

CHAPTER 2

Theory

This chapter describes the theory behind producer gas engine research. It is divided into two main topics. They are biomass gasification and gas engine fundamentals. The first part explains fixed bed gasifiers, the reactions in gasification processes, composition of producer gas and characteristics of biomass related to gasification. The second explains the combustion of gaseous fuels, premixed-charge of gas engine, SI producer gas engines and diesel fuel with producer gas, or dual fuel engines.

2.1 Biomass Gasification

2.1.1 Fixed bed gasifier

Gasification is the conversion of biomass by heat in the presence of a limited supply of air to gases that can be used to run an engine. Biomass is a term used to describe the source of the renewable fuels, such as wood, agricultural crops, and their waste products, that can be used to produce a renewable energy. An example of the use of this is the production of producer gas. The temperature of the breakdown of the biomass is higher than 700°C. In the presence of air, carbon is turned into producer gas. This gasification process takes place in a gasifier. Gasifiers can be classified as various types. They can be fixed bed, fluidized bed, entrained flow and twin-bed gasifiers. This research was performed using only a downdraft gasifier, and therefore, this section need only to explain the fixed bed type of gasifier.

Fixed bed gasification is simple in operation, and design, appropriate for small gasifiers of less than 100 kW_{th} and most in batch or continuous mode. (Chopra et al, 2007). Fixed bed gasifiers come in three types, downdraft, updraft and cross draft, as shown in Figure 2.1.

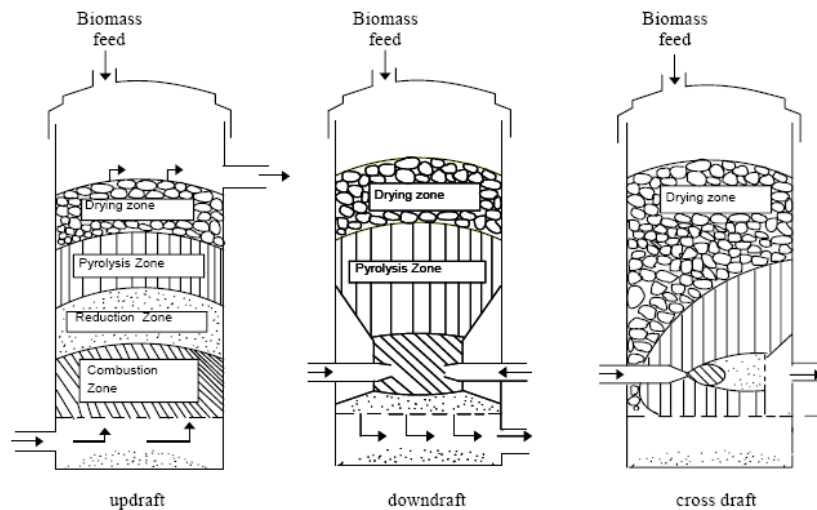


Figure 2.1 Downdraft, updraft and cross draft gasifier (Salam et al, 2010)

In downdraft gasifiers, the biomass is fed at the top, and the air is fed from the side and producer gas exits at bottom of gasifier. The pyrolysis gas is produced by the high temperature in the limited air, above the combustion zone. It is then reduced in the even hotter carbon below, into producer gas and hydrogen. Therefore, this gas product has a low tar content, and is suitable for internal combustion engines.

In updraft gasifiers, the biomass is fed at the top. The biomass is oxidised from the bottom in the incoming air. It is then reduced in red hot carbon, an endothermic reaction that produces less heat, pyrolyses the biomass immediately above the reduction zone. As heat rises so does the gas, the heat in the gas dries the incoming biomass before being extracted at the top of the gasifier. At the bottom of the gasifier the ash produced by burning the

biomass falls into an ash collector. This gas has high tar content, compared to downdraft gasifier.

In cross draft gasifiers, the biomass is fed at the top. The air is fed in at the side of the biomass. The ash moves downwards as in all gasifiers. The gasifier design operates with low ash fuels like charcoal and coke, tars and volatiles are lower in these fuels. On the other hand, the use of charcoal and coke as a fuel make for a very high temperature and can cause problems with the fabric of the gasifier. This gasifier is appropriate for small scale applications of less than 10 kW.

Table 2.1 shows the details of technical and operational parameter values of each gasifier type. The downdraft gasifier design produces a better grade of gas for engines, than the other two. For the downdraft gasifier, the suitable biomass size is between of 20-100 mm and the moisture content of fuel should be in a range of 12-25%. This gasifier has a low tar content, which reduces the amount of additional gas cleaning. However, the disadvantages of gasifiers are fuel sensitive, load fluctuations and high slag formation.

Table 2.1 Characteristics of fixed bed gasifiers
(Brandin et al, 2011), (Rajvanshi, 1986)

Characteristics	Downdraft	Updraft	Cross draft
Fuel size (mm)	20-100	5-100	5-20
Moisture content (%)	12-25	40-60	10-20
Turndown ratio?	3-4	5-10	2-3
Startup time (min)	10-20	15-60	10-20
Temperature of gas out (°C)	700	200-400	1250
Quantity of tar (g/Nm ³)	0.015-5	30-150	0.01-0.1
Cold gas heating value (MJ/Nm ³)	4.5-5.0	5.0-6.0	4.0-4.5
Power capacity (kW _{th})	<5000	<20000	10
Size of gas cleaning section	small	Large	small
Sensitivity to fuel	High	low	High
Sensitivity to load fluctuations	High	low	High
Slag formation	High	low	High

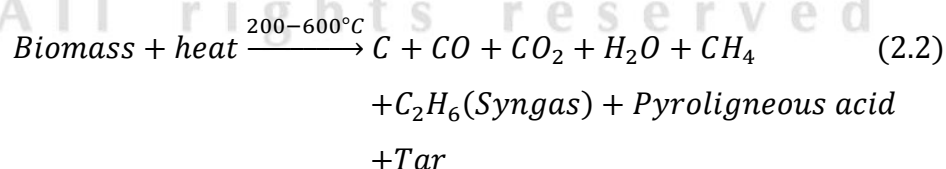
2.1.2 Gasification processes

Reactions of biomass gasification in fixed bed gasifier consist of four processes: drying, pyrolysis, combustion and reduction. The details are as follows.

The drying zone is for taking the water/moisture content out of the body of biomass. This process reduces the weight of the fuel, the size and color changes into a dark color. The average energy used to evaporate water is 1.26 kcal/kg. The products of this zone are steam and the volatile parts of the biomass, the temperature in this zone between of 100-135°C. The chemical reaction of drying zone is given as



In the pyrolysis zone (or distillation zone,) the biomass is decomposed with high heat in limited oxygen. The reaction is exothermic. The heat produced causes the biomass to release all of its volatile constituent parts to boil off forming a volatile gas (syn-gas) and leaving a pure carbon residue. The product of pyrolysis (syn-gas and carbon) move to the oxidation zone and some will breakdown to small molecules such as carbon dioxide and water. The temperature in this zone is between of 200-600 °C. The chemical reaction of pyrolysis zone is given as



Oxidation zone or combustion zone is where oxygen re-acts with carbon and hydrogen. In the complete combustion process, the carbon is converted into carbon dioxide and hydrogen is converted into water. The combustion

reaction is exothermic and temperature of this zone between 1100-1500°C. The chemical reaction of oxidation zone is given as



Reaction zone, carbon dioxide, water and incombustible gas from pyrolysis zone are push through a red hot charcoal bed and converts products of previous zone into carbon monoxide hydrogen and methane. The chemical reaction of (6) and (7) are major reduction reactions and starting to exothermic, the gas temperature is reducing and between 800-1000°C.



2.1.3 Producer gas

Producer gas is generated from gasification process. Normally, this gas was made from coal and later from biomass which can be obtained from agricultural and industrial residues. The main composition of producer gas is carbon monoxide, hydrogen, methane, carbon dioxide and nitrogen. Analyses of composition of producer gas are given by gas chromatography. Table 2.2 shows composition of producer gas in downdraft gasifiers while operating with charcoal or wood. The main constituents of charcoal

Producer Gas included carbon monoxide (29.6-30.5%), hydrogen (3.7-8.5%), carbon dioxide (5-12%) nitrogen (49.5-60%) and a small amount of methane (0.35-1%). While, the use of wood gives carbon monoxide (19-26.4%), hydrogen (13-22%), carbon dioxide (2-4.8%) nitrogen (38.4-59.5%) and methane (0.8-3.5%). In comparing combustible gas, hydrogen and methane of wood are higher than. On the other hand, carbon monoxide of charcoal is more than wood. The use of wood provides high calorific value more than charcoal. Because, the wood has high moisture content that means the water lead to the increase of hydrogen (Das et al, 2011). However, the more moisture may affect fuel combustion. The use of wood must be careful of tar and moisture content in the producer gas, because that can wear of engine and lead to maintenance, repair and reliability (Reed et al, 1988). The highest calorific value of producer gas from wood is higher than that of charcoal, both are between of 4.71–6.89 MJ/Nm³ and 4.4-5.0 MJ/Nm³ respectively. However, to increase the calorific value of gas can input steam, carbon dioxide or fraction of oxygen in gasifier.

Table 2.2 Composition of biomass Producer Gas from downdraft gasifiers

Biomass	Volume Percentage (%)					Calorific value MJ/Nm ³	Reference
	CO	H ₂	CH ₄	CO ₂	N ₂		
Charcoal	30	7	1	2	60	5.00	FAO, (1988)
Charcoal	30.5	8.5	0.35	4.8	49.5	4.64	Dussadee et al., 2015
Charcoal	29.6	3.7	0	-	59.5	4.4	Sombatwong., (2013)
Wood	19	16	3	12	52	5.50	FAO, (1988)
Wood	26.4	21.9	3.5	9.8	38.4	6.89	Tongorn, (2007)
Wood	25	15	1.3	10	48.7	5.11	Pendey et al., (2012)
Wood	22	13	0.8	5	59.5	6.34	Pratik et al., (2009)
Wood	23	20	1.5	11	43.7	4.71	Chawdhury et al.,(2011)

2.1.4 Characteristics of biomass related to gasification

The type of biomass to substitute for fossil fuel has different properties. Details of charcoal and wood are shown in Tables 2.3 and 2.4. In the

gasification process, the major parameters affecting gasifier efficiency include elemental composition, moisture, ash, volatile matter, bulk density and morphology. The details of parameters on gasification are as follow.

Moisture content

In general, biomass has a moisture content that is water quantity in the material. The moisture content in biomass can be calculated from ratio of the water weight per weight of total material. For combustion in gasification processes, the use of low-moisture content biomass is better than high moisture content. Because the moisture content is a barrier to combustion; the heat that is lost to evaporation of moisture contained in the biomass (Bahadori et al, 2012). Eventually, the heating value of gas, quality gas and cold gas efficiency is reduced, while the tar level is higher.

Elemental composition

The elemental compositions of the biomass are important in relation with heating value and emissions. The main elemental compositions of wood for producer gas include carbon (46-50.6%), hydrogen (5.20-5.98%), oxygen (42.88-44.90%), nitrogen (0.05-1.40%) and sulfur (0-0.03%). While, producer gas from charcoal are include carbon (66.4-75.6%), hydrogen (0.91-3.3%), oxygen (13.81-18.40%), nitrogen (0.2-0.28%) and sulfur (0-0.2%), as shown in Table 2.4. Comparing of both biomasses for gasification process, the use of charcoal has high carbon more than wood while hydrogen is low. The high carbon content in biomass leads to high carbon monoxide of producer gas. Meanwhile, the biomass with high hydrogen content leads to a high percentage of hydrogen in gas.

Ash

Normally, the ash content of wood and charcoal are between 2.30-15.8 % and 0.36-3.35% of the biomass's weight, respectively, shown in Table 2.3.

The quantities of ash depend on biomass type. Therefore, the uses of biomass in gasification process that affected on the reactor design, especially, the ash removal system. The melting behavior of ash leading to slagging and accumulate in an inner reactor.

Volatile matter

Quantity of volatiles has a major impact on tar production in the gasification process, depending on type of biomass and reactor design system. The temperature and heat rate affect volatile matter, together with physical property. The compositions of tar are approximately 200 chemical species. The use of updraft gasifier produces more tar content than downdraft gasifier (Salam et al, 2010). Generally, the content of volatile matter in wood and charcoal are between 75.3-79.7% and 23.8-30%, respectively, as shown in Table 2.3.

Table 2.3 Proximate analysis and high heating value of biomass

Type of biomass	FC (%)	VM (%)	Ash (%)	HHV (MJ/kg)	Reference
Longan charcoal	56.7	26.9	7.75	22.5	Tippayawong et al, 2010
Redwood charcoal	67.7	30.0	2.30	28.8	Parikh et al, 2004
Parawood charcoal	49.9	23.8	15.8	20.3	Manabunying,2004
Longan wood	16.6	77.4	2.50	17.8	Tippayawong et al, 2010
Redwood	19.9	79.7	0.36	20.7	Parikh et al, 2005
Eucalyptus wood	21.3	75.3	3.35	18.6	Parikh et al, 2005

Table 2.4 Ultimate analysis and density of biomass

Type of biomass	C (%)	H (%)	O (%)	N (%)	S (%)	Density (kg/m ³)
Longan charcoal	-	-	-	-	-	290
Redwood charcoal	75.6	3.30	18.40	0.20	0.20	-
Parawood charcoal	66.4	0.91	13.81	0.28	0.00	210
Longan wood	48.8	5.20	44.60	1.40	0.00	620
Redwood	50.6	5.98	42.88	0.05	0.03	450
Eucalyptus wood	46.0	5.82	44.90	0.30	0.00	495

Bulk density and morphology

Bulk density of biomass is ratio of mass per a unit volume of material. Different types of biomass have different bulk densities and depend on species. Usually, the bulk density of wood is in a range of 450 - 620 kg/m³. The charcoal is between 210-290 kg/m³. This is lighter than wood, as shown in Table 2.4. In the engineering work, the bulk density and morphology of biomass is related with transportation, collection and storage facility (Kargbo et al, 2009).

2.2 Gas Engine Fundamental

2.2.1 Combustion of gaseous fuels

The combustion of gaseous fuel is the chemical reaction of the gas with oxygen. The reaction was exothermic and heat energy can be applied to work. Fundamentally gas combustion reaction must have three factors, including gaseous fuel, oxidizer and heat source. The highest composition of gaseous fuel is hydrocarbons. The heating value of each gas will be different and depend on composition of the gas that includes carbon, hydrogen, methane, carbon monoxide and carbon dioxide. The samples of gaseous fuels are producer gas, biogas, natural gas, oil gas and liquid petroleum gas. Most gaseous fuels are used in industrial, power production and transportation.

In the combustion of gaseous fuel, the flame is divided into two types ; premixed and diffusion flames. The samples of premixed flame include Bunsen burner, gas appliance stoves and SI engine etc. The diffusion flames are those in candles, welding torch and diesel engine etc. However, this study examined premixed flames only, due to the similarity of combustion phenomenon with the in cylinder combustion of the spark ignition engine. The premixed flame phenomenon is related to the research work conducted

here. The combustion characteristics of premixed flame can be explained with Bunsen burner. The main focus of that combustion is gaseous fuel that mixes with oxygen until homogeneous before start of combustion. The gaseous fuel is fed into the tube and flows through nozzle in the bottom of burner. The flow of gas is laminar and parabola in shape. The pressure of gaseous fuel is reduced with gas flows through nozzle, the air in and the around nozzle flow mixes with gas at air inlet and flow up to the top of the Bunsen burner and where the gas is ignited becomes a flame. At the point tip, the velocity of flame is low with that loses of heat and leading to a stable flame. The flames will have three zones include dark zone, luminous zone and post flame zone. The dark zone is unburned gas area. The luminous zone is burning gas area and that release heat. The post flame zone is the back of flame, that zone has product of burned gas. The temperature of flame is increasing rapidly and spread throughout the mixture. If the mixture is in the tube, the flame propagation is combustion wave that moves along the tube. The velocity of flame in tube is burning velocity or flame speed. Normally, the burning velocity is lower than speed of sound and is called deflagration.

Consideration of the burning velocity from combustion can be analyzed from laminar premixed flame. The assumptions for analyzing flame speed in the system are: steady flow, the constant section area tube, one-dimensional flow, no external heat source, and ideal gas. Figure 2.2 shows combustion of laminar premixed flame with constant section area tube. The laminar premixed flame may be considered for stationary flame or propagation flame. For stationary flame, the velocity of flame is equal to unburned gas flow while the velocity of flame in propagation flame is more than unburned gas flow. The propagation flame, the velocity of flame can flow backward and forward. The velocities of flame are backward flow, provided velocity of air fuel mixer is less than velocity of flame and lead to flashback. Whereas the velocities of flame forward, means the velocity of air fuel

mixer is more than velocity of flame. These flame characteristics are liftoff and blow off in the end.

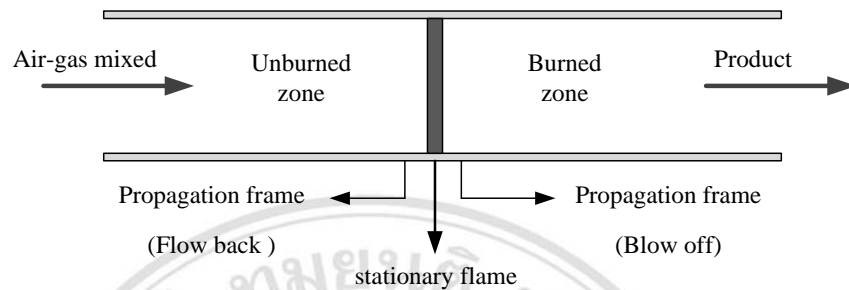


Figure 2.2 Combustion of Laminar premixed flame

The flame stability of gaseous fuel can be achieved with the avoidance of flashback and liftoff of flame. The flashback is related to the safety of the device. The liftoff flame is related to incomplete combustion and represents the flame is distant from the exit of the gas, that is caused by the velocity of air fuel mixed being too high. When the high velocity of gas is blow off velocity. The related factors include types of fuel or oxidation, air-fuel ratio, temperature of mixed, combustor pressure etc. Figure 2.3 shows flame stability of Producer Gas from biomass gasification with air oxidation. The suitable of air-fuel ratio for flame stability is between 0.79-1.2 m/s. While, the low and high reactant velocity is between 0.79-1.60 m/s and that is proportional to the air-fuel ratio. For producer gas flashback, the air-fuel mixed of that is in lean mixed and less than 0.79 of air-fuel ratio. The reactant velocity in beginning is flashback in 0.6 m/s. The blow off of the producer gas, the lower reactant velocity of blow off is 0.8 m/s and 1.25 m/s with occur in lean mixer and stoichiometry.

A typical laminar premixed flame is divided into three zones include preheat zone, reaction zone and product zone as show in Figure 2.4. The preheat zone is unburned of gas, that gas gets heat from the reaction zone. The concentration of the air fuel mixture is higher and some spread of flame

radicals. The reaction zone, these zones are including the flame visible to the eye. The temperature of this zone is rapidly increasing while the concentration of the air fuel mixture is rapidly declining and causing another product. The colors of orange flame are soot and the blue are flame radicals, respectively. The product zone is constant with the maximum temperature.

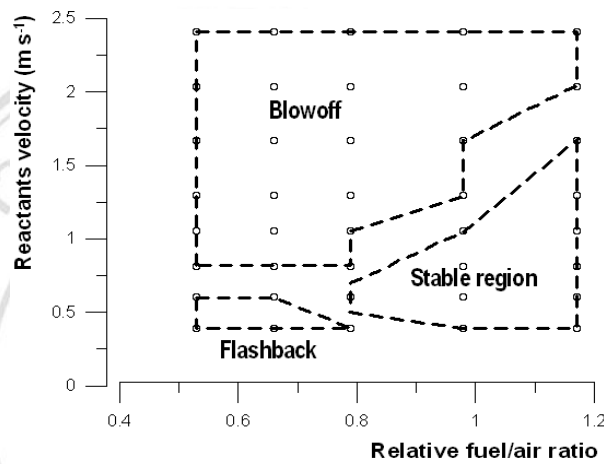


Figure 2.3 Flame stability of producer gas (Hernandez et al, 2012)

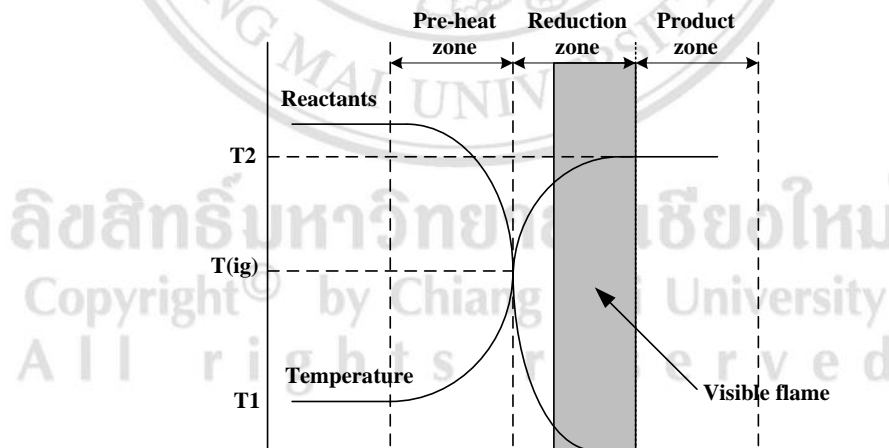


Figure 2.4 Laminar premixed flame

2.2.2 Factors influencing burning velocity of gaseous fuels

Factors that affect the burning velocity of gaseous fuel include stoichiometry, concentration of oxygen, additives, pressure and temperature.

Table 2.5 shows effect of stoichiometry on laminar burning velocity of various gaseous fuels. The maximum burning velocity is dependent on stoichiometry that means adjusting the air fuel ratio before combustion. Considering burning velocity of combustible gas in producer gas, hydrogen has highest burning velocity of 2700 m/s. The carbon monoxide has widest limit of flammability but burning velocity is lower than hydrogen. The burning velocity is 0.45 m/s. The burning velocity of methane is close carbon monoxide nevertheless the flammability limit is narrower. The burning velocity is 35 cm/s. The maximum burning velocities of three gases are found just to the rich mixer. In comparing with producer gas that operates on SI engine (Shidhar et al, 2004), the pressure and temperature in experiment are 0.1 MPa and 300 K, respectively. The components of combustible gas are carbon monoxide (20%), hydrogen (20%) and methane (2 %), the burning velocity is 0.50 m/s which is about 42 percent more than methane. The fraction of oxygen in the air is important as it can increase burning velocity. However, addition of oxygen concentration in the air must be controlled accordingly with air fuel ratio, and must be in range of stoichiometry (Bibrzycki et al. 2010). Putting in additives can catalyze and will have an effect on increasing burning velocities. Example, filling hydrogen and steam with methane, the increasing fraction of hydrogen will increase burning velocities, while addition of steam concentration lead to decreased burning velocities (Boushaki et al., 2012). The burning velocity decreases with increased pressure and flame temperature. The cause of the increase is due to less active radicals available to diffuse upstream to enhance flame propagation (Borman et al., 1998). The effect of reactant temperature and increasing burning velocities leads to increase reactant temperature. The burning velocities of these experiments goes from 4.7 m/s to 9.5 m/s, the flame temperature is increase from 425 K to 700 K (Saeed et al., 2003). However, the reactant temperature is less important than the ignition temperature which is the lowest temperature that gas can ignite, without regarding to the ignition delay time and an external source of

ignition. Table 2.6 shows auto-ignition temperature in air of gaseous fuel at 20 °C and 1 atmosphere. The auto-ignition temperature is important and related with directly CR of SI engine. The use of gaseous fuel with low auto ignition temperature leads to knocking of the engine. In the other hand, the gaseous fuel with high auto-ignition temperature was unable to be used with low CR engine and the power output was low. Then fuel type is suitable for single CR.

Table 2.5 Effect of stoichiometry on laminar burning velocities
(Borman, 1998), (Shidhar et al, 2004)

Fuel + Air	$\phi = 1$ (by mass)	Lean (by mass)	Rich (by mass)	Laminar burning velocities (cm/s)		
				$\phi = 1$	Lean	Rich
CO	29.50	12.5	74	45	12	23
H ₂	29.50	4.0	75	270	65	75
CH ₄	9.47	5.0	15	35	2.5	14
Producer gas	1.35	-	-	50	10.3	12

Table 2.6 Auto-ignition temperature of gaseous fuel (Hagos et al, 2014)

Fuel	Auto-ignition temperature (°C)
Carbon monoxide	609
Hydrogen	400
Methane	537
Propane	470
Methanol	385
Natural gas*	540
Producer Gas*	625

Component of producer gas: carbon monoxide (29.6%), hydrogen (19.66%), methane (5.27%), carbon dioxide (5.41%), nitrogen (40.56%)

2.2.3 Combustion in spark ignition engines

Combustion of spark ignition engines is divided into two zones including burned zone and unburned zone (Tinaut et al., 2005), as shown in Figure

2.5. In burned zone, combustion produced gas expansion compresses the unburned mixture ahead of the flame and displaces it toward the combustion wall. The combustion produced gas expansion also compresses those parts of the charge which have already burned, and displaces them back toward the spark plug. During the combustion processes, the unburned gas elements move back toward the spark plug. Further, elements of the unburned mixture which burn at different times have different pressures and temperature just prior to combustion. Figure 2.6 shows characteristics flame propagation of burned and unburned in top cylinder of SI engine. The flame propagation is smooth spherical and spread over a large area to the cylinder wall, whereas in fact the actual flame propagation is turbulent premixed flame with a thin wrinkled, the cause of swirl, turbulence, bulk motion and squish etc. (Heywood, 1988).

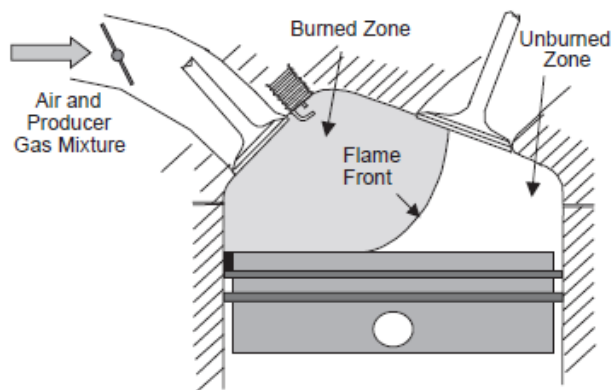


Figure 2.5 Analysis combustion characteristics on a spark ignition engine

(Tinaut et al., 2005)

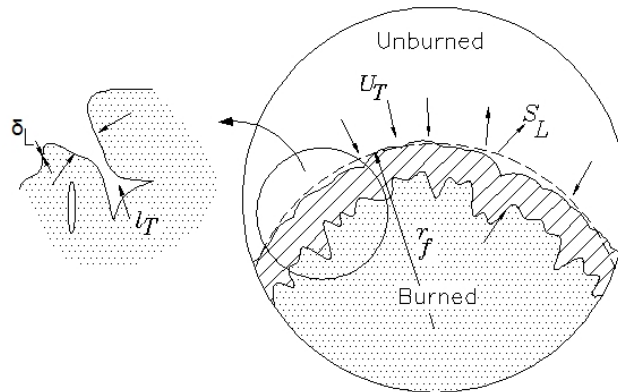


Figure 2.6 Flame propagation characteristics of a spark ignition engine
(Sridhar, 2003)

Figure 2.7 shows the stages of flame development in SI engine, with a set of shadowgraph photographs taken at intervals of the spark plug electrode gap in one cylinder. The combustion on SI engines starts when electrical energy is fed into the discharge, the arc expands and exothermic chemical reactions capable of sustaining a propagating flame develop. The outer boundary of this developing flame kernel is approximately spherical and smooth with modest irregularities, corresponding to a thin reaction zone with high temperature gases inside. As this developing sheet-like flame grows, it interacts with the turbulent flow field in the vicinity of spark plug and spreads thoroughly in the chamber. The generality of flame structure in the burning process is thin, moderately wrinkled but simply connected, front or reaction sheet between unburned and unburned and burned gas. The thickness of the front is about 0.1 mm which is comparable to the thickness of a laminar flame.

The combustion stages of SI engine start and end at top dead center (TDC) position. Whereas, the combustion will occur before at the TDC about 20 degrees and finish a few after TDC actually. Combustion processes on SI engine are divided into three stages: ignition delay, propagation of flame, and

afterburning, as shown in Figure 2.8. First stages is the ignition delay (a to b), the pressure in cylinder is increase with crank angle moving on TDC. The ignition delay is a lag in air-fuel mixing while reacting to the combustion. The delayed mixing of the charge is called physical delay and the remaining delay is called chemical delay. The delay of SI engine depends on chemical delay and temperature that is the main factor on ignition timing of engine. Second stages is the propagation of flame (b to c), the pressure in cylinder rise rapidly. The pressure increase at start of ignition and ends when highest pressure which occurs after TDC. The burning velocity has an influence on pressure rise in cylinder which quickly combusts and leads reducing knock and increases efficiency. The parameters affecting ignition delay and propagation of the flame included type of fuel, air-fuel ratio, turbulence of gas, CR, load, pressure and temperature of charge, engine speed etc. The process of after end combustion, the pressure is reduced.

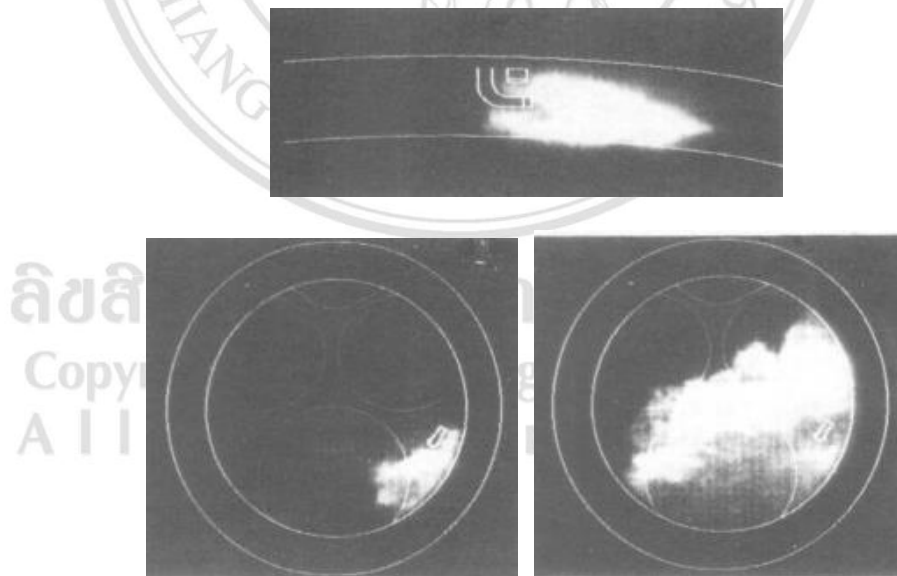


Figure 2.7 Development of a flame kernel in a SI engine (Bates, 1989)

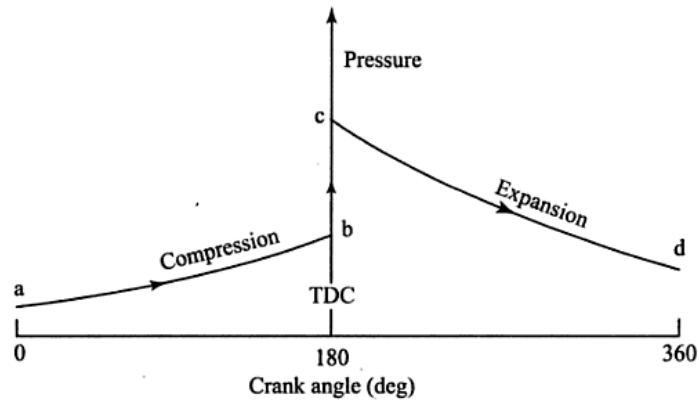


Figure 2.8 Stages of combustion on SI engine (Ganesan, 2002)

In Figure 2.9, it shows the combustion stages in SI producer gas engine with varied CR and compared original diesel engine (Sridhar, 2003). The use of low calorific value has caused ignition delay and the retarding of flame propagation. While, the selection of a CR was affect both combustion. Therefore, the use of producer gas with SI engine is only suitable with an appropriate CR. For the effects of pressure and air-fuel ratio on producer gas combustion is shown in Figure 2.10. Experimental use of combustor was similar to actual combustion chamber of the SI engine (Serrano et al, 2008). The detail of image has provided the effect of pressure, mixture and time on laminar burning velocity. Increasing the pressure in the cylinder during combustion will increase the rich flame and laminar burning velocity and cause a power output increase when applied to the engine. Simultaneously, the air-fuel ratio is stoichiometric, the characteristics of flame was better lean and rich mixer.

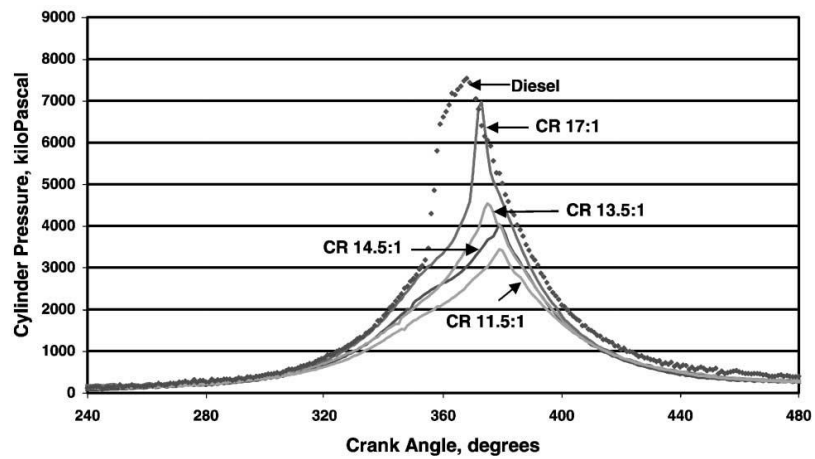


Figure 2.9 Effect of CR and type of fuel on stages of combustion (Sridhar et al, 2000)

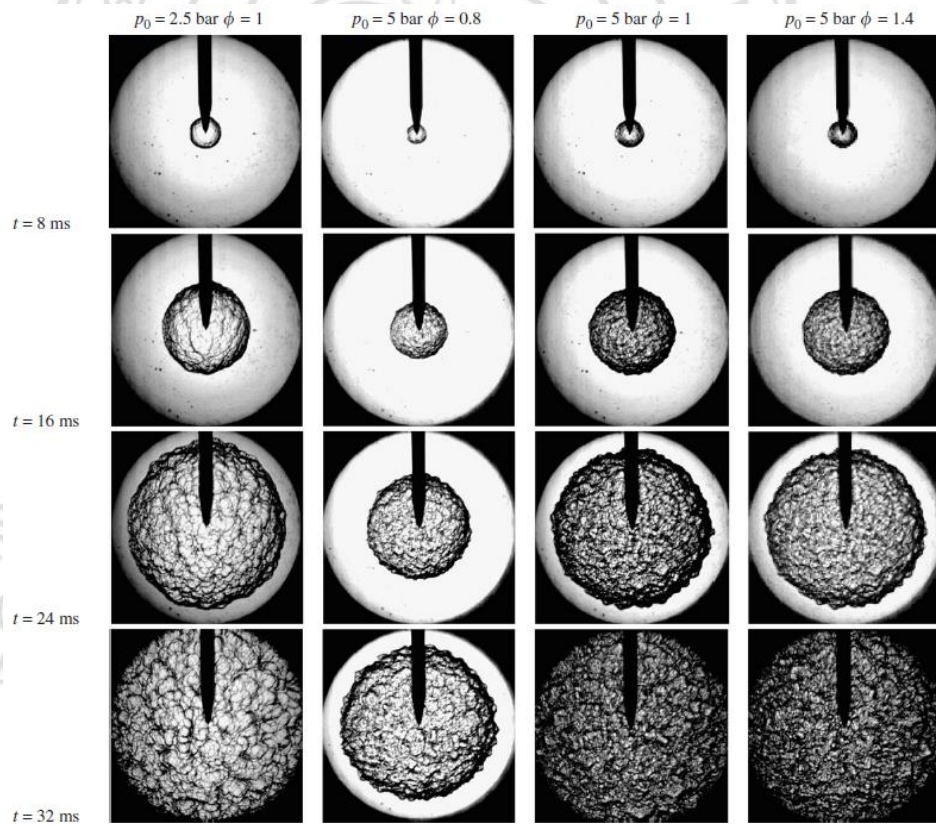


Figure 2.10 Characteristics of flame is varied pressure and air-fuel mixer (Serrano et al., 2008)

The equation of laminar burning velocity for various air fuel mixed of internal combustion engine are as follow (Turns, 2012)

$$S_L = S_{L,0} \left(\frac{T}{T_0}\right)^\gamma \left(\frac{P}{P_0}\right)^\beta (1 - 2.1Y_M) \quad (2.11)$$

when T is temperature in cylinder, T_0 is reference temperature (298 K), P is pressure in cylinder, P_0 is reference pressure (1 atm), Y_M is the mass fraction of diluent present in the air mixture, $S_{L,0}$ is laminar burning velocity reference, γ and β are function of the equivalence ratio. The equation can be defined by

$$S_{L,ref} = B_m + B_2(\phi - \phi_M)^2 \quad (2.12)$$

$$\gamma = 2.18 - 0.8(\phi - 1) \quad (2.13)$$

$$\beta = -0.16 + 0.22(\phi - 1) \quad (2.14)$$

when ϕ is air fuel ratio of each fuel and B_m , B_2 and ϕ_M can be defined from Table 2.7 (Turns, 2012)

Table 2.7 The values of B_m , B_2 and ϕ_M

Fuel	ϕ_M	B_m (cm/s)	B_2 (cm/s)
Methanol	1.11	36.92	-140.51
Propane	1.08	34.22	-138.65
Isooctane	1.13	26.32	-84.72

However, for producer gas operated SI engine, the laminar burning velocity expressed as. (Shidhar, 2003)

$$S_L = \left(\frac{P}{P_0}\right)^{0.2744} 94.35(0.96 + 1.2(\phi - 1))(1 - 2.4Y_M) \quad (2.15)$$

2.2.4 Producer gas engine

The producer gas engine is internal combustion engines using producer gas as a primary fuel or replaced original fuel that is gasoline or diesel. Previously, the use of producer gas on internal combustion engine was divided into 2 types. First, the application in spark ignition engine is 100% of producer gas. Second, application in compression engine or diesel engine in dual mode which is, perhaps, called a dual fuel engine. The main reason to apply that engine is due to the fuel crisis and rising oil price in 1973 and 1979 (FAO, 1988) and Second World War in 1920-1940. However, development of technology and application is rather ambiguous. The development of producer gas started in the 18th Century to take advantage of producer gas that was produced by The Town Gas Company in London, England. The first fuel produced was called producer gas from coal and was used for lighting in the houses and streets of the city. This sometimes is called "Town Gas". Earlier it had been found to produce gas from the distillation of wood. Later in 1816, that technology expanded to USA where it was mainly used for light manufacturing industry enabling people to work at night. In 1839, the first commercial gas generator is updraft gasifier with air oxidation. Development of gasifier used different fuels and had been widely used as an energy source in the industry. While, that industry started to take off with widely available liquid fuels in 1920. However, during 1920-1940. Second World War there was a shortage of liquid fuel. Up until 1973 to 1979 the fuel crisis, they had to pay attention and trying to develop this technology again, till the present.

The producer gas engine can be classified into 2 systems. It consists of gas generator or gasifier system and the engine for generated electric power or

water pump or mills. The major component of gas generator system consists of gasifier, gas cooling and gas cleaning units, shows in Figure 2.11. A gasifier producing producer gas for engine normally, there are three types such as up draught, downdraught, and cross-draught gasifiers. Basic element of a gasifier includes feedstock, hopper, combustion chamber, air nozzles, grate, shaker linkage and insulation. They can use many fuels, namely coal, wood, charcoal and residues from agricultural and industry product. A gas cleaning unit includes a cyclone, a venturii and packbed scrubber, biomass filter, fabric filter, and paper filter. Water cooling e reduced the temperature of producer gas, and was the common heat exchanger. The internal combustion engine to generate electric power consisted of a surge gas tank, air-gas mixer and generator. The surge gas tank continuously acts as a gas flow control unit, controlling the amount of gas and its pressure. The air-gas mixer controls the correct ratio of air with the producer gas, approximately a 1:1 ratio of fuel to air by volume. Variations in the producer gas mixture cause sharper changes in engine power than in similar variations with a gasoline a gasoline mixture. An elementary gas mixer for SI engines using producer gas fuel includes a gas control valve and air control valve. When running, suction from the engine draws air from the gas producer, through the gas cleaning and gas cooling system, and into the air-gas mixer where air is mixed with the gas, then into the engine. The engine can then run and produce the electric power.

Before 2000, the performance of a producer gas engine whose power output was reduced by 40-50%, while the thermal efficiency is very low when compared with an original gasoline engine. But since 2000 to the present, improvements of engine performance has increased, possibly engine development by Sridhar and Raman research. Increasing CRs of producer gas engines lead to increase power output, 17:1 is the highest CR and 21% is the highest thermal efficiency (Sridhar et al, 2003). Recent research was carried out to operate producer gas on a gas engine at 12:1 of CR and

compared diesel engine and natural gas engine shows in Figure 2.12 (Raman et al, 2013). The power output efficiency of producer gas engine is lower than natural gas engine and diesel engine on low and medium load while the efficiency is similar to the natural gas engine on high load. However, the cost grid electricity of producer gas was less than with compare original or dual fuel engine (Aung, 2008), (Dasappa et al., 1999), beside the resource is a renewable energy and environmental friendly. The emissions of the producer gas engine are low, harmful gas which consists of CO, HC and NO_x while CO₂ and O₂ are rather higher compared to gasoline (Munoz et al., 2000), (Shah et al., 2000). The major problem of low engine performance is low energy density of producer gas however engine wear with dust and tar content in gas is a problem. Therefore, before use through the engine, the producer gas needs to remove both impurities to the standards of gas for internal combustion engine (Hasler et al., 1999). Table 2.8 shows standard value of the producer gas quality requirement for internal combustion engine. The existing tar levels in producer gas for the engine should be less than < 100 mg/Nm³ while the particles are less than < 50 mg/Nm³ with < 10 μm of particle size.

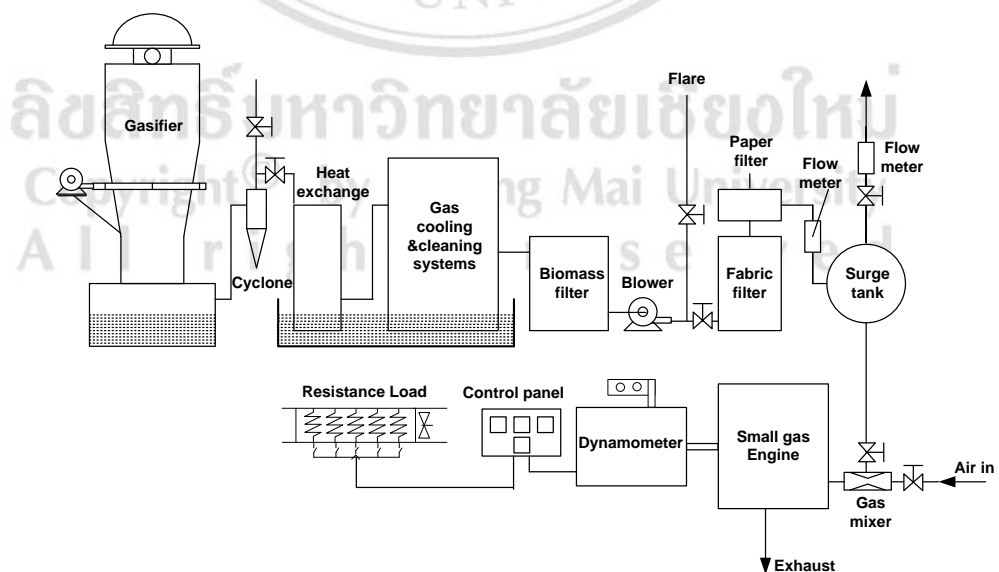


Figure 2.11 Overview of SI producer gas engine (Homdong et al., 2014)

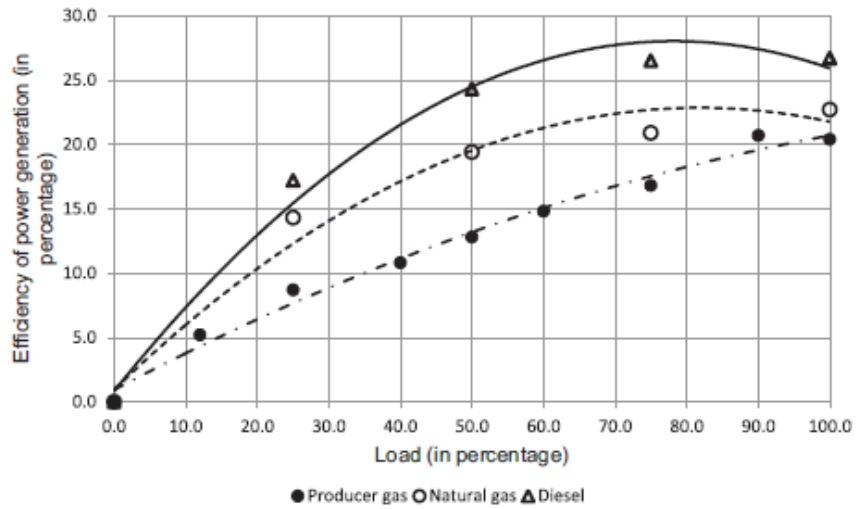


Figure 2.12 Power output efficiency of SI producer gas engine (Raman et al, 2013)

Table 2.8 Producer gas quality requirement for internal combustion engine

Impurities in gas	Unit	IC engine	Gas turbine
Tar	mg/Nm ³	< 100	-
Particles	mg/Nm ³	< 50	< 30
Particle size	μm	< 10	< 5
Alkali metals	mg/Nm ³	-	0.24

2.2.5 Dual fuel engine

Dual fuel engine is the engine using two types of fuel for combustion in the cylinders of an internal combustion engine. The two types of fuel are consisting of liquid and gas fuels. The purpose of creating the engine is to enhance the flexibility of the fuel. In particular, gaseous fuel that is readily available from industrial production or can be made by fermentation or gasification processes, then the cost of gaseous fuel is low. The major reason for this engine is low emission and sound compared to original engine.

The original of dual fuel engine is a diesel engine that has been converted into using gas. Gaseous fuels popularly used in dual fuel engines are producer gas, biogas, liquid petroleum gas and natural gas etc. The principle of dual fuel engines is to start the engine on diesel, that brings air and producer gas into the cylinders when the engine is on compression stroke, the engine unable to combustion in cylinder due to the auto-ignition temperature of producer gas is higher than diesel. Normally, the auto-ignition temperature of producer gas is about 625 °C while that of diesel is 210 °C. At about 20 degree of BTDC, the injector injects diesel into the cylinder at high pressure. The diesel and air is drawn in and burnt in cylinder. When the temperature in cylinder is equal to the auto-ignition temperature of producer gas, producer gas can be introduced into the diesel engine; it burns rapidly in the combustion chamber. The pressure and temperature increase leading to driving the piston back down the cylinder and incur work expansion. The major fuel of this engine is producer gas and diesel is used as pilot fuel. The component of diesel-producer gas can be classified into 2 systems; gasifier system and engine for generated electric power shown in Figure 2.13. The gasifier system is similar to SI producer gas engine while the engine is different. The component of gasifier system in dual fuel engine include gas generator, heat exchanger, cyclone, venturi scrubber, tar box, mist eliminator, gas holder, moisture separator (Tongorn, 2007). The dual fuel engine performance is interesting, because it includes diesel replacement rate, thermal efficiency and emissions. Figure 2.14 shows diesel replacement rate of small diesel-producer gas engine. Increasing load will increase the diesel saving. The maximum is 64.21% at higher load while the use of low pressure fuel of injector leads to save the diesel better than high pressure fuel. Adjusting diesel injection timing to higher than original diesel engine will increase diesel replacement. The cause of the need to increase injection timing is the slow burning velocity of air and producer gas (Tongorn, 2007). The use of alternative fuel like vegetable oil or biodiesel is another way to reduce fuel costs. Whereas, the

power output is lower than diesel oil in pilot fuel (Banapurmath et al., 2009).

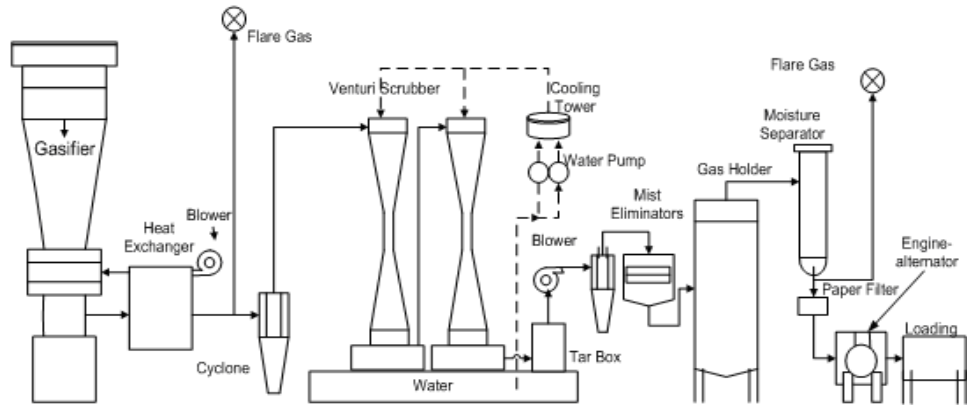


Figure 2.13 Overview of diesel-producer gas engine (Tongorn, 2007)

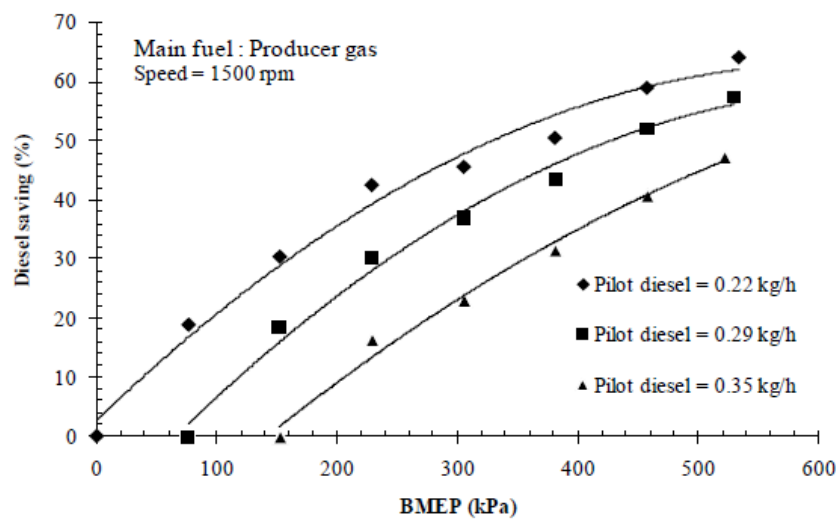


Figure 2.14 Diesel replacement rate of dual fuel engine (Sombatwong et al, 2013)

Figure 2.15 shows brake thermal efficiency of dual fuel engine with diesel engine. The brake thermal efficiency of dual fuel mode is lower than diesel mode. Generally, the brake thermal efficiency of diesel engine is between of 30-35%, but the dual fuel mode is less than 25 %, and that depends on

several factors such as pressure of fuel of injector, injection timing, air-gas mixer, load and speed etc.

Table 2.9 shows the emission of engine on dual fuel and diesel mode. The CO, HC and CO₂ of dual fuel engine are higher than diesel engine while NO_x, and SO₂ are lower than the diesel engine. For the smoke density, the emissions measured of both engine was unclear, but considering the nature of fuel, dual fuel engine is likely to release of less smoke density than the diesel engine. In this problem this engine is similar to the SI producer gas engine, except on the cost of diesel oil which affects the price of energy is higher than using biomass alone.

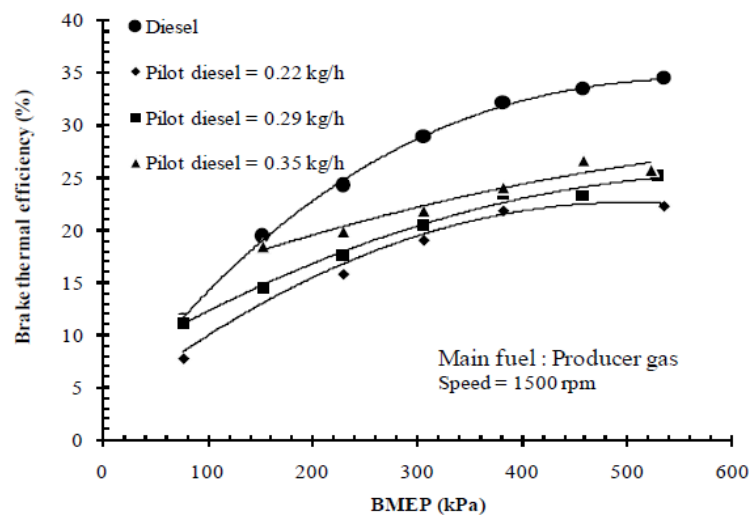


Figure 2.15 Brake thermal efficiency of dual fuel engine
(Sombatwong et al, 2013)

Table 2.9 Emission of the dual fuel engine and diesel engine

Reference	Mode	CO	HC	NO _x	SO ₂	CO ₂	Smoke
Ramadhas et al, 2007	Dual	High				High	High
	Diesel	low				low	low
Uma et al, 2004	Dual	High	High	low	low		low
	Diesel	low	low	High	High		High
Dasappa et al, 2011	Dual	High		low			
	Diesel	low		High			
Lekpradit et al, 2000	Dual			low		High	
	Diesel			High		low	



 ลิสสิทธิ์มหาวิทยาลัยเชียงใหม่

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