Experimental Investigation of Combustible Gases from Primary Combustion Chamber of a High Temperature Air Combustion Incinerator

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Abstract

Incineration is an alternative way to dispose of municipal solid waste. It has more advantages, e.g., reduction in volume and weight of waste, destruction the contamination in waste, recovery of energy, etc., but it's drawback is the higher net treatment cost compared to disposed in landfill. The overall objective of the research is to overcome a higher operating cost of the incineration by applying High Temperature Air Combustion (HiTAC) technology, i.e., supplied of highly preheated combustion air above an auto-ignition temperature of combustible gas from primary combustion chamber (PCC) to completely burn these gases in secondary combustion chamber (SCC) without or minimizing an auxiliary fuel; the highest portion of all of the treatment cost. The specific objectives of this study are to investigate the concentraion, heating value and gas flow rate of combustible gas from PCC in difference of primary air flow rate and chamber's temperature which are importance to design the SCC and determine secondary air flow. The experiment were conducted in a lab-scale 17.5-kW of capacity controlled-air incinerator with the range of primary air flow rate 0 - 20 percent of stoichiometric air and sawdust was used as a solid fuel. The sample gases were analyzed by two gas analyzers. One was an on-line gas analyzer which indicated directly and continuously the composition of the gas. Another one was Gas Chromatography that measured percent composition of CO_2, CO, CH_4, N_2, H_2 and O_2. The major components of combustible gases are carbonmonoxide and hydrogen. The composition and heating value of combustible gases are highest at primary air flow rate of 10 percent of stoichiometric air and the chamber preheating temperature of 700°C with 2.6664 MJ/Nm^3 of HHV, gas flow rate of 1.80 Nm^3/h and gas yield of 0.51 Nm^3/kg-sawdust.

Keywords: *Combustible gas, Controlled-Air Incinerator, High temperature air combustion (HiTAC), Thermal treatment*

1. Introduction

The waste generated in many countries was disposed in landfill because of lower net treatment cost compared to incineration, e.g., 56% in U.S.A [1], over 90% in India [2]. In Japan, island country, the most of waste was treated by incineration of 73% and by landfill of 23% [2]. In 2003, the total waste generation in Thailand was 14.4 Million tons which classified to the waste generated in Bangkok 24%, municipality 31% and others 45%. From the total of waste generated, only 35% of waste was sanitary landfill, but the others 65% was open dumping [3]. A drawback of incineration is higher net treatment cost with normally range from US$25-$100 (in 1998) compared to the net treatment cost of landfilling ranges from US$10-$40 [4]. So that it is not attractive to use incineration for waste treatment. However, incineration has more advantages, e.g., reduction in mass and volume of waste, destruction the contamination in waste, recovery of energy, etc. The major

portion of treatment cost of incineration coming from a using an auxiliary fuel [5] in the secondary combustion chamber (SCC) which it has to operate at high enough temperature to maintain the desired, thus, decontaminating the waste to eliminate risk to health and environment. Since the recommended range of primary combustion chamber (PCC) and SCC temperature for infectious material destruction from U.S. EPA is in the range of 540-980°C and 980-1200°C, respectively [6], the temperature of each chamber is to be controlled to near preset values; this is done by using thermocouple signals from each chamber to the controller where they are compared with the preset values. The signal differential is used to actuate the on-off control of the burners. To reduce the treatment cost, one must reduce the consumption of fuel in the combustion process. Thus the research and development on incineration technology to burn the waste without or with minimized an auxiliary fuel using is worth investigating. An innovative technology, High Temperature Air Combustion (HiTAC), will be applied to this purpose which it was successfully developed for industrial furnaces; it has been demonstrated to provide about 30% reduction in energy (and also CO_2 emission), 50% reduction of pollutants, and about 25% reduction in the physical size of the facility compared with the conventional type of furnace design. Furthermore, extremely low levels of nitric oxide emissions have been demonstrated in several field trials [7,8]. In present research, HiTAC is applied to reduce the treatment cost in thermal destruction of waste. An interesting approach to minimize treatment cost of the waste incineration appears to be supplied of highly preheated air above an auto-ignition temperature of combustible gases from the PCC to completely burn these gases without or with minimizing an auxiliary fuel which is the highest portion of all of the treatment cost. However, the amount and the composition of combustible gas from PCC need to be investigated firstly.

2. Theory [9,10]

The combustion in PCC of a controlled-air incinerator (used in this study) is in sub-stoichiometric condition or partial oxidation which the combustion products are volatile matters and combustible gases as same as the producer gas generated from gasification process. So that, the reaction in PCC can be explained by gasification process. Generally, a fixed bed gasifier can be regarded as consisting of four different zones, e.g., drying zone, pyrolysis zone, reduction zone, and combustion zone in which different chemical and physical process take place (Figure 1).
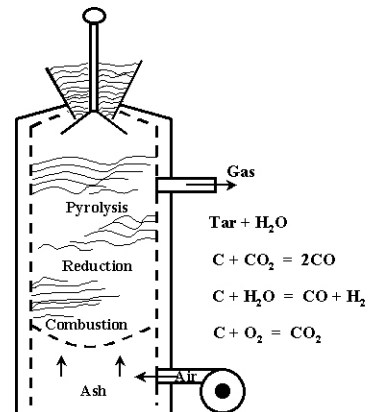

Figure 1. Schematic diagram of updraft gasifier

The processes taking place in the drying, pyrolysis and reduction zones are driven by heat transferred from the combustion zone. In the drying zone, the moisture content of fuel, e.g., biomass, solid waste or coal evaporates. Essentially dry fuel enters the pyrolysis zone from the drying zone. Pyrolysis converts the dried fuel into char, tar vapour, water vapour and non-condensible gases. The char produced in the pyrolysis zone passes through combustion and reduction zones. In the oxidation zone, carbonized fuel comes into contact with the oxygen. In the reduction zone, the products of complete combustion, e.g., CO_2, H_2O, etc., undergo reduction by the carbonized fuel. Complete gasification of biomass involves several sequential and parallel reactions. Most of these reactions are endothermic and must be balanced by partial combustion of gas. This involves a number of reactions taking place simultaneously as follows:

The overall combustion reaction taking place in the combustion zone can be written as :

$$C + O_2 = CO_2, +393,800 \, kJ \, / \, kg \, mole \, carbon \qquad (1)$$
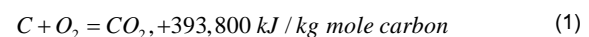
The air introduced contains besides oxygen, water vapour and inert gases. The inert gases are normally assumed to be non-reactive with the fuel constituents. However, the water vapour reacts with the hot carbon according to the water gas reaction:

$$C + H_2O = H_2 + CO, -131,400 \, kJ \, / \, kg \, mole \, carbon \quad (2)$$
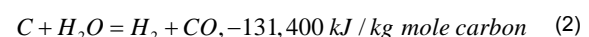
CO_2 produced in the oxidation zone is reduecd to CO according to the Boudouard reaction:

$$CO_2 + C = 2CO, -172,600 \, kJ \, / \, kg \, mole \, carbon \qquad (3)$$

Another important reaction taking place in the reduction zone is the water shift reaction :

$$CO + H_2O = CO_2 + H_2, +41,200 \, kJ / kg \, carbon \qquad (4)$$
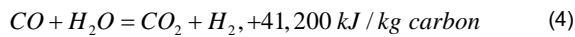
Some methane formation also takes place in the gasifier. This can be presented by simple overall reaction:

$$C + 2H_2 = CH_4, +75,000 \, kJ / kg \, mole \, carbon \qquad (5)$$
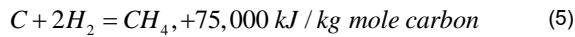
3. Objective of study

The purpose of this first phase of study is to investigate the operting conditions which generate maximum combustible gases from PCC in difference of primary air flow rates and the chamber preheating temperature. Data from these experiments will be used to further study on the HiTAC phenomena in SCC.

4. Materials and method

4.1 Controlled-air incinerator

A schematic of 17.5-kW of laboratory-scale controlled-air incinerator used in this study is illutrated in Figure 2.
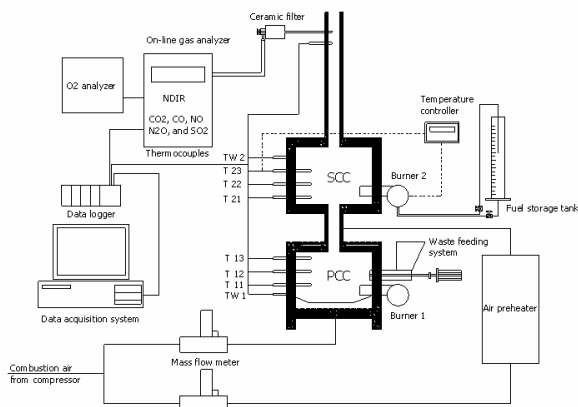

Figure 2 : Schematic diagram of laboratory scale incinerator

Incinerator has two combustion chambers; PCC and SCC, which are made of 3 mm thick mild steel and thermally insulated inside with 2.5 cm ceramic fiber and lined with 6.5 cm of castable cement. Sawdust, as a fuel, was fed by screw feeder system, which consists of a hopper, a screw feeder, and a 0.4-kW, AC, synchronous, 3-phase motor inverter, and burned under a sub-stoichiometric condition with primary air supplied under the hearth in the PCC. The combustible gases were driven off from PCC and went to SCC. The primary air flow was measured by rotameter with reading scale 0-12 m^3/h, Brooks: Model: SN: V36594. Diesel oil burners for PCC with a burner capacity in the range of 14-39 kW was used to preheat PCC before testing.

4.2 Measurement and data acquisition systems

Chromel-alumel thermocouples (K-type) of 1.6-mm diameter protected by ceramic rods were used for continuous measurement of the temperature at eleven locations along the height of incinerator; 4 ports for PCC (T_{w1}, T_{12}, T_{13}, T_{14} from bottom to top of chamber), and 1 port for stack (T_{st}). Temperature data signals were sent to the data logger (Yokogawa: DA100 & DS600) and were shown real time in personal computer. The combustible gases were intermittent taken from the centerline of the neck between PCC and SCC for continuous measurement of NO, NO_2, O_2, and CO by electrochemical analyzer. The sample gases also were collected in a gas containers to analyze the gas composition by Gas Chromatography.

4.3 Raw material and auxiliary fuel

In order to have a consistent waste material property and ease of preparation of the waste materials for the experiments, sawdust with size in the range of 0.85-5 mm was selected for use in this study. Analyzed properties of sawdust are given in Table 1.

Table 1 Average properties of sawdust

Properties	As-received basis	Dry ash-free basis
Proximate analysis (%wt)		
Moisture	8.45	-
Ash	2.20	-
Volatile matter	73.40	82.15
Fixed carbon	15.95	17.85
Ultimate analysis (%wt)		
Carbon, C	51.20	57.35
Hydrogen, H	6.50	6.20
Nitrogen, N	0.055	0.065
Sulphur, S	0.06	0.07
Oxygen, O	40.00	36.35
Ash	2.20	-
Net calorific value, kJ/kg	18,000	20,300
Bulk density, kg/m^3	93 kg/m^3	

5. Experiment methodology

The PCC was preheated by diesel oil burner to the required wall temperature of 500,600 and 700 ^{o}C. For each condition of preheating wall temperature, the primary air was supplied into PCC at different rates; no primary air supply, 10% of stoichiometric air and 20% of stoichiometric air. When the wall temperatures reached to the required values, a

primary chamber burner was switched off, sawdust was fed at 3.5 kg/h. All of temperature measurements were recorded and shown real time in personal computer. When steady-state conditions inside the chamber approached, started to measure the gas composition and concentration.

6. Results and discussion

6.1 Combustible gas concentration

The major component of combustible gases was carbonmonoxide which measured by on-line gas analyzer. The average value of CO concentration showed in Fig. 3. CO concentration, the most significant contribution to the heating value of the combustible gases, increased with primary air flow up to 10% of stoichiometric air due to more gasification reaction taking place and then decreased with more increased in primary air flow which resulted from higher degree of oxidation.
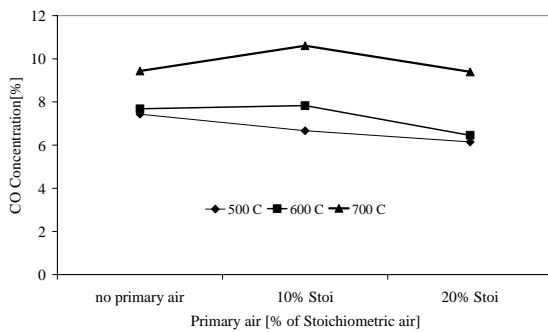

Figure 3 CO concentration

6.2 Combustible gas temperature

The combustible gas temperature showed in Fig. 4. An increasing of primary air flow resulted in increasing combustible gas temperature due to higher degree of oxidation. The preheating wall temperature also had effected to combustible gas temperature by higher preheating wall temperature resulted in higher combustible gas temperature.
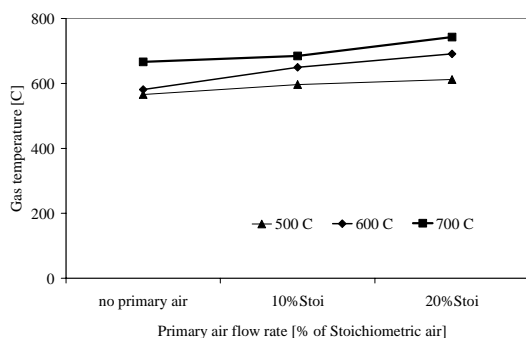

Figure 4 Combustible gas temperature

6.3 Destruction efficiency

The destruction efficiency defines as the ratio of mass of sawdust loss and mass input as shown in equation (6). The destruction efficiency is showed in Fig. 5. As aforemention, the higher primary air flow meaned higher degree of oxidation which resulted in higher destruction efficiency and preheating wall temperature also had effected in the same manner.

$$\text{Destruction efficiency} = \left[\frac{\text{mass input - mass remaining}}{\text{mass input}} \right] *100\% \quad (6)$$
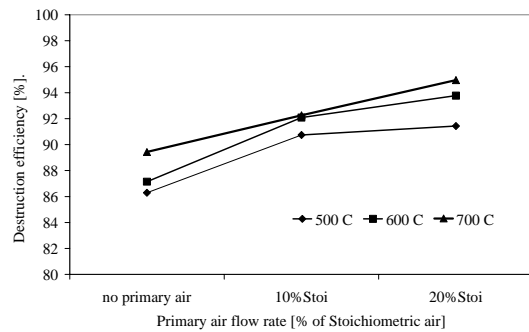

Figure 5 Destruction efficiency

6.4 Effect of wall-preheating temperature

Effect of wall preheating temperature on gas temperature and CO concentration are showed in Fig. 6 and 7. As wall preheating temperature increased, gas temperature will be increased and CO concentration also increased due to higher destruction efficiency or higher rate of gasification. The preheating wall temperature $500^{\circ}C$, $600^{\circ}C$ and $700^{\circ}C$ showed the same trend of CO concentration, but higher concentration could be seen in higher preheating wall temperature which should be a resulted of the higher rate of reaction occurred in the higher preheating wall temperature.
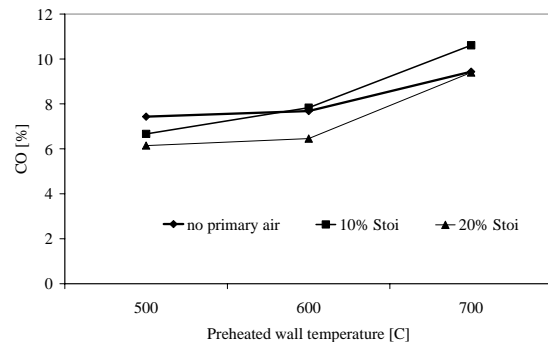

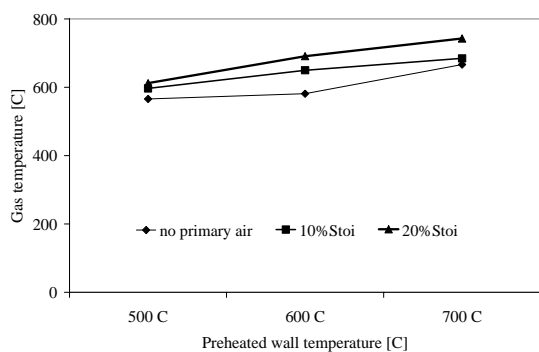Figure 6 Effect of wall preheating temperature on CO concentration

Figure 7 Effect of wall preheating temperature on gas temperature

6.5 Gas flow rate, higher heating value and gas yield

From the above results, the best condition (higher CO concentration) of testing ranges was the preheating wall temperature of $700^{o}C$ and primary air flow 10% of stoichiometric air. The sample gases from this condition were collected to analyze by Gas Chromatography; GC. The results from GC analysis (Table 2) were used to estimate combustible gas flow, higher heating value and gas yield which equal to 2.6664 MJ/Nm^3, 1.80 Nm^3/h, and 0.51 Nm^3/kg-sawdust, respectively. The higher heating value was lower compared to the value obtained from previous study [11,12,13] with in the range of 3.50-6.00 MJ/Nm^3 and can be considered as low-BTU gas. This result was due to the operating manner of this type of reactor which was not design for producing the combustible gas as an gasifiers.

Table 2 Gas compositions for wall preheating temperature $700^{o}C$ and 10% of stoichiometric air

Gas composition	%vol of gas
CO_2	9.4133
O_2	2.4876
CH_4	1.5372
CO	10.6165
H_2	2.5816
N_2	73.3637

7. Conclusions

The primary air flow and preheating combustion chamber wall temperature had effected to combustible gases generation. An increasing in primary air flow resulted in increasing combustible gases concentration up to a peak at primary air flow of 10% of stoichiometric air and then started decreasing as more increased in primary air flow. Moreover, an increasing in primary air flow resulted in increasing in gas

temperature, destruction efficiency as the higher degree of oxidation. The preheating wall temperature also had effect to gas temperature, combustible gases concentration and destruction efficiency by which higher preheating temperature showed higher gas temperature, gas concentration, and destruction rate. The highest combustible gas concentration was measured in case of 10% of primary air flow and preheating wall temperature at $700^{o}C$ with 2.6664 MJ/Nm^3 of HHV, gas flow rate of 1.80 Nm^3/h and gas yield of 0.51 Nm^3/kg. This condition will be used to further investigation in the next phase of study.

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