich zone separated from an oxidising zone to prevent NO production and burn the remaining fuel in a flue gas combination The results demonstrated that total PG combustion is possible. The nitrogen concentration of the biomass feedstock influences NOx emissions from PG combustion. Researchers have noted this out, (Sethuraman 2011); (Van Huynh 2013).

They observed that thermal NOx is substantially lower than fuel-NOx, which accounts for the majority of overall NOx emissions. Furthermore, NOx emission does not fluctuate considerably with changing the combustion equivalence ratio, but it increases significantly with increasing the combustion heat load. According to the numerical calculations, (Sukumaran 2013) proposed that by engineering combustion conditions and employing a bluff body, fuel NOx generation may be decreased. This strategy will allow the majority of NOx creation to flow through the fuel-rich zone and into the upstream zone, reducing both fuel NO-formation and thermal NOx formation.

(Al-Halbouni 2007) The continuous air staging (COSTAIR) combustor was created to burn low calorific value gas fuels, including PG fuel (see Figure 2.1). (b). Their combustor performed better in terms of NOx and CO emissions (at 3% O2 vol.), which were less than 20 ppm throughout a wide range of fuel/air ratios. To evaluate the operability of the nozzle and harmful emissions of the combustion process, a commercial combustor-based air staged diffusion burner was tested for PG fuel burning (Baina 2015). According to the results, an optimal operating fuel power input of roughly 5.8 kW is required to provide low CO and UHC concentrations under a combustion equivalence ratio of 0.68. In a series of studies, a staged combustion chamber was adjusted to enhance combustion of biomass pyrolysis gas and connected with a micro gas turbine to provide a full load of 80 kWe, (F. L. Fantozzi 2009); (F. L. Fantozzi 2010); (P. B. Laranci 2011); (P. a. Laranci 2011). The primary goal of their research is to identify the combustion characteristics, which include turbine input parameters such as temperature, pressure, and mass flow rate of the flue gas combination, as well as pollutant emissions from the combustion process.

A naturally aspirated, slightly aerated burner suggested by (Sutar 2016), was created in order to burn PG from a downdraft gasifier cook-stove. They observed that improved burner efficiency increases the overall thermal efficiency of the cook-stove by roughly 15% to 45 percent, with a planned burner efficiency of 53-88 percent and CO emission within acceptable limits. Figure 2.1 is an example of an air-staged burner.

- for four stages of fuel–air mixing
- for continuous air staging (COSTAIR).

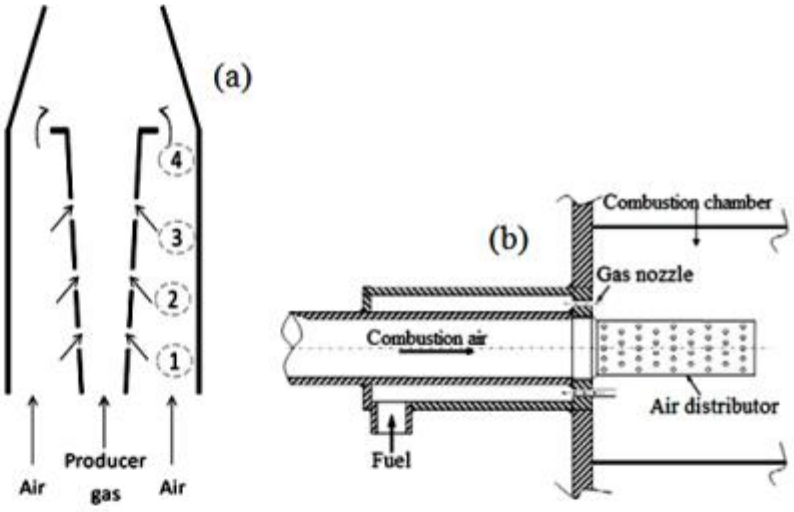


Figure 2.1: (a) Four staged burners are depicted schematically. *(Sukumaran 2013)* and (b) air staging indefinitely (COSTAR) *(Al-Halbouni 2007)* for producer gas combustion.

2.2 Determination of Reaction Regime Under Flameless Combustion

Different definitions exist in the practical combustion process to explain the border of flameless combustion based on the relationship between temperature and internal gas recirculation rate or dilution level. (Wünning 1997) Flameless oxidation regime (FLOX) is denoted by a furnace temperature larger than the auto-ignition temperature (Tig) of the fuel and a dimensionless recirculation ratio (KV) greater than 3 (KV > 3). KV is defined as the ratio of the mass flow rate of exhaust gas recirculation (meg) to the sum of the mass flow rates of combustion air (mA) and fuel (mF):

$$KV = meg / (mA + mF)$$

Other advancements in combustion technology (Tsuji 2003), High-Temperature Air Combustion (HiTAC) was carried out based on preheating combustion air, which depends on the combustion air temperature and its oxygen Enthalpy (temperature) concentration. When the oxygen content falls below 15%, (A. K. Gupta 1999) When the combustion air temperature is higher than Tig, the combustion process can transition into the HiTAC regime.

(Cavaliere 2004) evaluated both the FLOX and HiTAC regimes and offered the description of the Moderate and/or Intense Level of Dilution (MILD) combustion regime, which may be mathematically expressed as follows:

1. Prior to combustion, the starting reactant temperature (Tin) must be greater than Tig, Tin > Tig.
2. The temperature rise throughout the combustion process (T) is smaller than Tig, T < Tig.

Flameless combustion can occur with a wide variety of beginning reactant conditions, where the input flameless mixture temperature must be sufficiently hot when operating at low reactant dilution levels, or a greater dilution level is required (Wang 2014). (Rao 2010) Figure 2.2 depicts a typical diagram of the definitions of the flameless combustion regime. Non-premixed approach flameless combustion based on hot flue gas recirculation is depicted in this image. When the recirculation ratio exceeds 0.5, the reactant is diluted into a low oxygen concentration of approximately 12% with an inert species concentration of about 88 percent while preheating the reactant temperature above the auto-ignition temperature; this zone corresponds to flameless combustion.

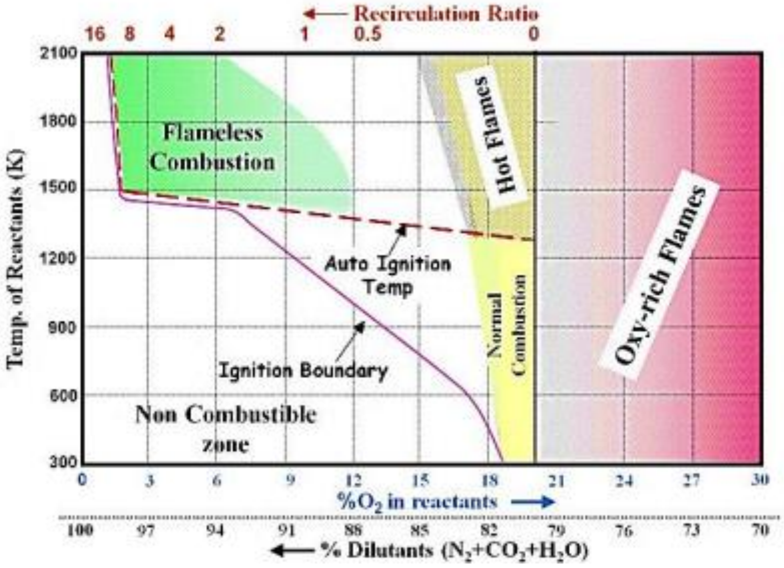


Figure 2.2: Different O2 concentration, recirculation ratio, and reactant temperature-based combustion regimes *(Rao 2010)*

2.3 PG Combustion in Swirl Flow Combustor

Swirl flow patterns, which are created by introducing tangential reactant streams into the combustion chamber, are another method for improving flame stability. This method results in strong cyclonic flow inside the combustion chamber and a lengthy residence period for the fuel/air interaction. (Lewis 2012) conducted an experimental investigation on a premixed-swirl flow combustor with tangential and axial air inlets at a maximum power input of 675 kW According to the study, it can generate a mainly steady combustion and an efficiency of roughly 93 percent over the combustor.

A cyclone combustor with tangential intake and exit ports was built for non-premixed combustion and was linked with a gasifier to directly burn raw producer gas (Syred 2004). This combustor can create a consistent flow, good mixing, and burnout rates without the need of any complicated hot gas cleaning systems. Another non-premixed cyclone combustor with an axial exit was also designed and manufactured by (Dattarajan 2014) to burn a raw producer gas produced during the gasification process Their combustor may produce successful results, as evidenced by the attainment of high flue gas temperatures (>1023) with burnt out materials in the flue gas mixture.

A pressurized cyclone combustor (K. A. Al-Attab 2011) was created and built to use as a heat source for tiny gas turbines and hot air generators (K. A. Al-Attab, 2017); (K. A. Al-Attab 2014) . As illustrated in Figure 2.3, the combustor operated in premixed combustion mode and had a single tangential input and exit port (b). It was used as a hot gas cleaning system to burn PG from a gasifier coupled to a cyclone separator. The ideally built combustor resulted in full combustion, as evidenced by minimal CO emissions at the exhaust port (140 ppm). The system worked as a combined heat and power (CHP) system with an overall efficiency of roughly 58 percent and 35 kWth of hot air generation from the heat recovery unit, based on a two-stage micro gas turbine driven by dual-fuel (LPG-PG) and single-fuel mode of PG. The combustor can generate low emissions (150 ppm for both CO and NOx) and output combustor temperatures ranging from 800 to 1100 degrees Celsius, with a steady combustion process across combustion equivalence ratio ranging from 0.67 to 1.1.

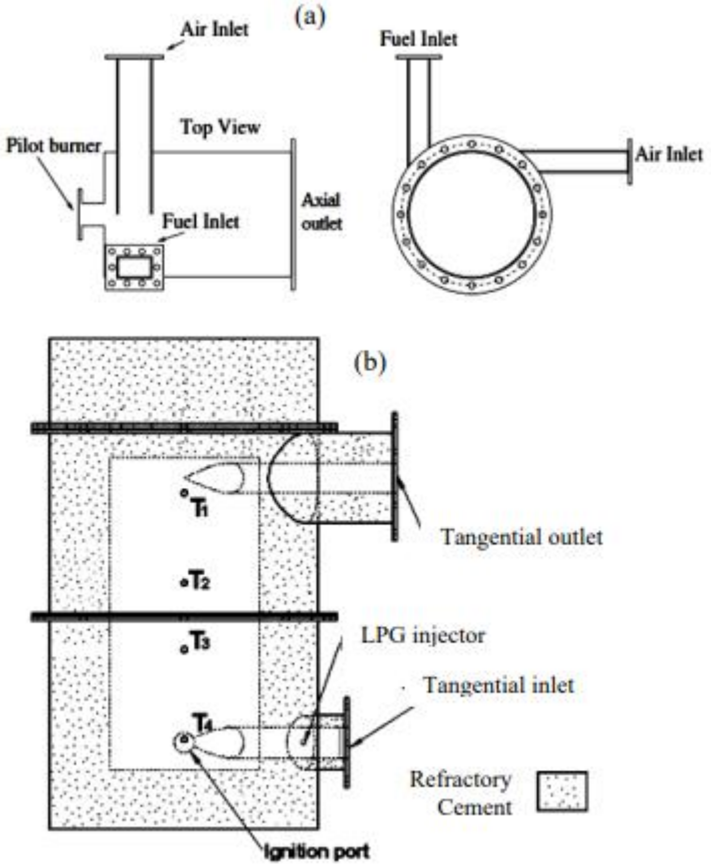
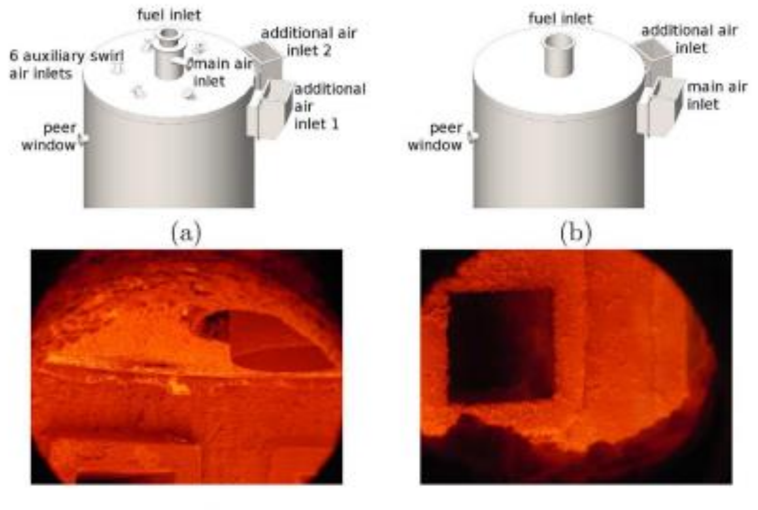


Figure 2.3: Diagram of a non-premixed cyclone combustor *(Dattarajan 2014)* and (b) premixed cyclone combustor *(K. A. Al-Attab 2011)*

2.4 PG Combustion under Flameless Combustions

To the best of the author's knowledge, flameless combustor paired with an actual gasifier has only been documented by (K. a. Kwiatkowski 2016). To begin, a numerical analysis on non-premixed combustion was undertaken using counter flow laminar modelling to categorise the regime of PG combustions. The combustion of a PG with a low preheating temperature was largely in traditional combustion mode, which may be shifted into high temperature combustion (HTC) mode by raising the reactant temperature. While a PG with a high preheating temperature and considerable dilution readily fell into flameless combustion phase. According to the numerical results, the effect of exhaust gas recirculation on the implementation of flameless combustion mode is insignificant. Even with a high value of exhaust gas recirculation, flameless combustion of the low preheating temperature PG is difficult to establish.

Actual combustions of PGs obtained from wood chip and feather gasification methods were also reported in this study. LHV for wood chip PG is 4.13 – 4.77 MJ/m3 and 1.8 – 1.91 MJ/m3 for feather PG. Flameless combustion of adequate preheating and diluting PG is simple in many burner designs. Flameless combustion was achieved in all configurations, as illustrated in Figure 2.4. These data were obtained using combustion chambers linked to a feather gasifier with a combustion air inlet temperature of approximately 295 K and a PG intake temperature of around 1000 K. Total organic carbon and CO emissions were nearly negligible, while NOx emissions were less than 150 ppm.



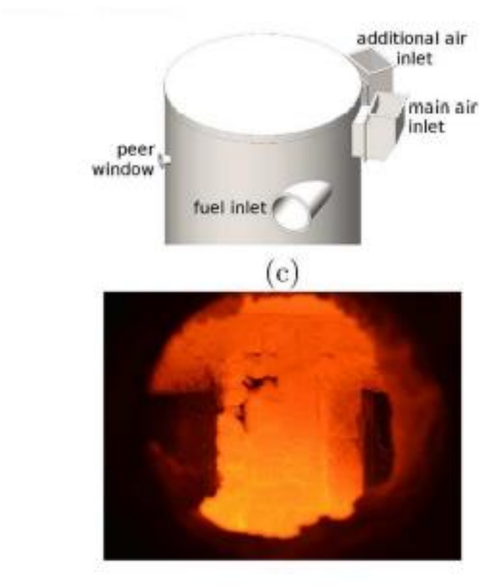


Figure 2.4: (a) Co-flow jets combustion configuration, (b) cross-flow jets combustion configuration, and (c) cyclonic cross-jets combustion configuration with flameless images at higher combustion chambers. *(K. a. Kwiatkowski 2016)*

CHAPTER 3: RESEARCH METHODOLOGY

This section discusses the research technique, which includes both experimental and numerical research. The investigation begins with a review of the definitions, applications, and benefits of the flameless combustion regime. It is claimed that in flameless combustion, exhaust gas recirculation is used to reduce NOx generation and increase thermal efficiency. The recirculated exhaust gas is the exhaust gas that is circulated and mixed with the combustion air prior to the reaction in flameless combustion. The combustor design was then created using the CAD programme SOLIDWORKS. ANSYS Fluent was then used to model the flameless combustion process using the NOx and CO emissions data from each combustor parameter. Minitab will be used to evaluate and enhance the collected data. The information provided led to the overall conclusion.

3.1 Combustor Design

The cyclone combustor design for the simulation was modified from earlier studies. The following is a slightly elevated summary of the SOLIDWORK design:

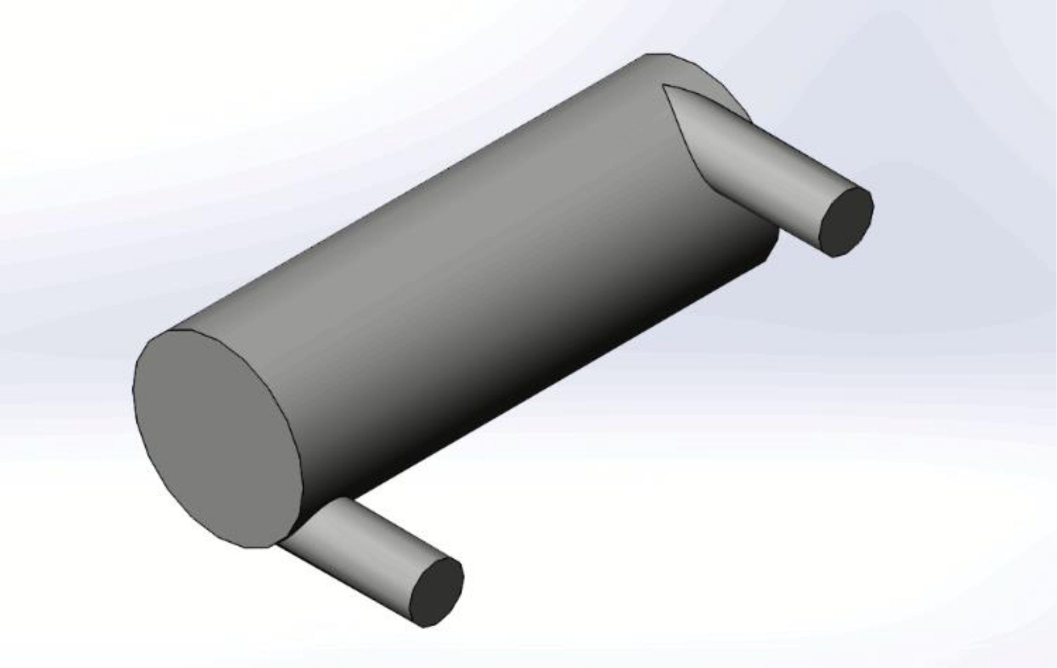


Figure 3.1: Combustor design

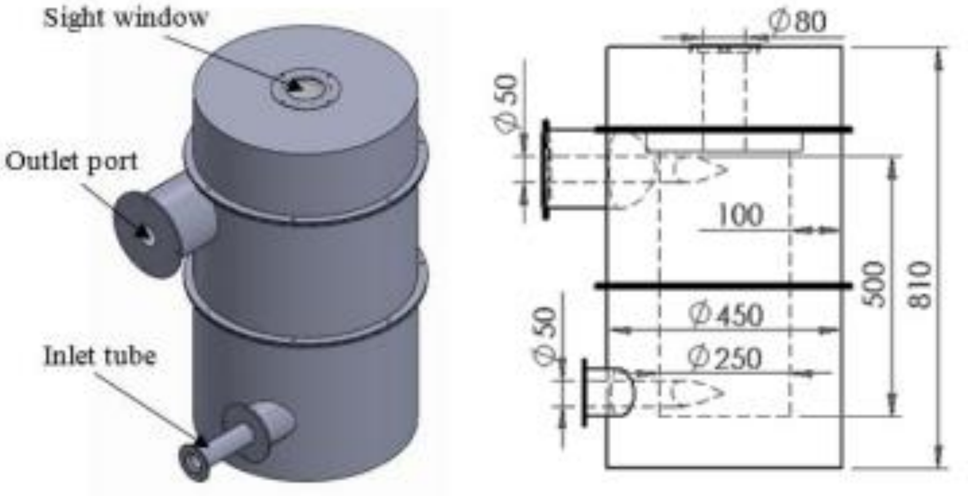


Figure 3.2: Premixed cyclone combustor model & schematic dimension in mm

However, as previously stated, the combustor parameter value will be changed during the optimization process. The details are as follows:

Table 1.1: Varying cyclone combustor parameter

Nozzle diameter, d (mm)	Combustor height, H (mm)
30	500
40	600
50	700

By using these parameter, combustor with varying parameter can be produced as shown below:

Table 1.2: Cyclone combustor design parameter set

Combustor Design	Nozzle diameter (mm)	Combustor height (mm)
A	30	500
B	30	600
C	30	700
D	40	500
E	40	600
F	40	700
G	50	500
H	50	600

I	50	700

Based from the parameter, the sequence A, B, C are the combustor with same nozzle diameter with increasing combustor height while A, D, G are the combustor with same height with increasing nozzle diameter.

3.3 Combustion Simulation using ANSYS Fluent (CFD)

ANSYS software was used for numerical modelling. The CFD code ANSYS-Fluent was used to solve a set of governing equations, comprising the equations of mass, momentum, species transport, and energy in Cartesian coordinates as shown below:

$$\frac{\partial \rho \tilde{u}_j}{\partial x_j} = 0$$

$$\frac{\partial \rho \tilde{u}_i \tilde{u}_j}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[(\mu + \mu_t)\left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i}\right)\right]$$

$$\frac{\partial \rho \tilde{u}_i \tilde{Y}_n}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\rho D_n + \frac{\mu_t}{SC_t}\right)\left(\frac{\partial \tilde{Y}_n}{\partial x_j}\right)\right] + \dot{\omega}_n$$

$$\frac{\partial \rho \tilde{u}_j \tilde{H}}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\lambda \frac{\partial \tilde{T}}{\partial x_j} + \frac{\mu_t}{Pr_t}\frac{\partial \tilde{h}}{\partial x_j} + \sum_{n=1}^{N} \rho D_n h_n \frac{\partial \tilde{Y}_n}{\partial x_j}\right] - \sum_{n=1}^{N} h_n^f \dot{\omega}_n$$

Figure 3.3: ANSYS software numerical modelling

Where Dn is the mass diffusivity of species-, assuming a constant value for each species, Yn is the mass fraction of species-n, ω̇n is the rate of chemical reaction, ui/j is the velocity in vector components, P is the pressure, λ is the thermal conductivity, Pr is the turbulent Prandtl number, ρ is the density and μ is the dynamic viscosity. While the sign represents the Favre averaging, Sct is the turbulence Schmidt number = μt/Dt where Dt is the turbulence diffusivity and μt is the turbulent viscosity (Khaleghi 2015).

Computational fluid dynamics (CFD) simulation is utilised to gain a more realistic understanding of the combustion process. CFD modelling is a useful approach for understanding combustion and flame behaviour and designing new combustion chambers. The current study used CFD simulation with ANSYS Software. ANSYS Modeller is used to simulate the computational fluid domain of the combustor, and ANSYS Meshing is utilised to mesh it. An unstructured tetrahedral grid covers the whole volume of the domain. The following are some ANSYS settings for the flameless combustion simulation and design of the cyclone combustion chamber.

Computational Fluid Dynamics (CFD) simulation is used to acquire a more realistic understanding of the combustion process. CFD simulation is a valuable technique that is commonly used for analysing combustion and flame behaviour as well as building new combustion chambers. As illustrated in Figure 3.1, an unstructured tetrahedral grid type is applied to the full volume of the domain. The governing equations are solved using the Fluent package's CFD algorithm. Tables 1.3 & 1.4 below summarise the simulation's boundary conditions and parameters, respectively.

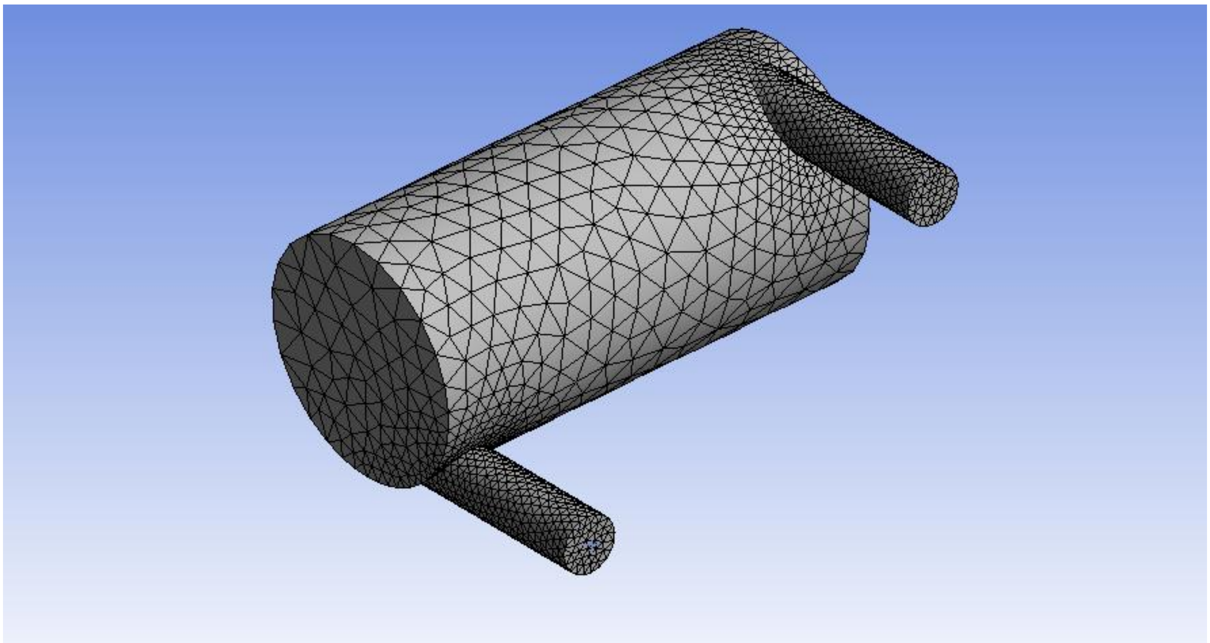


Figure 3.4: Design meshing

Table 1.3: Boundary conditions of simulation

Boundary condition		Detail setting
Fuel/air mixture inlet	Temperature	400K
	Pressure	Atmospheric
	Hydraulic diameter (dh)	Varied with d
	Turbulent intensity	~5%
	Mass flow rate	74 m3 /h
Pressure outlet	Hydraulic diameter	Varied with d
	Turbulent intensity	~5%

	Pressure	Atmospheric

Table 1.4: PG composition with lower heating value (LHV)

Species	Concentrations (Vol %)	LHV (MJ/m^3)
CH4	1.6	35.9
H2	11.5	10.8
CO	17.1	12.6
N2	54.6	-
CO2	13.1	-
O2	2.1	-
LHV of PG		4

Table 1.5: Input condition

d (mm)	F (m3/s)	A (l/min)	F/A	ϕ	mF/A	Vin	Jin
30	0.02	1200	0.017	0.89	0.038	53.13	0.61
40						29.89	0.95
50						19.13	1.7

For the gas mixture and chemical species, the species transport model is utilised. The ideal gas law is believed to be followed when mixing fuel and air. A set of those governing equations is calculated in the ANSYS FLUENT package using a steady-state and pressure-based segregated solver. For all variables, the SIMPLE method is used for pressure-velocity coupling with a second order upwind discretization scheme. The steady-state pressure-based solver was used in the modelling procedure. For all variables, the SIMPLE-algorithm was used for pressure-velocity coupling with second-order upwind discretization species mixing in conjunction with a typical reaction mechanism (two steps methane-air reaction and single step hydrogen-air reaction).

The experimental data of premixed or partially flameless combustion proved and validated the Eddy-dissipation concept (EDC) model (Mi 2009) (Li 2014). Furthermore, the conventional reaction mechanism produced appropriate temperature profiles based on experimental data for modelling low calorific value gas fuel burning in the flameless mode (Danon 2010). Hence, For the sake of this investigation, dealing with the turbulence chemical interaction is appropriate. For the radiation heat transfer model, P-1 with the weighted-sum-of-gray-gases model was adopted since it has various advantages such as decreased CPU demand and accurate prediction of the intricate combustor shape (Ilbas 2005). Another numerical research on the P-1 model with flameless combustion mode found that the numerical findings matched the experimental data (S. W. Hosseini 2015). For turbulence closure, the Reynolds stress model (RSM) with a conventional wall function is utilised. The RSM model was highly suggested for reliable prediction of swirl flow patterns when compared to the k- ε models (Danon 2010) (K. Z. Al-Attab 2011).

To cope with turbulence closure, the k- ε model and the complicated one Reynolds Stress model (RSM) are investigated. The k- ε standard and k- ε realisable turbulence models are not optimal in cyclonic flow patterns (Elsayed 2011) (Slack 2000) (Xiang 2005). The Renormalization Group (RNG) k- ε model is an upgraded version of the k- ε standard that allows users to enable a swirl flow factor that is predicted to be better than the regular k- ε model for highly cyclonic flow predictions (Chuah 2006). Other researchers strongly propose the RSM model for more accurate prediction of the axial and tangential velocities distribution in cyclonic flow patterns, and it is employed throughout the current CFD simulation for this work (Elsayed 2011).

ANSYS FLUENT includes many models of turbulence-chemistry interactions for the responding simulation approach, the reacting flow simulation, in the species transport model, notably Finite Rate/Eddy Dissipation (FR/ED), Eddy Dissipation (ED), and Eddy Dissipation Concept (EDC) (FLUENT 2016). These models are taken into account while determining the best model to use for the current combustor's numerical simulation of producer gas flameless combustion. It's because the EDC produces superior results for simulating flameless combustion when compared to other models (Christo 2005).

An essential element of flameless combustion is the reactants dilution ratio, which may be used to compute the rate of internal gas recirculation (Wünning 1997) and it is closely related to the geometry of the combustor (Liu 2013). For CFD simulation, the reactant dilution ratio can be expressed as Equation 1.0 & 1.1. It is also comparable to the reactants dilution ratio estimated from an empirical equation which (Khalil 2014) developed for a swirl combustor.

$$R_{dil,CFD} = m_{eg} / m_{F/A} = (m_{up} - m_{F/A}) / m_{F/A} \qquad (1.0)$$

$$R_{dil,Eq.} = 0.0059 \times V_{in} + 0.9805 \quad (1.1)$$

Where meg is the total mass flow rate of gas flowing upwards via a particular plane, mup is the gas density, and mF/A is the initial premixed charge of the arriving reactants.

Massive dilution of fresh reactants with hot flue gas can improve temperature uniformity throughout the combustion chamber. One of the primary benefits of flameless combustion mode is temperature uniformity (Tu) inside the combustor, which allows the residual fuel to completely react with oxygen, minimising CO emissions. Tu can be defined as the ratio of a specific temperature (Ti) at any position to the mean temperature (Tave) of the combustion volume (Veríssimo 2011), as shown in Equation (1.2).

$$T_u = |T_i - T_{ave}| \, / \, T_{ave} \quad (1.2)$$

3.5 DESIGN OF EXPERIMENT (DOE) PARAMETER OPTIMIZATION

Full factorial DOE is the form of DOE used for optimization because of its techniques to creating and carrying out experiments to assess the influence that different amounts of inputs have on outcomes. DOE basically determines what amounts of inputs will optimum the results. For this project, two variables were implemented: the nozzle diameter of the air inlet and the height of the cyclone combustor, each having three ranges (level), for a total of nine runs or data sets (3^2). The combustion simulation data will be tallied and loaded into Minitab. Minitab will evaluate the data and create the Pareto chart, which displays the absolute values of the standardised effects from biggest to smallest. In other words, the purpose of the Pareto chart is to identify the amount and significance of the impacts (Minitab, DOE n.d.).

Effects Pareto chart to examine the relative size and statistical significance of main and interaction effects. The chart depicts the following sort of effect:

- The chart displays the absolute value of the unstandardized effects if the model does not include an error component.
- If an error term is included in the model, the graphic presents the absolute value of the standardised effects.

The standardised effects are t-statistics that are used to test the null hypothesis that the effect is 0 percent. In addition, the chart displays a reference line to identify which effects are statistically significant depending on the significance threshold (alpha) (Minitab n.d.) (CUSUM n.d.). The findings will then be analysed by a response optimizer to identify the precise value of the combustor parameter that will achieve the best design based on NOx and CO emissions

A main effect is the effect of one independent variable on the dependent variable—averaging across the levels of the other independent variable. Thus there is one main effect to consider for each independent variable in the study. Main effects are independent of each other in the sense that whether or not there is a main effect of one independent variable says nothing about whether or not there is a main effect of the other. Researchers can use a basic effects analysis to break down interactions by assessing the influence of each independent variable at each level of the other independent variable.

The Minitab programme will then generate an ideal solution and provide an optimization plot. This interactive graphic allows you to adjust the parameters of the input variables to do sensitivity studies and maybe improve on the first result. To determine the combination of input variable values that optimises a single answer or a series of responses, the Response Optimizer are utilized. Response optimization works best when combined with appropriate subject area expertise, such as background information, theoretical concepts, and knowledge gained via observation or prior experimentation (Minitab, Interpret the key results for Analyze Response Surface Design n.d.).