Gasification of Waste High Density Polyethylene/Wood Chip Mixtures in a Continuous Downdraft Gasifier System

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ABSTRACT

This experiment is study on gasification of municipal plastic waste mixed with wood chip. It was investigated in small scale continuous downdraft gasifier which was designed to continuously produce maximum power output of 100 kW. The reactor was continuously fed with 60 kg of mixture of woodchip and high density polyethylene waste (HDPE) from municipal solid waste as fuel. There are two type of fuel in this experiment which are 0 and 5% (by weight) of HDPE in fuel. In each case, varying air flow rate of 6 – 24 Nm^3/h to investigate the producer gas characteristics and gasification process. The results show that the producer gas contains CO_2, H_2, N_2, CH_4 and CO. The percentage of CO_2 was decreased but the percentage of CH_4 and CO was increased, it causes a higher calorific value of producer gas when the percentage of HDPE in fuel was increased.

Keywords: Continuous Downdraft Gasifier, HDPE, Municipal Waste

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Introduction

Nowadays, the consumption levels have fast increased from the rapid growth of the city. This is the direct causes of municipal waste, especially plastic waste which is from plastic carry-bag. The municipal waste causes the pollution in water and air and the presence of pathogens causing various ailments. Information of solid waste data collection from Bangkok Metropolitan Administration (BMA) in 2011 showed information of 9,237 tons solid waste collection per day, the solid wastes were conveyed 95 percent of daily collection to landfill facility in Phanom Sarakham district and Kamphaeng Saen district, and another 5 percent would be removed by composting.

In 2011, the annual report from the office of industrial economics showed the amounts of waste recycling could be 12,823,500 tons which consist of glass, paper, plastic, metal, aluminum and tire. These are able to feed into recycling process 77, 59, 29, 90, 71 and 37 percent respectively. The information also showed that only 29 percent of plastic waste could be recycled, for other would be passed into direct burn process which is causes of environmental problems.

Gasification is Thermo-Chemical process which can transform solid fuel into fuel gas, for example, woods, coals, dungs, agricultural wastes and hydrocarbon composition (Sheth *et al.*, 2009; Minchener, 2005; Erlich *et al.*, 2010) they can transform to combustible producer gas after gasification. The producer gas from gasification can replace natural gas and gasoline in internal combustion engine to reduce petroleum gas consumption which cost higher. In this study, we use plastic waste (plastic carry bags) with wood chips fed into continuous downdraft gasifier to produce combustible gas as an alternative energy. This will be useful for stabilizing energy, and be able to reduce wastes into landfill process.

Objective of the study

To study the conversion of waste to energy and also reduce amount of waste in landfill.

Materials and Methods

Raw Material

High density polyethylene waste was from On-Nut area landfill (On Nut district, Bangkok). It was dried out and then chopped into 4-5 cm long. Wood chip (called 0%HDPE) was from north eastern forest of Thailand had a size of 2x 2.5x 0.5 cm. The results of proximate analysis and ultimate analysis of all fuel are shown in Table 1.

Continuous Downdraft gasification system

The continuous flow downdraft gasifier system is controlled by Programmable Logic Control (PLC) for continuous operation without stopping to add fuel and remove ash. The continuous flow downdraft gasifier system consists of Gasifier, Gas cleaner and cooler, fuel feeder and ash remover system. The details are as follow:

Downdraft gasifier was designed to release a maximum power output of 100 kW_{th}, it also has hopper to work as fuel passage way to Pyrolysis zone and Combustion zone. There are Drying and Pyrolysis process in hopper. Hopper size is 60 cm dimension with 57 cm height, the bottom of hopper is connecting to combustion zone where oxygen was limited to oxidation with fuel to produce thermal energy for other zones. Reaction in combustion zone is an exothermic, temperatures in this zone are between 800 - 1,100 ºC, and dimension is 40 cm with 40 cm height connecting to reduction zone. Reaction in reduction zone is for changing producer gas and steam from combustion zone to be combustible gas, and temperatures in this zone is between 600 – 900 ºC, its size is 30 cm dimension and 11.5 cm height. At the bottom of reduction zone is connecting to ash pit which has 30 cm dimension and 25 cm height, at the bottom also has screw feeder, 10 cm dimension and 160 cm total in height, to remove ash from gasifier as shown in Fig. 1 with 7.5 Hp induced draft fan to feed air into gasifier.

The procedures of producer gas cleaning start after producer gas discharged from gasifier, it also contaminated with ash, tars and steam. Cyclone collector performs to trap these particles, and these particles will fall down into below dust storage tank. Meanwhile, producer gas will be flowed up to cyclone collector into wet scrubber, wet scrubber also help to trap remained dust in producer gas by spraying water from upper side which revere producer gas direction (the spraying water is also help cooling down producer gas) making steam and tars condensing into liquid form with spraying down water flowing into the below storage tank.

Table 1 Proximate analysis, Ultimate analysis and higher heating value for different fuel

Analysis	**HDPE**	**Woodchip**
Proximate (wt%)		
Volatile Matter	92.22	41.02
Fixe Carbon	0.85	55.99
Ash	6.93	2.99
Ultimate (wt%)		
Carbon	75.30	45.45
Hydrogen	13.4	5.63
Oxygen	11.23	48.64
Nitrogen	0	0.23
Sulphur	0.12	0.05
Moisture (%)	6.93	15.85
H.H.V (MJ/kg)	38.23	21.66

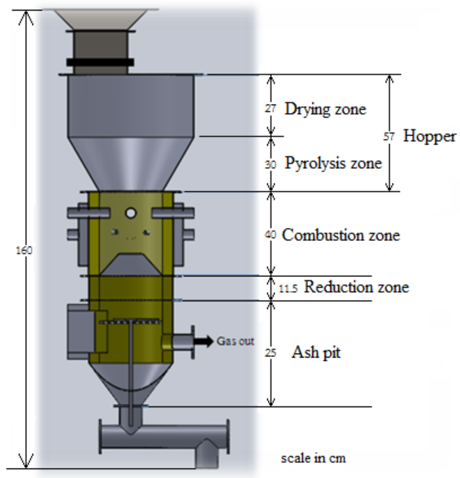


Figure 1 Downdraft Gasifier

Fuel feeding and ash removal systems are functions to run gasification continuously, to re-fuel and remove ash from the gasifier. These systems consist of 2 sets of screw feeders and 6 sets of slide gates (air-lock) installed to gasifier, all operations are controlled by PLC, as shown in Fig.2.

Experimental procedure

After the experimental apparatus has already been installed according to the experimental equipment layout shown in Fig. 2, fill the fuel in the hopper and light the pilot fire port at the combustion zone. Then turn on the induce draft fan and set the air flow rate to let the air into the gasifier at 6 Nm^3/h. Record the temperature inside the gasifier and when the temperature tends to be stable (approximately 120 minutes after start recording) and the fuels inside the gasifier are combusted until the fuel level inside the gasifier is decreased to the neck of the hopper (the lowest point of drying zone) as shown in Fig. 1, then we put 60 kg fuel into the screw feeder (automatically feed into hopper) and recorded combustion time. Wait until all systems are stabilized then we collected producer gas (approximate 40 minutes) by gas bag to be analyzed by Gas chromatography (GC-2014, Shimadzu).

The experiment stopped when fuel level in fuel storage tank decreased to the throat of hopper, recorded combustion time, and repeat these procedures by varying air flow rate at 6, 12, 18 and 24 Nm^3/h. In this experiment, we used 2 kinds of solid fuel which were wood chip only (called 0% HDPE) and the mixture of wood chip with HDPE 5 percent by weight (called 5%HDPE).

Gasification process analysis

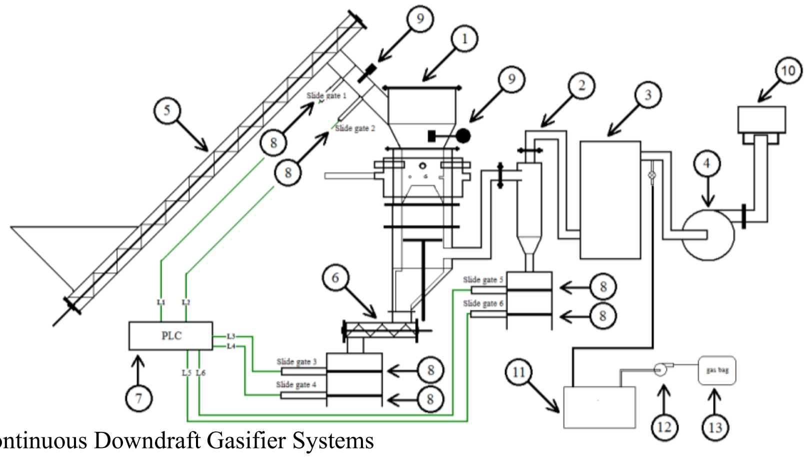
The parameters of gasification process details are as following;

1. Gas Composition was Analyze by Gas Chromatography (GC-2014, Shimadzu) which could detect CO, CH_4, H_2, CO_2 and N_2 in producer gas.

2. Temperature in downdraft gasifier were collected at drying zone, pyrolysis zone, combustion zone, reduction zone and ash pit by thermo-couple type K

3. Higher Heating Value of producer gas, HHV could be calculated by equation (1) from concentrations of combustible gas (CH_4, CO and H_2) in producer gas. MF is mole fraction from each gas, HHV_{gas} is higher heating value of each gas and V is volume of producer gas

$$HHV_{gas} = \sum(MF + HHV)/V \qquad (1)$$



No.	Equipment
1	Downdraft Gasifier
2	Cyclone collector
3	Wet scrubber
4	Induce draft fan
5	Fuel's-screw feeder
6	Ash's-screw feeder
7	PLC
8	Slide gate (Air-Lock)
9	Fuel's level-sensor
10	Flare
11	Gas cleaner
12	Vacuum pump
13	Gas bag

Figure 2 Continuous Downdraft Gasifier Systems

4. Gas production rate (Q_{gas}) could be calculated by equation (2) that Q_{air} is air flow rate. $N_{2,air}$ was concentration of Nitrogen in air and $N_{2,gas}$ is concentration of Nitrogen in producer gas

$$Q_{gas} = Q_{air} x [N_{2,air}/N_{2,gas}] \quad (2)$$

5. Cold Gas Efficiency (CGE) is a ratio of energy in producer gas and energy input from fuel. Calculate by equation (3). HHV_{fuel} is higher heating value of fuel and $\dot{m}_{fuel}$ is fuel consumption rate

$$CGE = \frac{[HHV_{gas} x\, Q_{gas}]}{[HHV_{fuel} x\, \dot{m}_{fuel}]} x\, 100 \quad (3)$$

Results and discussion

In this study, the results of producer gas from wood chip (called 0%HDPE) and mixture of wood chip with HDPE 5% (called 5%HDPE) producer gas will be as following

1. Gas Composition

Gas composition of producer gas was analyzed by Gas Chromatography. The results are shown in Table 2. In both cases, we found that when the air flow rate increases CO, H_2 and CH_4 tend to be higher too, while CO_2 and N_2 tend to decrease when the air flow rate is higher as shown in Fig. 3(a) and Fig. 3(b).

Comparing between the gas compositions of the producer gas produced in case of 0%HDPE and 5%HDPE at the same air flow rate, the result shows that the producer gas produced by case of HDPE 5% has higher concentration of CO and CH_4 while H_2 and CO_2 are lower than the case of HDPE 0%. This is because when HDPE in the fuel receives heat, it will crack and become volatile matter ((shown in equation (4)) after heating. (Lopez *et al.*, 2015).

The increase of CH_4 concentration is caused by cracking of HDPE in the fuel not by the methanation reaction ((shown in equation (5)) (Na *et al.*, 2003). while the increase of CO is caused by the mixture of Carbon content in the fuel and HDPE which is higher than the carbon content in case of HDPE 0%, shown in Table 1, and also effected to decreasing of CO_2 concentration.(Pinto *et al.*, 2001) CO could be produced by boudouard((shown in equation (6)) and water gas (primary) reaction ((shown in equation (7)). In the same time, higher temperature at reduction zone and ash pit produced CO_2 by water gas (secondary) reaction ((shown in equation (8)), and water gas shift reaction ((shown in equation (9)) (Gracía *et al.*, 2007).

$$HDPE \xrightarrow{heat} Char + VolatileMatter \quad (4)$$

$$CO + 3H_2 \longrightarrow H_2O + CH_4 \quad (5)$$

$$C + CO_2 \longrightarrow 2CO \quad (6)$$

$$C + H_2O \longrightarrow CO + H_2 \quad (7)$$

$$C + 2H_2O \longrightarrow CO_2 + 2H_2 \quad (8)$$

$$CO + H_2O \longrightarrow CO_2 + H_2 \quad (9)$$

Table 2 The gas composition for different case

HDPE (%)	Air Flow rate (Nm^3/h)	Gas Composition (% by volume)				
		CH_4	*CO*	*H_2*	*CO_2*	*N_2*
0	6	5.19	1.96	10.38	12.26	70.22
0	12	6.54	4.43	17.67	11.74	60.06
0	18	6.51	4.36	18.75	11.44	58.94
0	24	7.25	3.64	17.61	9.97	60.89
5	6	5.36	2.47	13.28	12.17	66.72
5	12	6.74	4.56	16.90	10.45	61.35
5	18	7.46	4.44	16.85	9.95	61.30
5	24	8.04	4.68	17.44	9.78	60.05

2. Gasifier Temperature

The temperature inside various zones of downdraft gasifier are shown in Table 3, it is found that the temperature inside downdraft gasifier in case of 0% HDPE and 5% HDPE were increase according to higher air flow rate. When the air flow rate are 18-24 Nm^3/h, the temperature inside reduction zone and ash pit shall be higher due to the heat released from equation 7 and 8. This can be found in both cases. In case of 5% HDPE when the air flow rate is 24 Nm^3/h, some of CH_4 shall be oxidized by the O_2 that remains from combustion zone and become CO_2, resulting in higher temperature in reduction zone and ash pit.

3. Higher Heating Value of producer gas

The Higher Heating Value of producer gas (HHV) in this experiment shows that in case of 0% HDPE at the air flow rate of 6, 12, 18 and 24 Nm^3/h, the HHV of the producer gas were 3.63, 5.36, 5.53 and 5.67 MJ/Nm^3 respectively. while case of 5% HDPE, it is found that at the air flow rate of 6, 12, 18 and 24 Nm^3/h, the HHV of the producer gas were 4.14, 5.41, 5.67 and 6.01 MJ/Nm^3 respectively as shown in Fig. 4(a). It is found that the HHV of the producer gas produced by 5% HDPE were higher than the HHV of producer gas produced by 0% HDPE at the same air flow rate because the combustible gas in the producer gas is higher.

4. The fuel consumption rate

Fuel consumption rate at the air flow rate 6, 12, 18 and 24 $Nm^3/$, in case of 0% HDPE are 5, 8.45, 11 and 14.5 kg/h respectively, fuel consumption rates of 5%HDPE are 4.62, 7.64, 8.74 and 15 kg/h respectively at the same air flow rate, as shown in Fig. 4(b) We also found that fuel consumption rate tended to be increase by higher air flow rate which fed to gasifier. At 6-18 Nm^3/h air flow rate, fuel consumption rate of 5%HDPE was lower than 0%HDPE. However, we found that 0%HDPE consumed lower level than 5% HDPE at 24 Nm^3/h air flow rate. Due to high flow rate related to higher temperature at combustion zone which caused HDPE in mixed fuel rapidly vaporize at pyrolysis zone, could affect to high fuel consumption (Gracía *et al.*, 2007). While feeding 6-18 Nm^3/h air flow rate was unable to affect rapid vaporization as temperature at pyrolysis zone was not high enough for this reaction, and density of 5% HDPE was also lower than 0% HDPE causing slower combustion which resulted lower consumption rate.

Table 3 Temperature in gasifier for different case

HDPE (%)	Air Flow rate (Nm^3/h)	Temperature (°C)				
		Drying	*Pyrolysis*	*Combustion*	*Reduction*	*Ash*
0	6	35.66	55.79	843.26	502.79	213.61
0	12	39.31	49.52	883.58	534.69	232.52
0	18	45.46	58.37	906.32	706.43	274.77
0	24	45.62	115.84	963.92	755.90	316.27
5	6	37.33	56.44	864.85	501.08	213.87
5	12	37.85	52.70	892.07	534.46	235.18
5	18	42.55	60.36	904.03	748.94	285.77
5	24	44.87	103.58	961.60	776.45	331.76

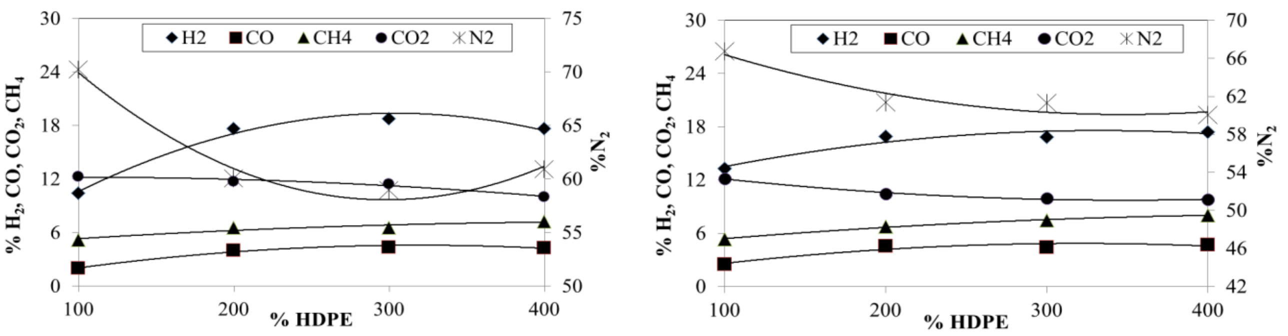
5. The gas production rate

Gas production rate at air flow rate 6, 12, 18 and 24 Nm^3/h, in case of 0% HDPE were 9.0, 15.78, 24.13 and 31.14 Nm^3/h respectively, and case of 5% HDPE were 9.47, 15.45, 23.20 and 31.57 Nm^3/h respectively, as shown in Fig. 4(c). The Gas production rate directly varies to air flow rate. The results from this study have shown the gas production rate similarities of both case of fuel.

6. The Cold Gas Efficiency (CGE)

The cold gas efficiency in case of 0% HDPE at the air flow rate of 6, 12, 18 and 24 Nm^3/h, the CGE were 30.21, 46.20, 55.99 and 56.21 % respectively, while in case of 5% HDPE at the air flow rate of 6, 12, 18 and 24 Nm^3/h, the CGE were 37.75, 48.65, 66.93 and 56.27% respectively as shown in Fig. 4(d).

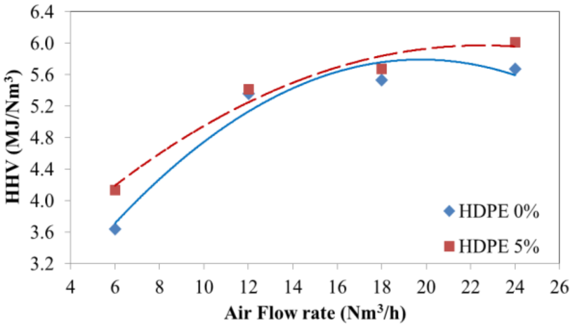
The CGE in case of 0% HDPE tends to increase according to higher air flow rate. While case of 0% HDPE have higher CGE when the air flow rate is higher between 6-18 Nm^3/h. However, when the air flow rates increase to 24 Nm^3/h, the CGE were decrease because at the air flow rate of 24 Nm^3/h, there are exceed O_2 remaining from the combustion zone, so the oxidation reaction occurs in reduction zone and ash pit. It can be seen from the higher temperature in the reduction zone and ash pit that cause higher CO_2, making the combustible gas lower. In the case that the air flow rate is 24 Nm^3/h, the fuel consumption rate shall be high, resulting in lower CGE.



(a) (b)

Figure 3 (a) Producer Gas compositions in case of 0%HDPE

(b) Producer Gas compositions in case of 5%HDPE



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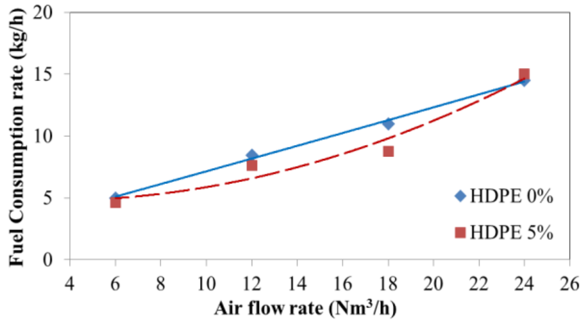

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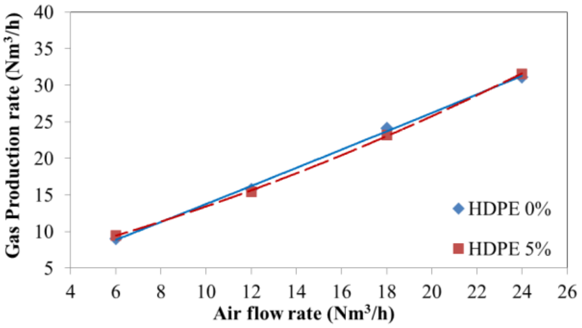
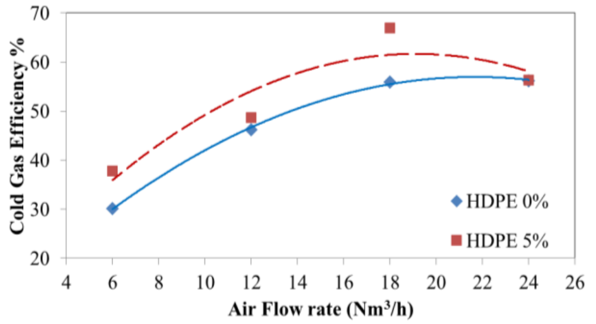


(c)



(d)

Figure 4 (a) HHV of producer gas vs. air flow rate for different fuel

(b) Fuel consumption vs. air flow rate for different fuel

(c) Gas production rate vs. air flow rate for different fuel

(d) Cold gas efficiency vs. air flow rate for different fuel

Conclusions

The addition of HDPE in fuel affects the producer gas compositions. The concentrations of CO, CH_4 are increase but CO_2 concentration is decrease when compared with a case of 0% HDPE fuel at same air flow rate. Therefore, HDPE addition results in increasing of HHV of producer gas.

The fuel consumption rate of case 5% HDPE are lower than case 0% HDPE in the air flow rate range of 6-18 Nm^3/h. While at air flow rate 24 Nm^3/h, a case of 5% HDPE has higher fuel consumption rate than case 0% HDPE, because pyrolysis zone temperature was high enough to rapidly vaporize HDPE into gas phase, therefore it resulted higher fuel consumption rate.

At the same air flow rate, the cold gas efficiency of producer gas produced from case of 5% HDPE are higher than the producer gas produced from case of 0% HDPE. However, in the case of HDPE 5% at the air flow rate between 6-18 Nm^3/h, the cold gas efficiency tends to be higher but it is lower when the air flow rate reaches at 24 Nm^3/h.

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