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Abstract. Due to the lack of the instrument, a biomass incinerator operating parameter can be studied through the stack gas for a preliminary to the incinerator operating parameters design and development. The main objective of this paper is to derive the equations which can be used to predict the air required to reach complete combustion through the stack gas analysis. Molecular mass of the biomass was determined based on the stack gas composition which was measured by means of hand-held gas detector. The ratio of the air flow rate supplied to the biomass rate is considered and monitored as well as the flame temperature of the stack gas at the outlet. By adjusting the air flow rate into the primary and secondary combustion zones, a stable and complete combustion was possibly reached. High stack gases temperature, percentage of oxygen or carbon dioxide by volume of the stack gases then were used as the criteria to the optimum operating parameters required. This method is helpful to the incinerator optimization with lack of instrument, since it is thought that the incinerator may meet domestic emission limits with good combustion control through proper and precise operation.

1. Introduction

The use of renewable energy, particularly biomass, has grown in popularity in recent decades as a result of environmental concerns and a large drop in fossil fuel supplies. Many studies on biomass energy over the last 20 years have shown that biomass's role in the energy mix is critical, and that biomass's importance in the energy mix has been growing more widespread and global over the last 20 years as studied by Mao et al [1]. Until today, the most popular way of getting energy from biomass has been thermochemical conversion, which includes burning, gasification, and pyrolysis [2]. Among the three methods discussed, combustion, which has been utilized as a source of heat for residential purposes for a long time, has remained the most popular in recent years.

Biomass solid fuel is known consists of a wide range of material but only a few types are suitable for use in the production of heat and power. Biomass solid fuel is comprised of a large variety of materials, but only a few varieties are ideal for generating heat and electricity. In the incinerator, biomass combustion is a complex process that involves a series of heterogeneous and homogeneous processes. Drying, devolatilization, gasification, char combustion, and gas-phase oxidation are the main steps in the process. The research of flue gas emission related with incinerator operating conditions is also required in order to find the optimum operating parameters during combustion in the incinerator. If not properly developed and operated, the incinerator can become a significant polluter. The flue gas from incinerator contains particles and gases which are harmful and toxic to human and environment. If the

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mixing level of the burnt biomass are better operated, the amount of pollutants to the environment will be reduced. The amount of pollutants released into the atmosphere will be reduced if the burnt biomass mixing level was enhanced. [3].

Combustion is a chemical reaction involve drying, pyrolysis, gasification, and reduction which simultaneously occurred a chamber and a large quantity of energy is released. A complete combustion can reach temperatures ranges from 700-1400 ^{0}C [4]. In order to accomplish nearly complete combustion, the combustion air must be mixed with the combustibles produced from the feedstock, and the temperature and residence duration must be regulated. However, biomass combustion is extremely difficult. It is mainly caused that the biomass generally has moisture < 50% and the volatile of 80%. Additionally, most incinerators are composed of locally sourced bricks and operate inadequately due to a lack of air combustion distribution throughout the chamber.

Fixed bed incinerator type is the most often utilized biomass feedstock for combustion. This incinerator is known flexible and relatively simple with low cost on fuel treatment and can covers wide range of the fuel sizes of 5-100 mm. However, it is limited on the incinerator capacity when used to generate thermal energy 150 MWth/50 MWe roughly [5]. The biomass feedstock is usually piled on the grate while it combusts with air provided through the grate's openings [6]. The incinerator stack gas contains particles and gases that are dangerous and toxic to people and the environment [7]. Usually, the pollutants in the form of particulate matter or fly ash, heavy metal, and gases which mainly influenced by the composition of the fuel, temperature, and the combustion conditions

Theoretically, the mixture of fuel and air will never be precise in the incinerator automatically. All fuels must have enough oxygen to achieve their combustion, thus extra air is always available in the form of an abundance of air. However, the excess air is less significant above of 20% [8]. However, the excess air increases combustion efficiency. Good mixing level can be achieved by employing a devices to provide enough and distributed air required entire the combustion chamber [9-10]. However, the only way to provide enough air combustion required is by increase the air flow rate into the combustion zones. But, further increasing the air flow lead to an intensification of the convective cooling or quenching regime [11-12].

Flame temperatures can reach 1650 ^{0}C depending on the heating value, moisture content of the biomass feed, amount of air used, and combustor design [13]. However, a conventional fixed-bed combustor restricted to the main problems on the gas-solid mixing causes highly incomplete combustion. Until now, the effort of increasing of combustion performance still based on experience, empirical data, and modelling with a small-scale in most cases [14-15].

The influence of excess air ratio, residence duration, and temperature in batch combustion was previously explored only in the case of a single wood feed particle, revealing a relationship between NO level and excess air ratio and temperature at the same time [16]. Based on the basic combustion route of a solid fuel, volatiles are released from the fuel as a gas and exit to the freeboard immediately after drying. If there is enough oxygen, it will combust and produce hot gasses. The rest is char and undergo burnout leaving the ash. It means that it is required sufficient oxygen in the freeboard zone. As a result, considerable attention should be paid to the air supply method's design in order to ensure better mixing of the biomass feed and oxygen in both combustion zones. The potential approach of increasing air supply is by dividing the combustion zones so that the combustion involves adjusting the air supply to the primary and the secondary zones separately as pictured in figure 1, where in the primary combustion zones can be set as an incomplete or reduction process (λ<1) with starved air supply causes produce mainly of combustible gases. The gases then flow to the freeboard zone or burnout zone, undergo the secondary reaction with excess air supply (λ>1) to complete the process and resulting of high product gas temperature. Several researcher have tried to implement this methods [17-20].

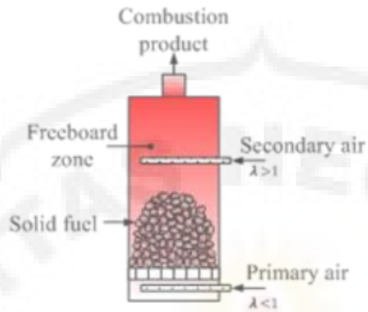

Figure 1. Staged air supply fixed-bed incinerator

To obtain a good incinerator performance, a modification to the conventional incinerator or single air supply with the aim to improve the combustion hydrodynamic flow is highly required. The combustion conditions must be approached on the air to fuel ratio (A/F) or stoichiometry conditions. Therefore, several researchers tried to increase especially the hydrodynamic of combustion by implementing staged combustion [15, 21-25]. This method makes it possible to control air more appropriate in the primary combustion below the stoichiometric condition to produce more carbon monoxide, flows to the hot freeboard zone, secondary combustor, hence the temperature of product gas can be increased significantly.

Staged air is a method for suppling oxidizing air which separated the air for primary and secondary combustion chamber. Some researcher called as an extreme-air-staging [26]. Staged air supply is very potential to maintain the air-fuel ratio during combustion owing to the cost-effectiveness. NOx emissions can be reduced by 50-80% using staged combustion, which comprises both staged air and staged fuel combustion [27]. This strategy has been tried in a laboratory scale to prove that air-staging has significance effect on efficiency with less gaseous and particulate emissions [28]. Therefore, direct experimental under real operating conditions or industrial scale purpose gains increasing importance to make incinerator units more competitive. However this point has been refuted and was revealed that the ratio of excess air was the main factor on the emission instead of temperature [19, 22, 29-30]. Some study also gives strengthening and supporting this point of view. Solutions refer to the published Journals. Another research focus on the combustion temperature effect that can be controlled through the amount of the fuel feeding and the air supplied.

By using a 50 kW of domestic stove with staged air supply, Serrano et al [31] discovered that raising the secondary air flow raised the flue gas temperature of pine chip burning while lowering the carbon monoxide level. With a similar appliance, Lamberg et al. [32] also verified that the air required is the main control to gases emission. Carvalho et al. [20] used an air excess control technique to reduce CO emissions from a 15-kW pellet boiler in their study. Carbon monoxide emissions were shown to be proportional to combustion chamber temperature, and hence could be regulated by adjusting the supplying air flow rate. Roy et al [19], who postulated a similar association between air surplus and CO in a 32-kW pellet boiler, had similar results. They claimed that the amount of oxygen in the flue gases affects the thermal input, overall efficiency, and thermal losses.

In this study, an incinerator which easy to operate is developed with overfeed pile burner model where the air combustion required is supplied by utilizing two air holes which make possible of controlling the air into the primary combustion zone at starved air supply. Due to a lack of oxygen, incomplete combustion occurs, with CO as the predominant resultant gas. The CO then undergo complete combustion in the freeboard zone causes high temperature combustion product. The goal of this research is to look into the operating parameters of a staged air incinerator by looking at the combustion product. The data will be utilized as the beginning condition for the existing incinerator in order to examine the current design's operating characteristics in order to improve incinerator design and operation.

2. Method

Any fresh of biomass solid fuel residue can be used as the feedstock sample in this study. The solid fuel was assumed in the average sized and has standard dryness. The combustion was performed by considering optimum parameters recommended such as the air to fuel ratio typically about 4−7 [5]. Due to the ignition temperature of the carbon atoms which is approximately 400 ^{0}C [32], therefore the operating temperature at the primary chamber (T_1) should be minimum at 400 ^{0}C and can vary between 400 and 500 ^{0}C by adjusting the primary air utilizing valve regulator and the feedstock supply. Meanwhile, the secondary chamber temperature (T_2) can vary above the temperature of primary chamber as pointed in figure 2.

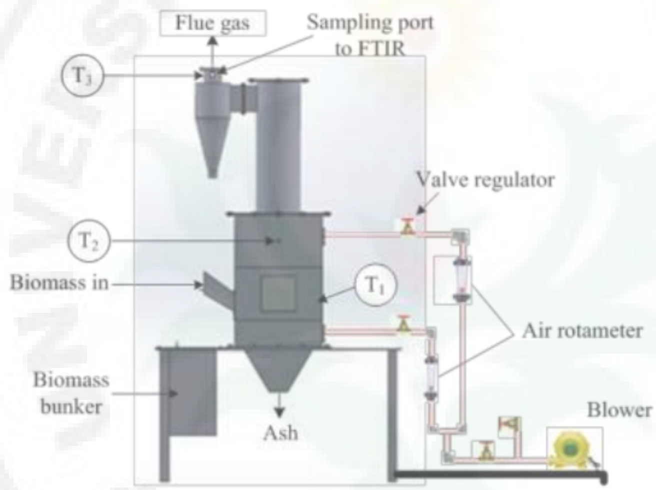

Figure 2. Skecth of the develop incinerator setup

The raw stack gas products (flue gases) were detected using hand flue gas detector which mainly consist of CO_2, H_2O, O_2, N_2, and the presence of noxious gases such as CO, NOx, SOx, and another gas which has kind of low content composition. The value of these gases must be satisfactory since they assure the safety of humans and plants after dilution into the ambient air. These stack gas compositions are used to evaluate the optimum incinerator operating parameter. By using the stack gas data, the molecular formula of the solid feedstock as well as the elemental constituent mass such as C, H, O, N, S, etc. can be determined by applying mass balances equation.

Amount of air supply is the key point of succeed combustion of feedstock. Complete and incomplete combustion are two condition which can be occurred during combustion. Complete combustion burns C, H, and S to CO_2, H_2O, and SO_2 respectively without uncombined oxygen. However, incomplete combustion resulted any unburned carbon, and gases such as H_2, CO, or OH. The following equation can be a general combustion reaction of the solid feedstock in the incinerator,

$$xC_{y_1}H_{y_2}O_{y_3}N_{y_4}S_{y_5} + (1/\phi)V_{O_2}.(3.76N_2 + O_2) \rightarrow aCO_2 + bH_2O + cO_2 + dN_2 + eCO + fNO_x + gSO_x \quad (1)$$

Where subscript *x* is the amount of feedstock (molecular or mass base), *yi* is the amount of constituents, coefficient (*a-g*) are volume percentage of gas stack compound, ϕ is the equivalent ratio, that is the ratio between the actual air volume ($V_{a,act}$) and the stoichiometric air volume ($V_{a,st}$). For ϕ=1, the combustion is stoichiometric or complete combustion where there are no O_2 and CO in the gas stack. Due to fuel qualities, combustion mode, and incinerator design, complete combustion with theoretical air is difficult to achieve. Therefore, the combustion is performed by utilize air above the theoretical air which called excess air or $\phi>1$. For a furnace, ϕ_f has values between 1.05 and 1.7. Therefore, the equivalence ratio used is expressed as

$$\phi_f = \frac{V_{a,act}}{V_{a,st}} \quad (2)$$

Or

$$\phi_f = \frac{\dot{m}_{pri} + \dot{m}_{sec}}{\dot{m}_{f\cdot st} AF_{st}} \quad (3)$$

Where $\dot{m}_{pri}$ and $\dot{m}_{sec}$ are the primary and secondary air flowrate (kg/s). Usually, the incinerator utilized fully atmospheric air instead of pure oxygen which has a volume participation by 21%, therefore, every kilogram of feedstock, the stoichiometric amount of dry air required for combustion is

$$V_{a,act} = \frac{V_{O_2}}{0.21}\left[\frac{m_N^3 air}{kg\ fuel}\right] \quad (4)$$

The introduced air contains vapor (moisture) which is the amount of water in the air known as the absolute humidity (χ), then the stoichiometric volume of wet air (V_{aw}) required can be written as:

$$V_{aw} = (1 + 1.61\chi)V_{a,act}\left[\frac{m_N^3 air}{kg\ fuel}\right] \quad (5)$$

Therefore, the theoretical air flow rate required to be

$$\dot{V}_{act} = \dot{m}_f.\, V_{aw}\left[\frac{m_N^3 air}{h}\right] \quad (6)$$

The equation determines the stoichiometric volume of oxygen necessary for full combustion of a unit quantity of feedstock is

$$V_{O_2} = \frac{22.41}{100}\left(\frac{C}{12} + \frac{H}{4} + \frac{C-O}{32}\right)\left[\frac{m_N^3 O_2}{kg\ fuel}\right] \quad (7)$$

And the oxygen flowrate is expressed as

$$\dot{V}_{O_2} = \dot{m}_f.\, V_{O_2}\left[\frac{m_N^3 O_2}{h}\right] \quad (8)$$

The energy is generated during combustion included in the outflowing stack gas product. The maximum adiabatic flame temperature that can be achieved on a stoichiometric reaction for a given fuel, as well as the pressure and temperature of the reactants. Excess air can be utilized to adjust the temperature of an adiabatic flame. By assuming the incinerator as a control volume, steady state process, combustion chamber is adiabatic, stack gases as ideal gases, there are no work interactions, and the change of kinetic and potential energy are ignored, the energy balances equation can be expressed as

$$\sum_R n_i(\bar{h}_f^0 + \Delta\bar{h})_i = \sum_P n_e(\bar{h}_f^0 + \Delta\bar{h})_e \quad (9)$$

Where R and P refer to the reactants and products, respectively, $\bar{h}_f^0$ is the sensible enthalpy at the standard reference state of 25 ^{0}C and 1 atm. Incinerator efficiency is analyzed by using the CO_2 indicator. The following equation is utilized

$$\eta = \frac{CO_2}{CO_2 + CO} \times 100\% \quad (10)$$

3. Conclusion

The operating parameter of the biomass solid incinerator of fixed bed type with two stage air supply has been conducted. The study revealed that the operating parameter can be optimized by analyzing the combustion product during combustion. By using two stages air supply leads to improve a significant incinerator performance where in fact that the high-performance lead to decrease the pollutant. This theoretical analysis must be validated by using the real incinerator. In order to confidently proposed and building the real incinerator and a lot of tests should be performed by utilize a number type of solid biomass feedstock with their own characteristic.

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