Fundamentals of Cyclone Gasification Process and Operation

M.A. Miskam*, M.Y.Idroas, Z.A.Z. Alauddin, K.F. Mustafa

School of Mechanical Engineering, USM Engineering Campus,
Sri Ampangan, 14300 Nibong Tebal,
Pulau Pinang, Malaysia
*E-mail: mohd_azmanmiskam@yahoo.com.

Abstract

Biomass refers to all organic materials that are originated from plants. Biomass is being traditionally used as energy source especially for cooking and heating particularly in the developing countries. Different biomass conversion processes produce heat, electricity and fuels. Among all biomass conversion processes, gasification is one of the promising ones. Gasification is the conversion of biomass to a gaseous fuel by heating in a gasification medium such as air, oxygen or steam. The gas produced is combustible and can be used to generate power. Sawdust is one of the biomass fuel, produced in a great amount everyday from wood-based industries and dumped at landfill as a waste. With particle size less than 200 microns, cyclone separators have been one of the most popularly used industrial devices for separating sawdust from their carrying fluid. When the fluid, with the dispersed particles in suspension, is injected tangentially through the inlet pipe into the cyclone, then due to the specially designed geometrical feature of the cyclone the fluid acquires a spiraling motion, which first descends along an outer spiral and then ascends through an inner spiral. Simultaneously, a highly swirling particle flow is developed inside the cyclone. The dispersed particles, which have a different density to that of their carrying fluid, are driven by the centripetal acceleration to move relative to the fluid motion. The relatively larger particles possess a larger inertia and therefore acquire a stronger centripetal acceleration. When the centripetal acceleration is sufficiently large then the particles drift towards the sidewall and finally they are separated through the apex of the cyclone. If the particles drift at the sidewall can be partially burnt before it's collected at the bottom of cyclone. The combustion will produce gas and the producer gas leaves through the top outlet of the cyclone. Therefore the development of a new design cyclone gasifier will perform separation and gasification process. In order to invent this new design cyclone gasifier, a number of fundamental factors, which directly related to the cyclone gasification process and operation such as cyclone gasification mechanism, gasification theory and controlling parameters have to be studied. Furthermore, design basis for cyclone gasifier system and several keys for stable operation are also reviewed.

Keywords: Cyclone, Gasification, Sawdust.

1 Introduction

Concern over the depletion of fossil fuels in the future and increasing awareness of energy conservation have drawn worldwide attention. Therefore, energy from biomass is one of the most promising renewable sources of energy that are not depleted with time (Z.A. Zainal et al., 2001). In addition, these types of energy sources are considered as environmental-friendly (J.C. Elauria et al., 2003). Biomass is a substance made of organic compounds originally produced by fixing carbon dioxide in the atmosphere during the process of plant photosynthesis (Yukihiko M. et al., 2003). Since, the concentration of carbon dioxide in the atmosphere theoretically remain constant in cyclic flow, biomass is expected to become one of the key sources of renewable energy in the sustainable society of the future.

Different biomass conversion processes produce heat, electricity and gaseous fuels (Monique et al., 2003). There are several ways of producing electricity by thermal conversion of biomass: pressurized gasification with a gas turbine in a combine cycle mode, atmospheric gasification with turbine or an engine, and orthodox combustion with Rankine cycle (A. V. Bridgwater, 1995). The technologies for the primary conversion of biomass for electricity production are direct combustion, gasification, and pyrolysis (Richard L. Bain et al., 1998). Direct combustion involves the oxidation of biomass with excess air, giving hot flue gases, which are used to produce steam in the heat exchange sections of boilers. In air-based gasification cycles, biomass is partially oxidized by sub-stoichiometric amounts of oxygen to provide energy for thermal conversion of the remaining biomass to gases and organic vapors. In indirect gasification cycles an external heat source, instead of oxygen, is used to provide the energy for high-temperature steam gasification of the organic fraction of biomass to vapors and gases. In pyrolysis processes, indirect heating is also used to convert biomass to a mixture of gases and organic vapors. Pyrolysis is defined as the thermal destruction of organic materials in the absence of oxygen. Technically, therefore, indirect gasification is a pyrolysis process.

Among all biomass conversion processes, gasification is one of the promising ones. Gasification is the conversion of biomass to a gaseous fuel by heating in a gasification medium such as air, oxygen or steam. The gas produced is combustible and can be used to generate power. Normally, conventional gasifiers are based on gasification of biomass fuels in size of 10 mm to 100 mm. Currently, cyclones were studied to be an alternative gasifier to gasify smaller particles of biomass fuels.

C Syred et al., 2004 have studied the inverted cyclone gasifier coupled to a cyclone combustor in series for indirect firing of a small-scale gas turbine. The experimental studies were carried out on Commercial Austrian sawdust and Commercial Swedish wood powder with the size distributions were between 0.063 and 2 mm. Mohamed Gabra et al., 2001 discussed the comparison of alkali retention using bagasse in a fluidized bed and cyclone gasifier. The alkali retention in the fluidised bed gasifier was 12-4% whereas in the cyclone gasifier was about 70%. Mohamed Gabra et al., 2001 also have studied the performance of cyclone gasifier using two different biomass fuels. The first experiment is gasification of crushed bagasse in a two-stage combustor at atmospheric pressure, where the first stage is a cyclone gasifier. M. Gabra et al., 1998 demonstrated the sugar cane residue feeding system for a cyclone gasifier that designed to operate without interruption or large fluctuations. It was found that to eliminate the blockage in the downcomer channels, the powder should be more homogeneous. Salman Hassan et al., 2000 discussed the possibility of using the steam-jet ejector to inject wood powder and sawdust into the pressurized cyclone gasifier.

Since, Malaysia produced about 300 tons of sawdust from sawmill and wood-based industry, a new designed of cyclone gasifier system using sawdust as a fuel have been developed at University Science Malaysia (USM). This cyclone gasifier produces 200 kW_T outputs with combustion rate of 60 kg/hr. Figure 1 shows the system, including hopper, screw feeder, down-comers, blower, cyclone's chamber and char collector.

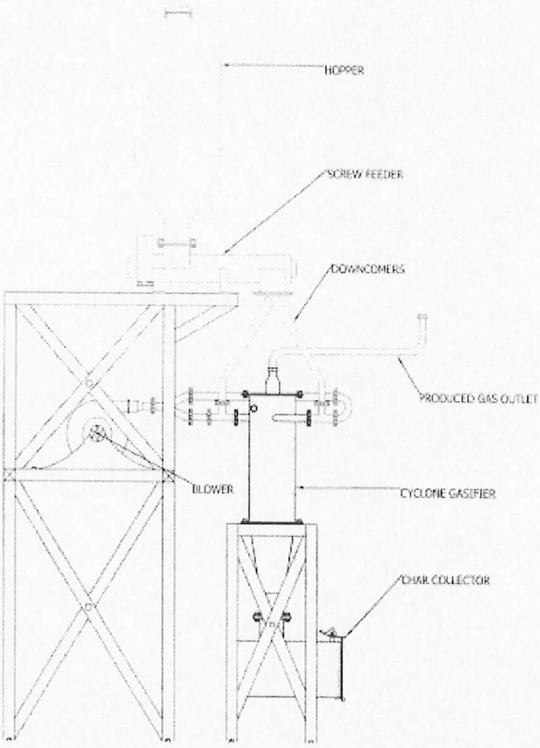

Fig 1 *A cyclone gasifier system developed at USM*

In this paper, an overview of the fundamental factors, which directly related to the cyclone gasification process and operation such as cyclone gasification mechanism, gasification theory and controlling parameters have to be studied. Furthermore, design basis for cyclone gasifier system and several keys for stable operation are also reviewed.

2 Mechanism of gasifying a biomass particle in the cyclone gasifier

The mechanism of gasifying a biomass particle in the cyclone gasifier can be suggested as follows (Mohamed Gabra et al., 2001). The combustible fraction of a solid fuel can be divided into volatile and non-volatile fractions. The overall rate of gasification of the biomass particle depend upon individual rates of the processes involved, i.e. drying, release of the combustible volatiles, mixing of the volatiles vapour and the oxidant, combustion of the volatile and the gasification of non-volatile combustibles. The rates of these individual processes depend upon the size of the fuel particle, the heat transfer with surroundings and the gas composition in the vicinity of the particles. The amounts of fuel gasified will also depend on the residence time, which will be quite different in different types of gasifier.

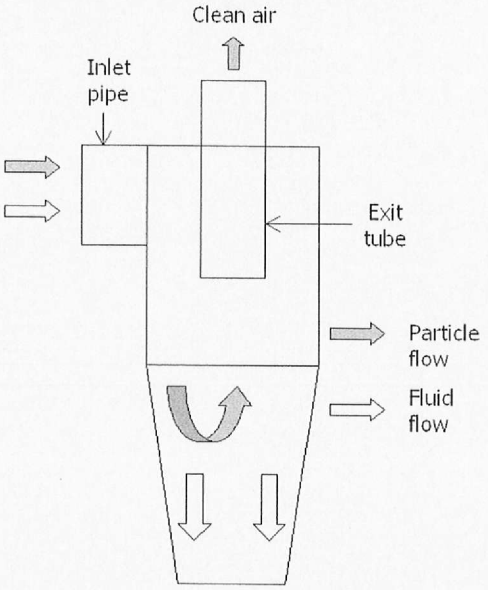

Fig. 2 A cyclone separator with tangential inlet

Syred et al., 1974, have studied the design of cyclones used as combustor. The most common cyclone design with tangential inlet is shown in Figure 2. The operation is simple, when the fluid, with the dispersed particles in suspension, is injected tangentially through the inlet pipe into the cyclone, then due to the specially designed geometrical feature of the cyclone the fluid acquires a spiraling motion, which first descends along an outer spiral and then ascends through an inner spiral. Simultaneously, a highly swirling particle flow is developed inside the cyclone. The dispersed particles, which have a different density to that of their carrying fluid, are driven by the centripetal acceleration to move relative to the fluid motion. The relatively larger particles possess a larger inertia and therefore acquire a stronger centripetal acceleration. When the centripetal acceleration is sufficiently large then the particles drift towards the sidewall and finally they are separated through the apex of the cyclone.

As soon as a biomass fuel particle enters the hot cyclone, it dries and is pyrolysed, which implies that a self-sustaining exothermic reaction takes place in which the natural structure of the biomass particle break down and devolatilisation start. The volatile combustibles are released and mixed with surrounding air. A diffusion flame is stabilized around the particle where the combustibles and the oxygen form a flammable mixture. Little oxygen can penetrate through the flame into the fuel particle. During this process, the size of the particles is only slightly reduced but the particle density is decreasing. The result is a residual solid (char) and a gas mixture composed primarily of carbon dioxide, carbon monoxide, hydrogen, water vapour, nitrogen and pyrolysis products including tar and hydrocarbons.

Biomass consists of 75-85% volatile matter, so pyrolysis plays a larger role in biomass gasification. After the oxygen around the particle is consumed and the volatile flame is extinguished, the char, tar and hydrocarbons are then gasified by reactions with the carbon dioxide and water vapour to give a fuel gas composed mainly of CO, H_2, CH_4 and C_2H_2. Most of the hydrogen that is produced remains free. However, a portion of hydrogen is found in methane and hydrocarbons, which are mainly results of the break-up of volatiles. Some methane may also be formed by reactions between hydrogen and carbon or hydrogen and carbon dioxide. The complete reactions of all tars, hydrocarbons and char with the gasification air depend on the equivalent ratio, the geometry of the cyclone gasifier and the residence time.

Producer gas, the gas generated when biomass fuels is gasified with air, consists of some 40 per cent combustible gases, mainly carbon monoxide, hydrogen and some methane. The rest are non-combustible and consists mainly of nitrogen, carbon dioxide and water vapour. The gas also contains condensible tar, acids and dust. These impurities may lead to operational problems and abnormal engine wear. The main problem of gasifier system design is to generate a gas with a high proportion of combustible components and a minimum of impurities.

3 The technology of gasification

3.1 The theory of gasification

Giltrap et al., (2003) describes thermochemical gasification as a process for converting solid fuels into gaseous form. The chemical energy of the solid fuel is converted into both the thermal and chemical energy of the gas depending on its chemical composition. The substance of a solid fuel is usually composed of the elements carbon, hydrogen and oxygen. In addition there may be nitrogen, sulphur and other trace elements. These latter are generally present only in small quantities and can be neglected with regard to the chemistry of gasification. In complete combustion, carbon dioxide is obtained from the carbon and water from the hydrogen. The chemical reaction formulae is described by:

$$C + O_2 \Leftrightarrow CO_2 \text{ - 401.9 kJ/mol} \tag{1}$$

$$H + 1/2O_2 \Leftrightarrow H_2O \text{ - 241.1 kJ/mol} \tag{2}$$

In all types of gasifiers, the carbon dioxide (CO_2) and water vapour (H_2O) are converted (reduced) as much as possible to carbon monoxide, hydrogen and methane, which are the main combustible components of producer gas. The gasification reactions are as follows:

$$C + CO_2 \Leftrightarrow 2CO + 164.9\ \text{kJ/mol} \quad (3)$$

$$C + H_2O \Leftrightarrow CO + H_2 + 122.6\ \text{kJ/mol} \quad (4)$$

$$CO + H_2 \Leftrightarrow CO + H_2O + 42.3\ \text{kJ/mol} \quad (5)$$

$$C + 2H_2 \Leftrightarrow CH_4 \quad (6)$$

$$CO + 3H_2 \Leftrightarrow CH_4 + H_2O - 205.9\ \text{kJ/mol} \quad (7)$$

Equation 3 and 4 are the main reactions on the reduction stage and require heat. Equation 5 is called water –gas equilibrium reaction. Equation 6 and 7 indicate from where methane may appear within the product gas. The ratio between the product of the concentration of carbon monoxide (CO) and water vapour (H_2O) and the product of the concentration of carbon dioxide (CO_2) and hydrogen (H_2) is fix by the value of the water gas equilibrium constant (K_{WE}). The reaction rate decreases with falling temperature. In the case of the water gas equilibrium the reaction rate becomes so low below 700°C.

$$K_{WE} = \frac{(CO)\ X\ (H_2O)}{(CO)\ X\ (H_2)}$$

3.2 Important parameters

3.2.1 Fuel characteristic

In order for gasification to function correctly there are a number of parameters that need to be maintained within certain limit. The use of sawmill residues must be carefully analyzed to offer the best technical, economic and environmental alternative (Paulo R. Wander et al., 2004). The parameters are particle size distribution, moisture and ash content, volatile matter content, heating value and bulk density.

Particle size distribution of the fuel particles is important for the particles flow in the downcomers, the injector feeder and the cyclone gasifier. The size distribution also determines the time required for gasification and the carry-over of particles with the product gas. C. Syred et al., 2004 have studied the inverted cyclone gasifier couple to a cyclone combustor in series for indirect firing of a small-scale gas turbine. The experimental studies were carried out using sawdust and wood powder where, the size distributions of the fuels were between 0.063 and 2 mm. Fredriksson C., 1999 also have studied the process of gasification in cyclone gasifier using wood powder. The cyclone designed in principle as a separation cyclone and the experiments were carried out with commercial Swedish wood powder fuels where, the raw material was grinding in a rotary cutter and then sieved to 98% under 0.8mm.

Table 1 *Size distribution of wood powder*

Size (mm)	Weight %
S>1	0.45
0.5-1.0	21.89
0.250-0.5	38.50
0.125-0.250	22.41
0.100-0.125	4.12
0.074-0.100	4.95
0.063-0.074	4.62
0.040-0.063	2.95
s<0.040	0.12
Sum	100.0
Mean value	0.368

The size distribution was determines by sieving a sample of 0.5 kg for about three hours. The results are shown in Table 1. Mohamad Gabra et al., 2001 discussed the alkali retention/separation during bagasse gasification in two-stage atmospheric cyclone gasifier. The size distribution of crushed bagasse and ground bagasse pellets are shown in Table 2.

When moisture content increases, the thermal efficiency of conversion decreases. Therefore, the amount of heat required for drying becomes excessive and this provides an upper limit to acceptable moisture contents for gasification systems. In practice, the moisture contents are between 10% and 20%. Moisture is actually involved in the biomass conversion process, providing the hydrogen molecules for hydrogen gas formation and for very dry feeds may have to be made up with the injection of steam.

The total ash content in the biomass and the chemical composition of the ash are both important. The composition of the ash affects its behaviour under the high temperatures of combustion and gasification. For example, melted ash may cause problems is gasification reactors. Such problems may vary from clogged ash-removal caused by slagging ash to severe operating problems from ash accumulation within the thermal reactor.

Volatile matter refers to the part of the biomass that is released when the biomass is heated. During this heating process biomass decomposes into volatile gases and solid char. Biomass typically has a high volatile matter content, up to 80% whereas coal, for example has a volatile matter content of less than 20%.

The heating value of differing biomass substrates can vary significantly. Wood, for example can vary from

8.4 MJ/kg to 17 MJ/kg. Bulk density will also vary significantly with the type of waste that is being gasified.

Table 2 *Size distributions of crushed bagasse and ground bagasse pellets*

Particle size (mm)	Crushed bagasse (%)	Ground bagasse pellets (%)
> 2.0	0	1
1.0-2.0	2	23
0.5-1.0	23	23
0.25-0.5	50	25
0.125-0.25	11	16
0.1-0.125	6	2
0.071-0.1	3	2
0.04-0.071	3	5
< 0-0.04	3	3

3.2.2 Product gas cleaning and cooling system

When a cyclone gasifier system is used in conjunction with an internal combustion engine, an important requirement is that the engine is supply with a gas that is sufficiently free from dust, tars and acids. The tolerable amounts of these substances will vary depending on the type and outfit of the engine. The tolerable average amounts for currently available engines are:

Dust: lower than 50 mg/m^3 gas
Tars: lower than 500 mg/m^3 gas
Acids: lower than 50 mg/m^3 gas

Gas cooling mainly serves the purpose of increasing the density of the gas in order to maximize the amount of combustible gas entering the cylinder of the engine at each stroke. A ten percent temperature reduction of the gas increases the maximum output of the engine by almost two percent. Cooling also contributes to gas cleaning and makes it possible to avoid condensation of moisture in the gas after it is mixed with air before the engine intake.

Generator gas cooler comes in three broad categories: natural convection cooler, forced convection coolers and water coolers. Natural convection coolers consist of a simple length of pipe. They are simple to use and clean and require no additional energy input. Forced convection coolers are equipped with a fan, which forces the cooling air to flow around the gas pipes. Its advantages are the extra energy input to the fan and the necessity to use gas-cooling pipes of small diameters. Which can lead to fouling problems. Water coolers are available in two types, the scrubber and the heat exchanger. The objective is generally to cool and clean the gas in one and the same operation. The principle is the gas is brought in direct contact with water, which is sprayed into the gas stream by means of a suitable nozzle device. The advantage of this system is its small size. Disadvantages are the need for fresh water, increased complexity of maintenance and some power consumption resulting from the use of water pump.

The major problem in producing an engine quality gas is that of dust removal. The amount of dust that is present in the producer gas at the outlet of the gasifier depends on the design of the equipment, the load of the gasifier and the type of fuel used. Investigation of the size and size distribution of producer gas dust were undertaken by Nordstrom, 1963 and the results are in Table 3. It is possible to separate about 60%-70% of this dust from the gas by a well-designed cyclone separator.

3.2.3 Equivalence ratios

In order to reduce the number of parameters on which the performance of the biomass gasifier depends, an equivalence ratio is defined to reflect the combined effect of air flow rate, rate of wood supply and duration of the run. The equivalence ratio for each run is calculated by:

Equivalence ration, ϕ

$$= \frac{(\text{Flow rate of air supply}) \times (\text{Duration of the run})}{(\text{Mass input of wood}) \times (A/F \text{ for } \phi = 1)}$$

Z.A. Zainal et al., 2002 have studied a downdraft biomass gasifier using furniture wood and wood chips. The equivalence ratio for the gasifier is found to be in the range 0.268-0.43, which is within the range for ideal and theoretical gasification (0.19-0.43) and (A/F) for $\phi = 1$ is 5.22 m^3. The experimental investigation shows that the calorific value of producer gas increases with equivalence ratio initially attain a peak and then decreases with the increase equivalence ratio. The gas flow rate per unit weight of the fuel increases linearly with equivalence ratio and the complete conversion of carbon to gaseous fuel has not taken place even for the optimum equivalence ratio.

The general literatures shows that an equivalence ratio of 0.3-0.35 kg_{O_2}/kg_{wood} is required in successful gasification. In small gasifiers with high heat losses a greater value is required typically resulting in 2-2.4 kg_{O_2}/kg_{wood}, producing a gas with low calorific value of 4.0-6.0 MJ Nm^{-3}.

Table 3 *Size distribution of producer gas dust*

Particle size of dust m.10^{-6}	Percentage in the gas %
Over 1000	1.7
1000-250	24.7
250-102	23.7
102-75	7.1
75-60	8.3
Under 60	30.3
Losses	4.2

3.2.4 Gasifier efficiency

Gasification efficiency is an important factor to determine the actual technical operation, as well as the economic feasibility of using the gasifier system. The gasification efficiency if the gas is used for engine applications is:

$$\eta_m = \frac{H_g \text{ x } Q_g}{H_s \text{ x } M_s} \text{ x } 100$$

In which:

η_m = gasification efficiency (%) (mechanical)
H_g = heating value of the gas (kJ/m^3)
Q_g = volume flow of gas (m^3/s)
H_s = lower heating value of gasifier fuel (kJ/kg)
M_s = gasifier solid fuel consumption (kg/s)

If the gas is used for direct burning, the gasification efficiency is defined as:

$$\eta_{th} = \frac{(H_g \text{ x } Q_g) + (Q_g \text{ x } \rho_g \text{ x } C_p \text{ x } \Delta T)}{H_s \text{x} M_s} \text{ x } 100$$

In which:

η_{th} = gasification efficiency (%) (thermal)
ρ_g = density of the gas (kg/m^3)
C_p = specific heat of the gas (kJ/kg°K)

ΔT = temperature different between the gas at the burner inlet and the fuel entering the asifier (°K)

Depending on type and design of the gasifier as well as on the characteristics of the fuel η_m may vary between 60 and 75 percent. In the case of thermal applications, the value of η_{th} can be as high as 93 percent.

3.3 Design basis of cyclone gasifier

The flow pattern in a cyclone is very complex (Giulio Solero et al., 2002). The complexity of the flow pattern inside the chamber is due to high turbulence level, strong anisotropy, three-dimensionality and possible non-stationary features typical of highly swirling motions. In cyclone the gas stream enters the cyclone inlet tangentially with suitable velocity so that the swirl motion will occurs along the inside space of the cyclone. It observed that, the gas flow is more spiraling downward from the inlet close to the wall of the cyclone until it reaches the bottom of the cyclone. At the bottom, the gas spiral changes direction and spirals upwards, towards the outlet, in the center of the cyclone (Shepherd et al., 1939). The rotating flow maintained by the tangentially directed inlet flow. The gas velocity is however well inside the turbulent flow region and will lead to a transfer of gas between the outer and inner flow (Alexander et al., 1949). The conical shield often built into the bottom of the tapered body of the cyclone prevents already collected material from being re-entrained. The particles that are not collected carried inward by the gas flow and removed through the exit duct.

The separation process that occurs inside a cyclone thought to be drive by the centrifugal force acting radial outward due to the curve path and the drag forces caused by the inward radial flow. The centrifugal force developed inside the cyclone accelerates the settling rate of the particles, thereby separating them according to specific gravity in the medium. Thus, the more dense material flung to the outer wall of the cyclone where the settling velocity is at its lowest and progresses downwards along the cyclone wall in a spiral flow pattern until it exits at the bottom cone. For small particles, the drag force maybe sufficient to move the particle towards the center of the cyclone. If the inward drag force is strong enough, and particles reach the central flow region where the flow is ascending, they will most likely to escape together with the outgoing gas. However, the centrifugal force will increase, as the particle is moving towards the radius of the outlet pipe due to the increased tangential velocity. Thus, the force on a particle may balance at some radius where the particle theoretically stops its radial movement and rotates in an orbit with a constant radius. In practice, the radial velocity is not constant in the tangential direction and the particle will consequently move. The particle can also change path caused by secondary effect such as turbulent eddies or collisions with other particles (Shepherd et al., 1949). At the bottom cone, a reverse vortex begins to form creating a low-pressure zone (generally referred to as the air core) flowing upwards along the axis of the cyclone, through the vortex finder and exits at the overflow.

Pressure drop over the cyclone is an important variable when evaluating performance of a cyclone. It is a measure of the amount of work that is required to operate the cyclone at the given condition, which is important for operational and economical reasons. Pressure drop defined as the difference in mean total pressure at the inlet and the outlet. The total pressure drop over a cyclone consists of losses at the inlet, outlet and within the cyclone body. The wall friction and the contraction of the inner vortex on entering the vortex finder cause the pressure drop in a cyclone. Accordingly, the total pressure drop is composed of two contributions. The first part is the pressure loss in the separation zone, cause by the friction of gas/surface or gas/solids/surface. Secondly, the pressure drops in the vortex finder and determined by the relationship between the tangential velocity, the radius and the mean axial velocity in the vortex finder.

Influence of temperature as parameter on separation efficiency and pressure drop should be investigates since the cyclone in this study is design to operate at high temperature. Results from experiments (M. Bohnet, 1995) show that the separation efficiency is significant influenced by temperature and the separation efficiency had shown to decrease with increasing temperature. Oppositely, the pressure drop will decrease with increase in temperature. These effects explained by the decreased density, increased wall friction and increased viscosity due to the increased temperature. All three variables have the effect of lowering the tangential velocity that accordingly lowers the pressure drop and separation efficiency. All these results based on conditions where the inlet velocity was constant between the different experiments (Fredriksson C., 1999).

3.4 Several keys operation condition

The fuel particles should be heated in sufficient high temperature after entering the cyclone to initiate volatiles and gasification reaction. So, the cyclone wall temperature is very important for this heating process. For stable process of gasification the experience shows that the wall temperature exceeds 600°C – 950°C and the equivalence ratio could be varied between 0.18 and 0.25 (Fredriksson C., 1999). As a result, a gas temperature ranging from 800°C to 850°C and the gasification process is running smoothly. When calculating the difference between input alkali with the fuel and alkali separated with char collected from the cyclone, the amount of alkali carried with the producer gas at cyclone outlet can be determined.

The cyclone wall temperature limits for stable gasification temperature were found to be in the range of 650–950°C. The equivalence ratios ranging from 0.25 to 0.21 and the gas temperature are on an average of 850°C. While, the bagasse feed rate is 39 kg/h. The system reached stable conditions after a few minutes and a char sample was collected from the bottom residue (Mohamed Gabra et al., 2001)

Deposition occurs when particles with molten ash or condensed liquid phase impacts on surfaces and remains there because of their high sticking coefficient. Alkali metals such as potassium (K) and sodium (Na) are generally form compounds with a relatively low melting point. The melting point of potassium carbonate and sodium carbonate is 891°C and 851°C respectively. Pure potassium sulphate melts at 1069°C, which is drastically reduced in combination with other potassium compounds such as potassium chloride, which has a melting point of 770°C. Deposition can be a problem even if the ash content in the fuel is low, as the flow rate is very high in gas turbine and thus the resulting amount of material could be considerable.

According to Misra et al., 1993 the corrosive alkali compounds are supposed to vaporise at temperature ranging from 800°C to 900°C. Despite a gas temperature at cyclone outlet in the range of 850–800°C, it was found that the elemental compositions of the ash in bagasse fuel, char and fly ash collected after combustion are almost the same. So, this show that these elements do not vaporise and therefore they do not significantly go into gas phase. One possible explanation is that even if the gas temperature is above the temperature of vaporisation for the ash forming elements, the residence time in the cyclone is too short for the large particles to reach a temperature where the alkali compounds vaporise. The particles containing char and ash are separated from the flow when they reached the lower outlet.

4 Conclusions

As the conclusion, this paper has achieved its objective to study the fundamental aspect of cyclone gasification process and operation. In designing cyclone gasifier system a number of fundamental factors, which directly related to the cyclone gasification process and operation such as cyclone gasification mechanism, gasification theory and controlling parameters play very important roles in development of cyclone gasifier system. Thus to design cyclone gasifier system using biomass fuels, these considerations have to be taken into account in order to determine the appropriate parameters as discussed earlier.

5 Acknowledgment

The financial assistance from University Science Malaysia Short Term Grant gratefully acknowledged.

References

[1] Z. A. Zainal, R. Ali, C. H. Lean and K. N. Seetharamu, Prediction of performance of a downdraft gasifier using equilibrium modeling for different biomass materials, Energy Conversion and Management, 42(12), pp.1499-1515, 2001.

[2] Yukihiko Matsumura and Tomoaki Minowa, Fundamental design of a continuous biomass gasification process using supercritical water fluidized bed, Hydrogen Energy, 29, pp. 701-707, 2003.

[3] J. C. Elauria, M.L.Y. Castro and D.A. Racelis, Sustainable biomass production for energy in the Philiphines, Biomass and Bioenergy, 25(5), pp. 531-540, 2003.

[4] Monique Hoogwijk, André Faaij, Richard van den Broek, Göran Berndes, Dolf Gielen and Wim Turkenburg, Exploration of the ranges of the global potential of biomass for energy, Biomass and Bioenergy, 25(2), 119-133, 2003.

[5] Richard L. Bain, Ralph P. Overend and Kevin R. Craig, Biomass-fired power generation Fuel Processing Technology, 54(1-3), pp. 1-16, 1998.

[6] Mohamed Gabra, Anders Nordin, Marcus Öhman and Björn Kjellström (2001), Alkali retention/separation during bagasse gasification: a comparison between a fluidised bed and a cyclone gasifier, Biomass and Bioenergy, 21(6), pp. 461-476, 2001.

[7] Giltrap DL, McKibbin R, Barnes GRG, A steady state model of gas-char reactions in a downdraft biomass gasifier, Solar Energy, 74(1), pp. 85-9, 2003.

[8] Paulo R. Wander, Carlos R. Altafini and Ronaldo M. Barreto, Assessment of a small sawdust gasification unit, Biomass and Bioenergy, 27(5), Pages 467-476, 2004.

[9] C. Syred, W. Fick , A. J. Griffiths and N. Syred, Cyclone gasifier and cyclone combustor for the use of biomass derived gas in the operation of a small gas turbine in cogeneration plants, Fuel, retrieved 5 March 2004, http://www.sciencedirect.com

[10] Fredriksson, C., Exploratory experimental and theoretical studies of cyclone gasification of wood powder, PhD thesis, Department of Mechanical Engineering, Division of Energy Engineering, Luleå University of Technology, Luleå, Sweden, 1999.

[11] Giulio Solero and Aldo Coghe, Experimental fluid dynamic characterization of a cyclone chamber, Experimental Thermal and Fluid Science, 27(1), pp. 87-96, 2002.

[12] Shepherd, C. B. and Lapple, Flow pattern and pressure drop in cyclone dust collector, Ind. And. Eng. Chemistry, 31(8), pp. 972-984, 1939.

[13] Alexander, R. McK., Fundamentals of cyclone design and operation, Proc.Aust.Inst.Mining and Met., pp. 203, 1949.

[14] M. Bohnet, Influence of the gas temperature on the separation efficiency of aero cyclones, Chemical Engineering and Processing, 34(3), pp. 151-156, 1995.

[15] Mahendra K. Misra, Kenneth W. Ragland and Andrew J. Bak, Wood ash composition as a function of furnace temperature, Biomass and Bioenergy, 4(2), pp. 103-116, 1993.

[16] A.V. Bridgwater, The technical and economic feasibility of biomass gasification for power generation. *Fuel* 745, pp. 631–653, 1995.