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Gasification of Solid Waste Biomass

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Abstract

Gasification of solid waste biomass was performed in this study using an updraft gasifier of a fluidized sand bed with date seeds as fuel and air as fluidizer. The date seeds were washed, dried, crushed and sieved to obtain different particle sizes. The thermo physical properties of date seeds, such as higher heating value, were evaluated experimentally. The fluidization velocity was calculated theoretically to achieve the gasification process of date seed.

It was found that the gasification of date seeds occurred at 550°C temperature with 355-500µm particle size and 2.22 m/s fluidization velocity. The higher heating value of date seed was 17,700 kJ/kg. The carbon content in date seed was little above 50%, which indicates that the solid waste of biomass date seed represents a valuable renewable source of energy in the near future if utilized correctly.

***Keywords**: Gasification, Fluidized Bed, Biomass, Updraft Gasifier.*

Nomenclature

V_{bed}	Volume of bed, [m^3]
V_{sand}	Volume of sand, [m^3]
m	Mass, [kg]
A	Area, [m^2]
h	Height of bed, [m]
ρ_{air}	Density of air, [$\frac{kg}{m^3}$]
ρ_{solid}	Density of solid, [$\frac{kg}{m^3}$]
e_{mf}	Porosity
A	Ash
VM	Volatile material
μ	Dynamic viscosity, [$\frac{N.s}{m^2}$]
$\dot{m}_{air}$	Mass flow rate of air, [$\frac{kg}{s}$]
$(\frac{F}{A})_{stch.}$	Stoichiometric fuel to air ratio, [$\frac{kg\ solid}{kg\ air}$]
$(\frac{F}{A})_{act.}$	Actual fuel to air ratio $\frac{kg\ solid}{kg\ air}$
$\emptyset$	Equivalence ratio
$\dot{m}_{solid}$	Mass flow rate of solid, [$\frac{kg}{s}$]
$\dot{V}_{air}$	Volumetric flow rate of air [$\frac{ft^3}{min}$
HHV	Higher heating value, [$\frac{kJ}{kg}$]
LHV	Lower heating value, [$\frac{kJ}{kg}$]
DAF	Dry ash free
FC	Fixed carbon

1. Introduction

Biomass is a biological material derived from living, or recently living organisms, that can be harvested as part of a constantly replenished crop. Biomass includes five main categories, which are: virgin wood, energy crops, agricultural residues, food waste and industrial waste. To convert biomass into fuel to produce energy, either direct burning, digestion or gasification is used [1].

Gasification is the process of converting fossil based carbonaceous materials into syngas fuel, which is a mixture of carbon monoxide and hydrogen. This is achieved by incomplete burning of the material at high temperatures without complete combustion, using rich mixture to produce syngas. The power derived from gasification of biomass and combustion of the syngas later is considered a source of renewable energy [2-3].

Janajreh and Al Shrah [4] used downdraft gasification system using wood to investigate its conversion efficiency. Wood chips of 0.5 cm thickness; 1-2 cm width and 2-2.5 cm length constitute the feedstock to the downdraft gasifier. It was found that the conversion rate of wooden pellets increased with increasing air flow, while the heating value of the producer gas reached the maximum value, then decreased as a result of dilution by cold air. Zainal *et. al.* [5] studied the effect of equivalence ratio in downdraft gasifiers on the conversion of wood chips. They found that the hydrogen production increased linearly with the equivalence ratio, whereas carbon monoxide, methane and the calorific value of produced gas reached a maxima, then declined as the equivalence ratio further increased due to the dilution effect of air. It was observed that the phenomenon of bridging which occurs when shredded chips create a bridge that obstructs the continuing flow of

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the wood pellets causing high localized temperatures inside the gasifier. Their work showed that bridging was reduced by using a 60^o angled-throat that provides smooth gravitational flow of wood through the combustion zone.

Joardder, Md. Uddin, & M. N. Islam [6] studied the converting of date seed waste into activated carbon and bio-fuel by fixed bed pyrolysis reactor. The date seeds in particle form were pyrolysed in an externally heated fixed bed reactor with nitrogen as the carrier gas. The reactor was heated from 400°C to 600°C. A maximum liquid yield of 50% wt. and char of 30% wt. were obtained at a reactor bed temperature of 500°C with a running time of 120 minutes. The oil is found to possess favorable flash point and reasonable density and viscosity. The higher calorific value was 28,636kJ/kg, which is significantly higher than other biomass derived. Minutillo [7] studied the plasma gasification technology. He developed a thermo chemical model to estimate the syngas composition and the energy required for gasification in plasma arc gasification reactor using air as plasma gas. The model was used to optimize the reactor performance under different operating conditions. M. Erol *et. al.* [8] developed new correlations for calculating the heating values of (20) twenty biomass fuels from their proximate analyses data with measured net heating values varying between 15,410 and 19,520kJ/kg.

The biomass studied included rapeseed, potato peel and soybean cake. The biomass samples were ground and sieved into a powder with a particle size of 0.180–0.250 mm and analyzed to obtain net heating values and contents of moisture, volatile matter, fixed carbon and ash.

Al-Widyan *et. al.* [9] studied direct burning of Jordanian olive cake (OC) in pulverized form in a vertical tube furnace with equivalence ratios from 0.8 to 1.4. The furnace design proved acceptable, and the pulverized OC burned efficiently. The maximum thermal and combustion efficiencies were 69% and 82%, respectively. The maximum flame temperature reached 980°C, and the cooling water temperature gradient was about 20°C. Exhaust gas analyses showed that the concentration of CO was below 1.6%, while the NO_x emission was within 550 ppm and the SO_x maximum concentration was 30 ppm.

In this study, gasification technology of dry updraft type gasification will be implemented to gasify solid waste biomass of date seed.

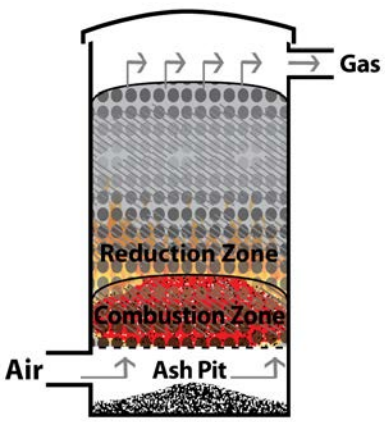

Figure1. Schematic diagram of an updraft gasifier [2].

A schematic diagram of an updraft gasifier is presented in Fig. 1, while Fig. 2 shows the position of biomass compared to coal on the O/C-H/C graph known as Van Krevelen diagram. To convert biomass to useful energy forms, gasification seems to be a promising thermo chemical technology. Physical and Chemical changes that take place during gasification of biomass are similar to typical carbonaceous material decomposition. These changes include drying, devolatilization, heat conduction, fissuring, shrinkage, and fragmentation of solid particles [3].

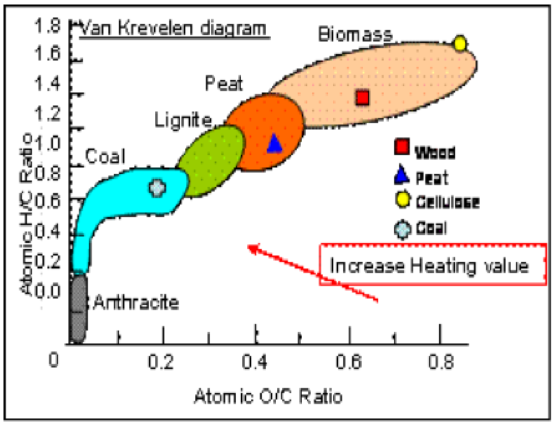

Figure 2. Van Krevelen diagram illustrating the composition and heating value of biomass compared to coal.

2. Theoretical Background

The chemical reaction during which a fuel is oxidized and a large quantity of energy is released is called combustion. The most common oxidizer used is air because it is free and available. Fuel combustion process is complete if all the carbon in the fuel burns to carbon dioxide (CO_2), all the hydrogen burned to water vapour (H_2O), and all the sulfur, if it exists, burns to sulfur dioxide (SO_2). That is, all the combustible components of a fuel are burned to completion during the process. On the other hand, if the fuel combustion process is incomplete, the combustion products contain any unburned fuel or components such as carbon (C), hydrogen ($H_{2(g)}$), carbon monoxide ($CO_{(g)}$), or OH. Gasification is best described as an incomplete combustion process because the products are carbon monoxide and hydrogen gases ($CO_{(g)}$ and $H_{2(g)}$) only. Controlling the air-fuel ratio is the key to have an incomplete combustion process, or gasification [10-11]. The chemical reaction of complete combustion of a fuel composed of carbon and hydrogen only is:

$$C_xH_y + a\,(O_{2(g)} + 3.76\,N_{2(g)}) \rightarrow x\,CO_{2(g)} + (y/2)\,H_2O_{(v)} + 3.76a\,N_{2(g)}$$

where; a = x + y/4.

2.1. Fuel-Air Ratio

The mass ratio of the amount of fuel burned to the amount of air used in complete burning of the fuel is called the Fuel-Air ratio (F/A). When burning a solid, the ultimate analysis of the fuel gives the weight percentage of each component of the fuel. The stoichiometric Fuel-Air

$$(F/A)_{stoich.} = \frac{0.232}{2.66C + 7.94H_2 + 0.998S - O_2}$$

ratio is found using the values of fuel components resulting from the ultimate analysis as:

The actual F/A has a different value from the stoichiometric value. The difference between the two values depends on many parameters, such as elevation, pressure and temperature. The ratio between the stoichiometric and the actual Fuel-Air ratios represents the Equivalence Ratio (Ø), found as:

$$\emptyset = \frac{(F/A)_{actual}}{(F/A)_{stoichiometric}}$$

The equivalence ratio can be less, greater or equal to 1. If ($\emptyset < 1$), the actual Fuel-Air ratio is more than the required amount for a complete combustion and the mixture is said to be rich. If ($\emptyset = 1$), the actual Fuel-Air ratio is equal to the stoichiometric Fuel-Air and the mixture is said to be stoichiometric. Finally, if ($\emptyset > 1$), the Actual Fuel-Air ratio is less than the required amount for complete combustion and the mixture is said to be lean. Gasification seeks a rich mixture to get the unburned elements from the fuel which can be done by increasing the value of the actual Fuel-Air which means ($\emptyset < 1$) [10-13].

2.2. Solid Fuels

Solid fuels find little practical applications because of the problems in handling the fuel as well as in disposing off the solid residue or ash after combustion. Compared to gaseous and liquid fuels, solid fuels are difficult to handle. Feeding of a solid fuel in any practical application is quite cumbersome. Due to previous problems and complications in the design of the fuel feed systems, solid fuels have become unsuitable to burn in their solid form, and attempts to generate gaseous and liquid fuels from solid fuels were carried out [10].

2.3. Fluidization of Solids

Burning of solids is much more complicated than burning liquids and gases. Solid fuels may be burned directly, but the most efficient method to burn a solid fuel is the fluidized bed combustion. In fluidized bed combustors, air is blown through the biomass bed. The bed under such conditions behaves like a boiling fluid and has an excellent temperature uniformity. The bed also provides a good contact between gaseous and solid phases. Using fluidized bed combustion to burn solids is preferred for many reasons such as liquid like behaviour is easy to control and automate, rapid mixing, uniform temperature, high rate of heat and mass transfer rates, and applicable for both large and small scale operations [10-12].

Experiments showed that the fluidization velocity is related to the pressure drop of the bed. Fluidization occurs when the upward force exerted by the fluid on the particles is sufficient to balance the net weight of the bed. When this condition is applied, the particles begin to separate from each other and float in the fluid. Fig. 3 shows the relation between the pressure drop and the fluidization velocities [13]:

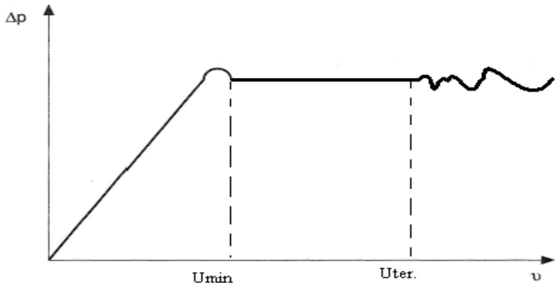

Figure 3: Pressure drop vs. velocity

When burning a solid, the minimum fluidization velocity and the terminal velocity must be known to limit the range of accepted velocity. Any velocity, less than the minimum fluidization velocity, does not give a fluidized bed. Similarly, any velocity, bigger than the terminal velocity, will result in dispersion of bed [12].

In this study, the minimum fluidization velocity and the terminal velocity to limit the range of operation were estimated using the equations below:

2.3.1. Minimum Fluidization Velocity, u_{mf} [12]

The minimum fluidized bed velocity is evaluated as follows:

$$u_{mf} = 0.0055\left(\frac{e_{mf}^{\ 3}}{1 - e_{mf}}\right)\frac{D^2\, g\,(\rho_{solid} - \rho_{air})}{\mu_{air}}$$

Where:

e_{mf} : Porosity of bed, $e_{mf} = \frac{|V_{bed} - V_{solid}|}{V_{bed}}$

Terminal velocity (u_{tf}), $u_{tf} = \frac{D^2\, g\,(\rho_{solid} - \rho_{air})}{18\mu_{air}}$

Desired velocity (u_d), $u_d = \frac{u_{mf} + u_{tf}}{2}$,

which lies in the range of fluidization velocity.

The combustion products from complete combustion of biomass generally contain nitrogen, water vapour, carbon dioxide and oxygen. In gasification, where there is a surplus of solid fuel and due to incomplete combustion, the products are combustible gases like carbon monoxide, hydrogen and traces of methane and other non useful products like tar and dust. The production of these gases takes place by the reaction of water vapour and carbon dioxide through a glowing layer of charcoal. The purpose of the gasifier is to create conditions such that the biomass is reduced to charcoal and charcoal is converted at suitable temperature to produce CO and H_2 [14-16].

2.3.2. Chemical Processes

In this work, an updraft gasifier system was used, with air as the fluidizer and date seed as the fuel. Four processes took place in the updraft gasifier as the fuel makes its way to gasification. These processes are drying, pyrolysis, combustion and reduction. Drying the feed is the main process in this zone. Various experiments on different gasifiers at different conditions have shown that the average condensate formed was about 6-10% of the weight of the gasified feed.

Some organic acids also come out during the drying process. These acids give rise to corrosion of gasifiers. In the pyrolysis process, the products depend upon temperature, pressure and heat losses. Up to 200°C temperature, only water is driven off. Between 200 and 280°C, carbon dioxide, acetic acid and water are driven off. The real pyrolysis, which takes place between 280°C and 500°C, produces large quantities of tar and gases containing carbon dioxide.

The combustion reduction reaction is exothermic and yields a theoretical oxidization temperature. The main reactions are:

$$C_{(s)} + O_{2(g)} = CO_{2(g)}$$
$$2H_{2(g)} + O_{2(g)} = 2H_2O_{(v)}$$

The products of partial combustion are water, carbon dioxide and some pyrolysis products. The pass through a red hot charcoal bed where the following reactions take place:

$$C_{(s)} + CO_{2(g)} = 2CO_{(g)}$$
$$C_{(s)} + H_2O_{(v)} = CO_{(g)} + H_{2(g)}$$
$$CO_{(g)} + H_2O_{(g)} = CO_{2(g)} + H_{2(g)}$$
$$C_{(s)} + 2H_{2(g)} = CH_{4(g)}$$

The first two reactions are the main reductive reactions and they are endothermic, which reduces the gas temperature. Many experiments show that the lower the reduction zone is, the lower the calorific value of the gas [10, 14].

3. Analysis

The experimental feed rate of both date seed particles and air should be estimated carefully to achieve gasification, not combustion. The following procedure shows the theoretical calculation of needed minimum fluidized bed velocity, actual fuel air ratio and mass flow rate of air and date seed particles, taking into consideration the dimension of apparatus and manufactured stainless steel gasifier pipe.

Volume of bed = V_{bed} = h x A_{pipe} = 0.0145 x 5.9x 10^{-4}

= 8.55 x $10^{-6}\ m^3$

Volume of sand = $V_{sand} = \frac{m}{\rho} = \frac{0.02}{1680}$

= 11.964 x $10^{-6}\ m^3$

Porosity = $e_{mf} = \frac{|V_{bed} - V_{sand}|}{V_{bed}}$

$= \frac{|8.55 - 11.964| \times 10^{-6}}{8.55 \times 10^{-6}} = 0.399$

Terminal velocity = $u_{tf} = \frac{D^2\ g\ (\rho_{solid} - \rho_{air})}{18\mu_{air}} =$

$\frac{(425x\ 10^{-6})(9.81)(1680 - 0.4225)}{18\ (377x\ 10^{-7})} = \ = 4.3856\ \frac{m}{s}$

Minimum fluidization velocity = u_{mf} =

$0.0055 (\frac{{e_{mf}}^3}{1 - e_{mf}})\ \frac{D^2\ g\ (\rho_{solid} - \rho_{air})}{\mu_{air}}$

$= 0.0055\ (\frac{0.399^3}{1 - 0.399})$ x

$\frac{(425x\ 10^{-6})(9.81)(1680 - 0.4225)}{(377x\ 10^{-7})} = 0.0458\ \frac{m}{s}$

Desired velocity at $550^o C$ = $u_{d@550^o C} = \frac{u_{mf} + u_{tf}}{2}$ =

2.2157 $\frac{m}{s}$

Air flow rate at $550^o C$ = $\dot{m}_{air@550^o C}$ = u_d

$\rho_{air@550^o C}\ A_{pipe}$ = 2.2157 x 0.4225 x 5.9 x 10^{-4}

= 5.523 x $10^{-4}\ \frac{kg}{s}$ = 0.5523 $\frac{g}{s}$

Stoichiometric Fuel-Air ratio = $(F/A)_{stch.}$

$= \frac{0.232}{2.66C + 7.94H_2 + 0.998S - O_2} =$

$\frac{0.232}{2.66(0.5084) + 7.94(0.0683) + 0.998(0) - 0.3788} = 0.153\ \frac{kg\ solid}{kg\ air}$

Gasification seeks a rich mixture ($\emptyset$ > 1), values of the actual Fuel-Air ratio $(F/A)_{act}$ defers linearly with the equivalence ratio. Many tests were done with different values of equivalence ratio to change the actual Fuel-Air ratio and find the most suitable value for gasification. It was found that at ($\emptyset$ = 1.49), gasification can be noticed and the parameters can be read easily by the gas analyzer. The relation between the actual Fuel-Air ratio and the equivalence ratio is plotted in Fig. 4 using the value of $(F/A)_{stch.}$ = 0.153 $\frac{kg\ solid}{kg\ air}$ as constant.

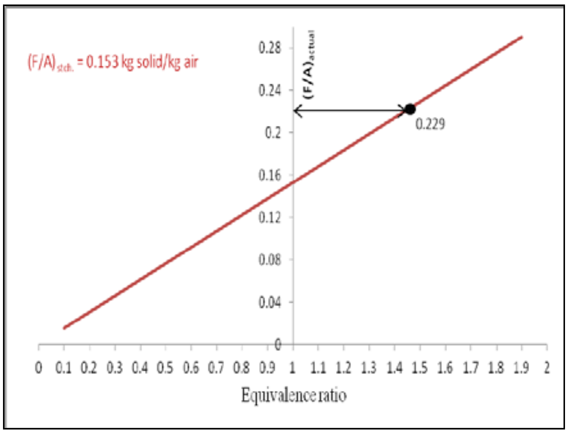

Figure 4. Actual fuel-air ratio vs. equivalence ratio

4. Experimental Work

The updraft gasifier was used in this work to gasify date seed. This gasifier, as shown in Fig. 5 and Fig 7, consists of a stainless steel pipe of 27.5 mm diameter that has a steel mesh welded above the bottom. The steel mesh has 600 holes to allow air to pass through it. Sand grains were put on the mesh to form the fluidized bed. Fluidization occurs when air passes through the bed of sand at a specified velocity. The pipe was heated to $550^{o}C$, and then feed falls on the bed to allow the gasification process to take place. The gas produced is taken from a small outlet at the top of the pipe. A gas analyzer is used to estimate the percentage composition of the gases with time. The temperature of the bed was measured every second of the experiment using a thermocouple that is inserted into the pipe.

4.1. Preparation of Date Seed

4.1.1. Drying:

The first step in preparing the date seed was to dry them in an oven at $105^{\circ}C$ for two hours. Drying was done to get rid of the moisture inside the seed and to prevent it from kneading when crushed.

4.1.2. Crushing:

After drying, the seed were crushed in a Jaw Crusher machine to prepare for sieving them in different particle sizes.

4.1.3. Sieving:

Separating each particle size from another is done using the shaker. The smallest sieve size is put in the bottom while the biggest sieve is put on the top as shown in Fig.5.

Figure. 5. Sieving shaker machines.

4.2. Thermophysical Properties of Date Seed

Proximate analysis and ultimate analysis were carried out to find the Fuel-Air ratio of the gasification process of date seed. Other thermophysical properties of date seed were estimated experimentally and are given in table 1. The density of date seed particles was determined using Archimedes method of volumes by the displacement of water; since the fluidization velocities calculation uses the true density which does not include the voids between the particles. So, this method was used because it finds the volume of the particles only and the voids are filled with water.

4.3. Updraft Gasifier

The combustion chamber was manufactured from a stainless steel pipe of a circular cross section area. Air enters from the bottom of the pipe through a small lane and passes through an iron mesh where the bed of sand lies. Feed is introduced manually from the top by another lane to be gasified. The pipe was heated in an oven for 24 hours to get rid of the dust and other dirt in the holes of the iron mesh and to prevent any obstacles to stand in the air path.

Table 1. Ultimate (dry, Ash free basis) and proximate (as received) analyses of date seed

Analysis	**wt %**
Ultimate:	
C	50.84
H	6.83
N	4.45
S	0.00
O	37.88
Proximate:	
Fixed carbon	16.311
Volatile matter	77.699
Moisture	5.01
Ash	0.98
Density, kg/m^3	1680
LHV, kJ/kg	16400
HHV, kJ/kg	17700

Product gases from the gasification process are taken from the pipe outlet directly to a cooling basin. The gas passes through a cylindrical glass pipe filled with small crushed pieces of cut glass. The cut glass is inserted into the glass pipe to increase the passing area of gases. To determine the concentrations of each combustible species, a gas analyzer was connected to the cooling basin. The measurement of the volumetric concentration of $O_{2(g)}$, $CO_{(g)}$ and $CO_{2(g)}$ were recorded during the gasification process.

The temperature of the fluidized bed during gasification was measured and recorded using a thermocouple of type "K" and a data logger to study the variation of the temperature of the fluidized bed with time from the beginning of feed entering until the gas analyzer rests. The gas analyzer used and gasification complete system are shown if Fig. 6 and Fig. 7.

Figure 6. Gas Analyzer

Figure 7. Experimental Apparatus

5. Results

The following figures represent the main findings of this work. These figures show the fluidized bed temperature, the concentration of oxygen and carbon monoxide during the gasification process.

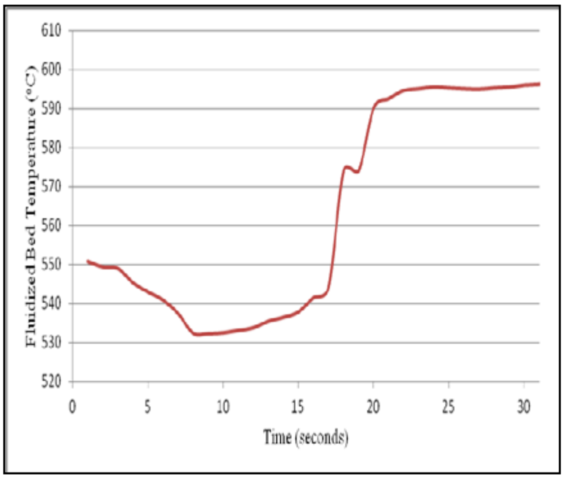

Figure 8. Fluidized bed temperature with time

It is noticed from Fig. 8 that the temperature of the fluidized bed decreased in the first stages of feeding due to heat transferred from the bed to the seed. While it started to increase up to 595° C when gasification occurred since the chemical reaction of gasification is exothermic. This also indicates that complete combustion did not take place; otherwise the temperature will increase to higher values.

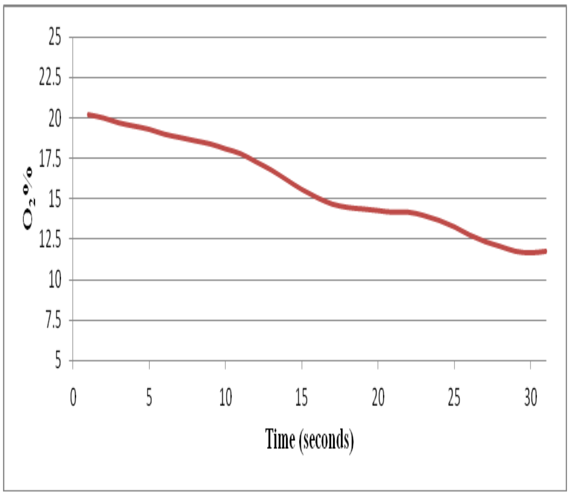

Figure 9. Oxygen concentration with time

From Fig. 9, it is seen that the level of oxygen, $O_{2(g)}$ decreased with time which indicates clearly that gasification is going on.

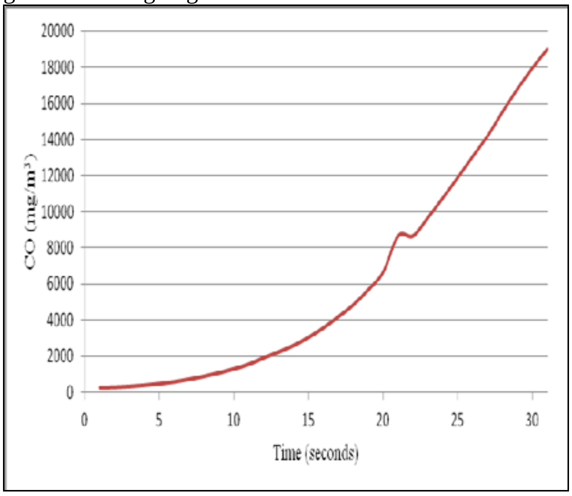

Figure 10. Volumetric concentration of $CO_{(g)}$ with time

Fig. 10 shows that the volumetric concentration of carbon monoxide, $CO_{(g)}$ has increased. This increase is not due to dissociation of carbon monoxide; since the temperature did not reach 850° C. This increase assures that gasification, not combustion, occurred successfully in this work.

6. Conclusion

In this study, the use of an updraft gasifier, with a fluidized sand bed to gasify date seed, proved to be a successful method to utilize agricultural solid waste. It was also found that the higher heating value of date seed reached 17,700kJ/kg, while the gasification process took place at 550° C temperature with 355-500µm particle size and 2.2157 m/s fluidization velocity. This ensures that solid waste of bio mass represent a valuable renewable source of energy in the near future if utilized correctly.

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