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The product yields and fuel properties from catalytic pyrolysis of plastic bag

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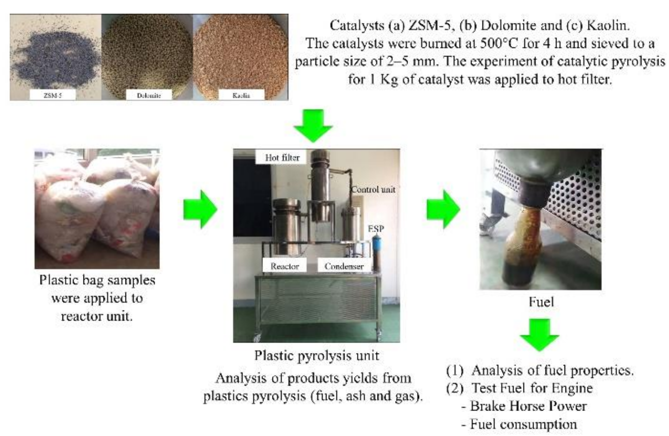
Abstract

The objective of this research was to study product yields and fuel properties. The fuel was then tested for use in the engine to study brake horsepower (BHP) and fuel consumption. The experiment began with pyrolysis of plastic bags in a fixed bed reactor at 500 °C with three catalysts: ZSM-5, dolomite, and kaolin. The analysis of fuel properties consists of higher heating value (HHV), density, viscosity, and flash point - fire point. For test engine of this research used 12 HP Kubota brand single-cylinder diesel engine, tested at a speed of 1,500 rpm, with a fuel temperature of 40 °C for determine the brake horsepower and fuel consumption. The results showed that non-catalytic, the highest yields of fuel were 65.70 wt%. This fuel has a (HHV) of 36.70 MJ Kg^{-1} and a fire point up to 133.30 °C. Results of engine tested show that it has a minimum BHP of 9.20 HP and a maximum fuel consumption of 1.10 Kg HP^{-1} h^{-1}. When catalytic pyrolysis of plastics with ZSM-5 catalyst, the fuel yields was reduced to 57.80 wt%. However, the alumina mixed in this catalyst allows the fuel maximum HHV of 43.20 MJ Kg^{-1}, flammable at 28.70 °C. Results of engine tested show that it has a maximum BHP of 11.90 HP and a minimum fuel consumption of 0.40 Kg HP^{-1} h^{-1}. The catalyst dolomite and kaolin increase the calorific value, reduce the viscosity, easily flammable, but overall, not as good as ZSM-5. It can be concluded that keolin catalysts are suitable for use in pyrolysis requiring increased fuel yield. The ZSM-5 catalyst was suitable for improving fuel quality. Therefore, this research should be continued with plastic pyrolysis using catalysts to improve the quality of the fuel for long-term engine testing.

Graphical Abstract



Keywords: Fuel; Catalytic Pyrolysis; Plastic Bag

Introduction

Plastic pollution is one of the most pressing environmental issues, as rapidly increasing production of disposable plastic products overwhelms the worlds could not to deal with them. Proper disposal of this waste is costly because plastics is naturally degraded very slowly, so that researchers are focused on studying how to dispose and convert this waste into a form of renewable energy. Examples include gasification of plastic waste into fuel gas [1 – 5] and fast pyrolysis of plastic waste into [6 – 20] fuel. This fast pyrolysis can transform plastic waste into liquid fuels like petroleum fuels.

Fast pyrolysis of plastics was thermochemical quick degradation of plastic particles with a reaction temperature of 400 – 600 °C [16]. When condenses the vapor produced by the rapid decomposition of plastics into a liquid, which were the primary product produced by the process. In 2017, Ratnasari et al [13] studied the production of fuel from plastic waste pyrolysis with ZSM-5 catalyst and found that it could produce more than 80 wt% of fuel and the resulting fuel was in the group of Gasoline up to 97.72 wt.%. In, 2018 Till et al [15] pyrolysis of plastic waste with a zeolite catalyst showed that the catalyst surface area increased the thermal cracking, resulting increase in the yield of the gas.

In 2019, Duanguppama et al [16] studied the fast pyrolysis of PVC plastics in a fluidized bed reactor found that the reaction temperature at 500 °C gave the maximum yields of fuel were 64 wt%. High heating value (HHV) 39.40 MJ Kg^{-1} and viscosity of 1004.20 cSt. When pyrolysis using Dolomite and Kaolin catalysts, the fuel content was reduced to 43 and 49 wt% respectively. However, the highest heating value of the fuel was 42.10 MJ Kg^{-1} when using Dolomite catalyst and the lowest viscosity decreased to 524.50 cSt when using Kaolin catalyst. In addition, Muhammad et al [8] studied the fast pyrolysis of plastics from electrical and electronic equipment, it was found that the ZSM-5 catalyst can increase the benzene content up to 10 wt% and increased gas content in the C_2-C_4 hydrocarbon group more than 20 vol% [8]. In 2020, Chaiphet et al [17] studied plastic waste pyrolysis in fixed bed reactors at a reaction temperature of 500 °C using three plastics: plastic bags, plastic bottles and plastic PVC. That plastic bags provide the highest fuel yields 65.70 wt%. In 2021, Marino et al [20] pyrolysis of PVC plastics was obtained with ZSM-5 catalyst. It was found that the catalyst reduced the chlorine content in PVC plastics to less than 90 ppm, resulting in better fuel quality because of decreased acidity. However, yields and properties of fuel from pyrolysis of plastic bags by catalyst have not been reported. There is also no test report on the fuel in the engine.

Therefore, the objective of this research was to study product yields and fuel properties. The fuel was then tested for use in the engine to study brake horsepower (BHP) and fuel consumption. The experiment began with pyrolysis of plastic bags in a fixed bed reactor at 500 °C with three catalysts: ZSM-5, dolomite, and kaolin. The analysis of fuel properties consists of HHV, density, viscosity, and flash point - fire point.

Materials and Methods

Research Process

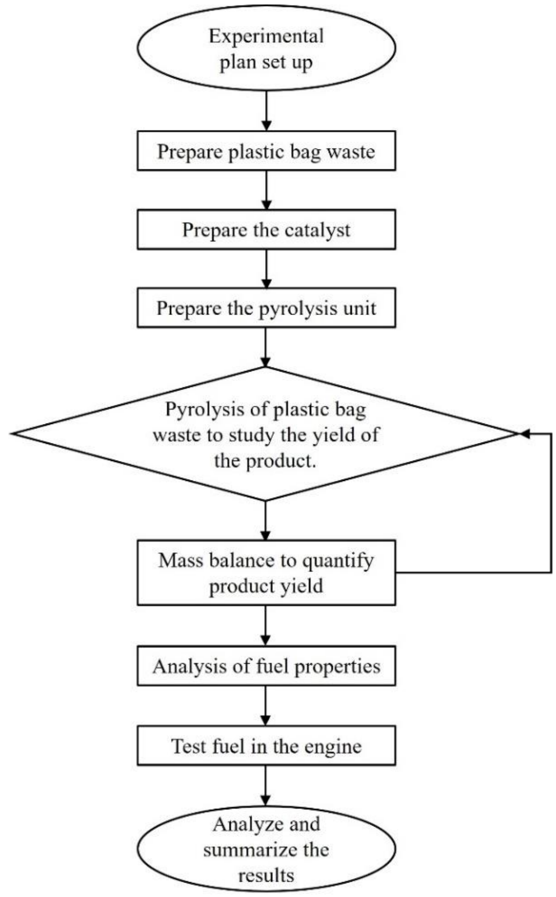


Fig. 1 Flowchart of the research process.

Fig. 2 Plastic bag samples.

Table 1 Characteristics of the catalysts.

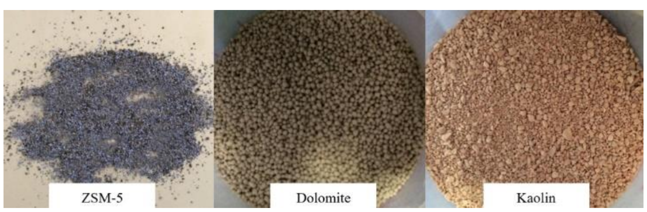
Catalysts		Bulk density ($Kg\ m^{-3}$)	Particle density ($Kg\ m^{-3}$)	BET surface area ($m^2\ g^{-1}$)	Mean pore diameter (nm)	Total pore volume ($Cm^3\ g^{-1}$)	Si/Al ratio
Type	Calcination Temperature/ Time						
ZSM-5	500 °C for 4 h	600	1,043	15.80	22.10	7.62×10^{-2}	14.43
Dolomite	500 °C for 4 h	1,128	1,728	32.60	13.70	0.20	N/A
Kaolin	500 °C for 4 h	987	1,474	13.30	50.10	0.18	N/A

Plastic Bag Feedstock

The plastic waste samples employed in this research was used plastic bag from Kalasin Province, Thailand. Plastic bags that were used wash and drying in the sun. The HHV was 28.20 MJ Kg^{-1} following analysis by DIN 51900 with S.M.D. Torino Bomb Calorimeter [16].

Catalysts

The catalysts: ZSM-5, dolomite and kaolin were burned at 500 °C for 4 h [16] and sieved to a particle size of 2 – 5 mm. The experiment of catalytic pyrolysis for 1 Kg of catalyst was applied to hot filter. The catalysts composed of ZSM-5, dolomite and kaolin has properties illustrate in the Table 1.



(a) (b) (b)

Fig. 3 Catalysts (a) ZSM-5, (b) Dolomite and (c) Kaolin.

The Plastic Pyrolysis Apparatus

The plastic pyrolysis was performed in a fixed-bed reactor unit, designed, and constructed at Department of Mechanical Engineering, Faculty of Engineering and Industrial Technology, Kalasin University, Thailand [17]. The plastic pyrolysis unit in Fig. 4 the components of a hot filter was a reactor, condenser, and an electrostatic precipitator (ESP). The plastic pyrolysis system of machine was controlled by automation. The reactor made from stainless steel grade diameter was 250 mm and the height of 700 mm. The hot filter made from stainless steel grade 304 diameter was 150 mm and the height of 800 mm. Non-catalytic experiment, was used 50 g of glass wool put into the hot filter and changed for every runs. While catalytic pyrolysis experiment, 1 Kg of catalyst put in the hot filter. The condenser was a compressor heat exchanger. The ESP operated at 15 kV DC was used the aid of fuel collection.

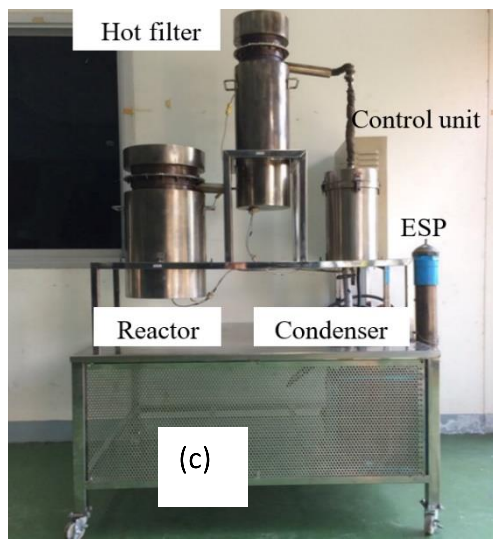


Fig. 4 Plastic pyrolysis unit.

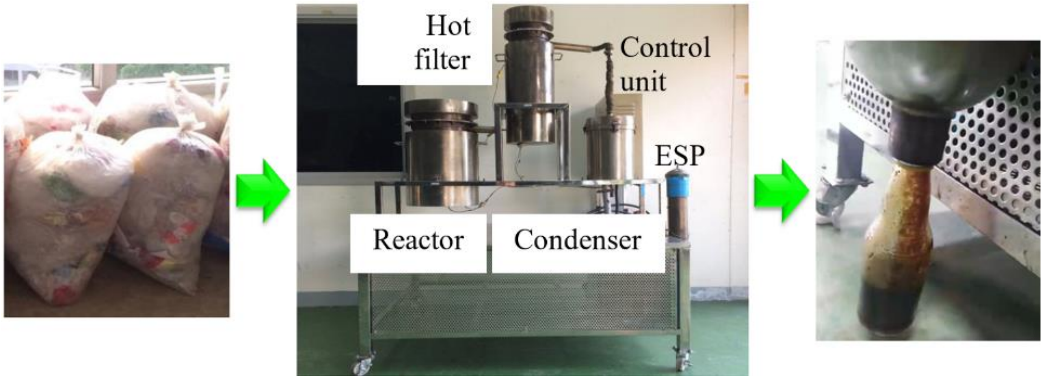


Fig. 5 Experiment of plastic pyrolysis.

Table 2 Analysis of fuel properties.

Analysis	Standard	The instruments
Higher heating value (HHV)	DIN 51900	Torino Bomb Calorimeter
Density	ASTM D4052	Digital Scales
Viscosity	ASTM D445	Kinetic Viscosity Analyzer
Flash point - Fire point	ASTM D**93**	Flash point - Fire point Set

Plastic Pyrolysis Experiments

The pyrolysis temperatures were measured, and controlled control unit (Fig. 5) set at 500°C for reactor and hot filter. For non-catalytic pyrolysis experiment, glass wool of 50 g was used as a filter medium in hot filter to reduce the ash residue with vaporization pyrolysis. While catalytic pyrolysis experiments, ZSM-5, Dolomite and Kaolin catalysts of 1 kg was used catalytic in a hot filter. For every experiment, approximately 1 kg of plastic bag was put in the reactor. The total experimental run duration for 2 h. When the pyrolysis experiment finished, the reactor and heated parts were leftwing cool for room temperature. Then, the reactor, hot filter and ESP unit were dismantled and weighed for mass balance calculation

Mass Balance

The fuel, ash and non-condensable gases were used for the main products from plastic pyrolysis. The yields of each product were calculated by weighing all parts of the plastic pyrolysis systems, that mainly comprised of reactor, hot filter, and ESP unit, before and after every experiment. The fuel yield was determined as a liquid weight from the product collection unit including condenser and ESP. The ash yields were combined solid masses collected from the reactor and hot filter. The gas yield was calculated by difference.

Fuel Properties Analysis

The properties of fuel were obtained from plastic pyrolysis illustrate in Table 2 according to standard fuel analysis [16].

Fig. 6 Engine performance test unit.

The following equations were used to calculate the brake horsepower and a specific fuel consumption brake.

Brake Horsepower

$$P = \frac{\left(\frac{2\pi Tn}{60}\right)}{1000} \quad (1)$$

$$BHP = \frac{P}{0.7457} \quad (2)$$

when P = engine brake power (kW), T =torque (N-m), n = engine cycle (rpm), BHP = brake horsepower (HP) the parameter, can writing text and Italic function (not use word equation function).

Fuel Consumption

$$Q_{mf} = Q_{vf}\rho_f \quad (3)$$

when Q_{mf} = fuel consumption (Kg s^{-1}), Q_{vf} = Volume of fuel (m^3 s^{-1}), ρ_f = Fuel density (Kg m^{-3}).

Specific Fuel Consumption Brake

$$Bsfc = \frac{3600Q_{mf}}{P} \quad (4)$$

when $Bsfc$ = brake specific fuel consumption (Kg kW^{-1} h^{-1}), P= engine brake power (kW), Q_{mf} = fuel consumption (Kg s^{-1}).

Results and Discussion

Products Yields from Plastics Pyrolysis

Pyrolysis of plastic bags at 500 °C showed that non-catalytic, the highest yields of fuel was 65.70 wt%. When catalytic pyrolysis, the yields of fuel was reduced significantly. Figure 4 illustrate that the dolomite catalyst reduced fuel yields content to a minimum of 56.20 wt%. Because the second cracking of the vapor-pyrolysis period occurs during a passing through the catalyst at the hot filter position increased content of non-condensed gas. Which could be observe from the dolomite catalyst had the gas yields content increased to 35.30 wt%. When determine the product yield in the case of three catalysts, it was found that the kaolin yielded a maximum fuel content of 60.40 wt% decreasing to ZSM-5 and dolomite, respectively.

The different of product yields were different BET surface area and mean pore diameter of the three catalysts. The dolomite catalyst has a maximum BET surface area of 32.60 m^{2}g^{-1}, thus exposed to the highest vapor of pyrolysis in the highest yield of non-condensed gas. This was consistent with the research by Syamsiro et al [9] reported that natural zeolite BET surface area 91.146 m^2 g^{-1} has a non-condensed gas contents of 37 wt%. While Y-zeolite BET surface area 780 m^2 g^{-1} has a non-condensed gas contents of 40 wt%. Consistent with research by Syamsiro et al [9] reported natural zeolite BET surface area 91.146 m^2 g^{-1} has a gas yield contents of 37 wt%. While Y-zeolite BET surface area 780 m^2 g^{-1}, the non-condensed gas content of 40 wt%.

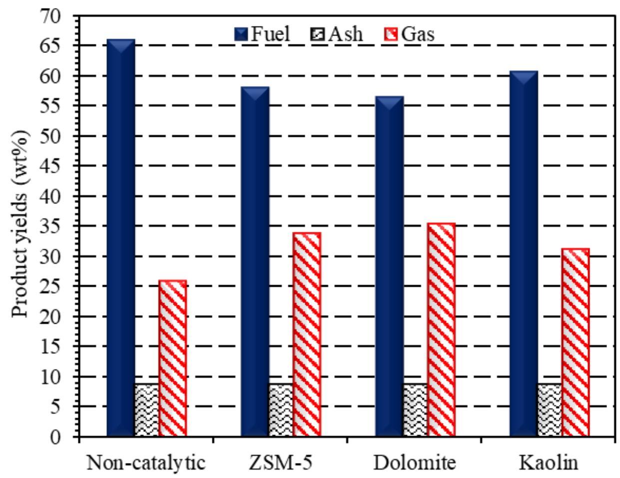


Fig. 6 Non-catalytic and catalytic pyrolysis to product yields.

The diameter of the fuel yield content was different, the kaolin has the mean pore diameter of 50.10 nm allowing the vapor it easily for condensing the highest fuel. While dolomite had the smallest mean pore diameter of 13.70 nm, resulting in lowest of the fuel content. According to Muhammad et al [7] research, pyrolysis plastics from waste electrical and electronic equipment recycling plant found that Y-zeolite had mean pore diameter 7.80 nm was fuel yields of 80 wt%. While ZSM-5 was mean pore diameter 5.60 nm had fuel yields of 77.50 wt%. However, the ash yield content from the three catalysts was the same at 8.50 wt%. Consistent with the research of Muhammad et al [7] reported that the plastic pyrolysis with a Y-zeolite and ZSM-5 had the ash yields similar to 8 wt%.

Fuel Properties

The fuel properties in Table 3 showed that catalytic pyrolysis of plastics increases the calorific value of the fuel. The ZSM-5 catalyst increased the HHV to a maximum of 43.20 MJ Kg^{-1}. It was expected that the fuel contains increase in hydrocarbons, because the catalyst changes the chemical structure of the pyrolysis vapor before the condensation to hydrocarbons form. Fig. 3 observed, it could be seen the catalyst significantly increases the gas yield content. According to Muhammad et al [7] found that use the ZSM-5 catalyst can increase the benzene content by up to 10 wt% and increased gas content in the C_2-C_4 hydrocarbon group more than 20 vol% [7].

Table 3 Properties of fuel.

Properties	Non-catalytic	Catalytic pyrolysis			Diesel
		ZSM-5	Dolomite	Kaolin	Shell V-Power
High heating value (MJ Kg^{-1})	36.70	43.20	40.50	41.80	43.50
Bulk density at 15 °C (Kg m^{-3})	937.50	892.30	902.10	913.40	8700
Kinematic viscosity at 40 °C (cSt)	1.30	1.10	1.00	1.20	182.40
Flash point (°C)	130.10	21.50	38.90	34.20	50.50
Fire point (°C)	133.30	28.70	42.60	39.70	56.10

The comparison of the catalytic efficiency for three catalysts revealed was ZSM-5 had the highest catalytic efficiency, resulting similar calorific value of petroleum fuels. This resulted of 14.43% alumina in ZSM-5 accelerated the production of hydrocarbons than dolomite and kaolin without alumina. According to Acomb et al [2], the addition of alumina from 0.50–1.25 g resulted increase the content of C_2 - C_4 in the fuel from 18 –35 vol% [2]. In addition, the catalyst improves the quality of the fuel, significantly reducing its density, viscosity, flash point and ignition point. By the ZSM-5 catalyst has reduced the highest fuel density, resulting similar to petroleum fuels. The catalyst also makes fuel easier more ignite than the Diesel Shell V-Power, because it has a 21.50 °C flash point and 28.70 °C of fire point.

However, when considering the viscosity, dolomite reduced the viscosity to a minimum of 1.00 cSt. This is because the mean pore diameter of 13.70 nm of the catalyst allows significantly smaller molecules of the fuels. It can be concluded that pyrolysis of plastic bags with ZSM-5 catalysts improves thermal efficiency best. While dolomite catalyst improved the viscosity the best.

Test Fuel for Engine

Resulted test of the BHP in diesel single cylinder engine 12 HP, it was found that the fuel from the plastic pyrolysis case without catalyst had BHP of 9.20 HP. When catalytic pyrolysis of plastic had the fuel that clearly helps the engine to have more BHP. The ZSM-5 catalyst gets fuel that gives the engine a maximum BHP of 11.90 HP, because the fuel obtained from this catalyst has a maximum HHV of 43.20 MJ Kg^{-1} and easiest flammable. Therefore, the highest thermal efficiency on combustion in the engine.

But, when considering the fuel obtained from the all catalysts, it shows that the fuel from pyrolysis with dolomite catalyst resulted in the engine having the lowest BHP of 10.80 HP. Consistent with analysis of the fuel properties from the dolomite catalyst had a lowest HHV to 40.50 MJ Kg^{-1}. It was confirmed that increase calorific value of the fuel from catalytic pyrolysis of plastic BHP.

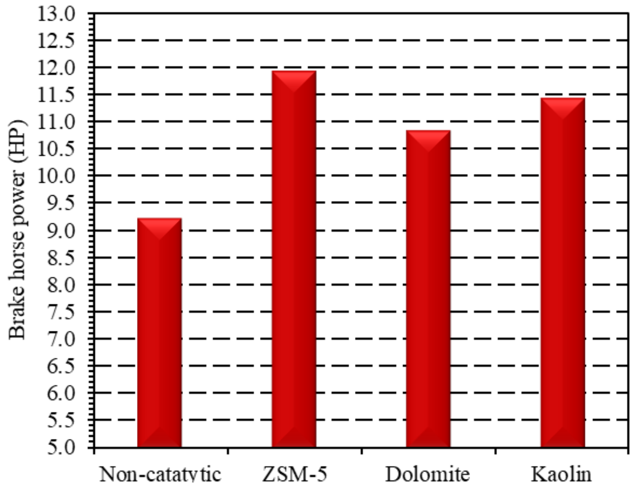


Fig. 7 Non-catalytic and catalytic pyrolysis to brake horse power of engine.

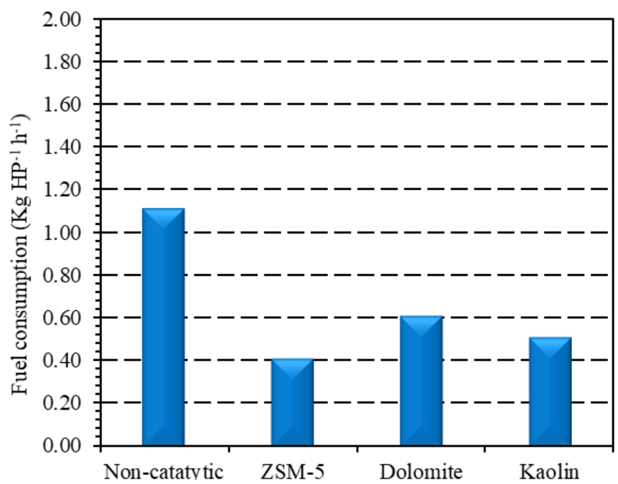


Fig. 8 Non-catalytic and catalytic pyrolysis to brake specific fuel consumption.

Figure 5 illustrate the fuel from plastic bag case non-catalytic pyrolysis has a maximum fuel consumption of 1.10 Kg HP^{-1} h^{-1}, which almost three times for the fuel form catalytic pyrolysis with a ZSM-5 catalyst. It was clear that the HHV of fuel results in the engine have a high BHP and low fuel consumption. This fuel consumption was consistent with research by Devaraj et al [6], reported that a mixture of 5 and 10% (waste plastic pyrolysis oil/diethyl ether) has fuel consumption in the range of 0.30 – 0.60 Kg HP^{-1} h^{-1} when increased the load from 20 – 100%.

Conclusion

The pyrolysis of plastic bags at 500 °C showed that non-catalytic, the highest yields of fuel was 65.70 wt%. This fuel has a HHV of 36.70 MJ Kg^{-1} and a fire point up to 133.30 °C. Results of engine tested show that a minimum BHP of 9.20 HP and a maximum fuel consumption of 1.10 Kg HP^{-1} h^{-1}. When catalytic pyrolysis of plastics with ZSM-5 catalyst, the yield's content of the fuel was reduced to 57.80 wt%. But, the alumina mixed in this catalyst allows the fuel to maximum HHV of 43.20 MJ Kg^{-1}, with flammable 28.70 °C. Results of engine tested show that a maximum BHP of 11.90 HP and a minimum fuel consumption 0.40 Kg HP^{-1} h^{-1}. The catalyst, dolomite and kaolin increased the calorific value, reduce the viscosity, easily flammable, but overall not as good as ZSM-5. Therefore, this research should be continue with plastic pyrolysis using catalysts to improve the quality of the fuel for long-term engine testing.

Acknowledgement

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