Effect of reaction time and microwave power on coil temperature during microwave-metal interaction pyrolysis of plastics

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Abstract. Rapid rise in production of plastic waste has posed a threat to environment due to its nonbiodegradable nature. In recent years, microwave assisted pyrolysis of plastic waste has emerged as a promising solution toward reduction of waste and recovery of value-added products and fuels. Previous works on microwave-metal interaction pyrolysis estimated only the peak value of coil temperature at a constant microwave power without monitoring complete reaction. The current study was directed toward investigating the effect of reaction time and variable microwave power on the coil temperature during microwave-metal interaction pyrolysis of plastics. The experiment was performed on individual plastics PS (polystyrene), PP (polypropylene) and LDPE (low density polyethylene) for comparative analysis. Pyrolysis was carried out for a reaction time of 30 minutes at different values of microwave power in the range of 500-2500 W. Type K thermocouple was used to monitor temperature of metal coil. Fluctuation in temperature of coil was found to be a consequence of interaction of coil and thermocouple with the microwaves. Maximum heating rate was observed in the first 5 minutes of microwave exposure. The slopes of average temperature versus microwave power were found to be nearly equal estimated as: PS = 0.24 °C/W, PP = 0.20 °C/W, LDPE = 0.18 °C/W, which indicated consistency in heating process for each plastic, achieved by the current set-up. Further, it was inferred that nature of plastic pyrolyzed had insignificant influence on coil temperature due to absence of direct contact between plastic and the coil.

1. Introduction
Over the decades, plastic has dominated the market due to its extensive application as household items, packaging, automobiles and numerous other areas. According to statistic, demand for plastic has increased by 5% every year since 1990 [1]. This has resulted in generation of enormous amounts of plastic wastes difficult to dispose. Disposal through landfill is not much encouraged due to limited availability of land area and adverse effects on surrounding environment caused by nonbiodegradable nature of plastic waste. Plastics of widespread use mainly consists of low density polyethylene (LDPE), high density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), polyethylene-terephthalate (PET) and polyvinyl chloride (PVC). Another option of plastic waste disposal is incineration. However, this method is not suitable with regard to environmental concerns. Based on previous report, incineration produce toxic emissions which are harmful to life [2]. Recycling of waste
can be used to solve the disposal problem but this again requires expensive input for recovery and separation of waste components [3].

With development of modern methods of waste disposal, tertiary recycling through pyrolysis has found great application toward energy recovery from waste. Pyrolysis is a process that involves thermochemical breakdown of organic material at elevated temperatures 350 to 900 °C in oxygen free environment, resulting in oil and gas yields with char as the solid residue. The oil fraction may be separated into condensable hydrocarbons comprising paraffins, isoparaffins, olefins, naphthenes and aromatics, and a non-condensable high calorific value gas [4]. Recently, microwave assisted pyrolysis (MAP) has emerged as a promising option with added benefits of rapid and uniform heating over conventional heating. MAP of plastic waste has great potential to produce value added chemicals and fuels demonstrated in a range of studies [3–8]. A novel technique in the field of microwave assisted pyrolysis was successfully introduced by research group of Zahid et al. [9]. This method was based on microwave-metal interaction pyrolysis using metal coil as a reactor for breakdown of PS. The study proved this alternative technique to be effective and competent to previous works where dielectric material had to be used as an adsorbent of microwaves to generate essential heating.

Past studies on microwave-metal interaction pyrolysis estimated only the peak value of coil temperature at a constant microwave power without monitoring complete reaction. The current study is directed toward investigating the effect of reaction time and variable microwave power on the coil temperature during microwave-metal interaction pyrolysis of PS, PP and LDPE. This work was based on modification of experimental set-up used in previous studies on microwave-metal interaction pyrolysis [9, 11, 12]. Effort was made to estimate the temperature of iron coil through proper insertion of thermocouple aligned to touch the coil. The variation in coil temperature as a function of reaction time and microwave power was used to study the heating behavior inside the microwave field.

2. Experimental setup

The virgin plastic samples of PS, PP and LDPE were used in the experiments. The plastic was purchased from Lotte Chemical Titan (M) Sdn. Bhd. The samples were in the form of pellets of size in the range of 2 to 3 mm. The sample size for plastic pyrolysis was taken to be 20 grams in all the runs. During the preliminary study, calorific values of sample plastics were measured as: PS = 40.9, MJ/kg, PP = 46.7 MJ/kg and LDPE = 46.4 MJ/kg, respectively. The thermal degradation range of each plastic was estimated from Thermogravimetric Analysis (TGA): PS = (378–439 °C), PP = (407–483 °C) and LDPE = (420 to 499 °C), respectively. The metal coil of iron wire was fabricated with internal diameter 5 cm, height 5 cm and gauge 1.5 mm. The wire was purchased from a local market in Malaysia, commercially available as binding wire made of mild steel. Iron purity was up to 99.8% as provided by the manufacturer. The lab-scale multimode microwave oven was fabricated by Uni 10 Sdn. Bhd. that operated at a frequency of 2.45 GHz with two magnetrons rated 1.5 kW each. The microwave power was variable and continuous in the range of 250 to 2640 W. The microwave produced continuous heating based on pulse width modulation using inverter power supply. Figure 1 shows schematic of the reaction assembly. The dimensions of the heating chamber were width 40 cm, height 50 cm and depth 46 cm.

The microwave oven was modified for the microwave-metal interaction. A galvanized iron (GI) pipe was used as a reactor to place the sample. This GI pipe was installed from the top centre of the microwave chamber such that, the base of the pipe was surrounded by the iron coil placed inside a clay pot. The pot was raised to the centre of the chamber using a metallic cylindrical support. Type K thermocouple was inserted through the top of the chamber adjustable along the vertical direction and touching the coil to give temperature reading. The thermocouple probe was built in the customized design of the microwave system and the temperature reading was displayed at the control panel display screen. Clay pot provided heat insulation to the reactor and can withstand high temperatures. The function of the coil was to provide microwave flux for longer duration due to the repeated reflections of the microwaves trapped inside the coil. As a result, the GI pipe reactor was heated to high temperatures within a short time interval. The idea of using cylindrical metal support was to
readily reflect the microwaves so that the essential microwave-metal interaction heating occurs only between coil and GI pipe.

**Figure 1.** Microwave-metal interaction pyrolysis set-up.

Heat generated through microwave-metal interaction using iron coil was used to pyrolyze the plastic samples. Temperature of coil was monitored for a total reaction time of 30 minutes at different values of microwave power in the range of 500-2500 W and for each plastic PS, PP and LDPE, selected for study. To investigate the consistency of heating process, average temperature attained by the coil during the entire reaction at constant microwave power was determined and plotted against the variable microwave power for each plastic.

### 3. Results and discussion

Figure 2 shows variation of coil temperature with the reaction time and microwave power. Microwave power was increased from 500 to 2500 W to study the temperature distribution during pyrolysis of PS, PP and LDPE, respectively. It was evident from the plots that heating rate was maximum in the first 5 min of microwave exposure and later stabilized with small fluctuations until the end of reaction period. This trend was observed in all the plastic samples.

During the pyrolysis of PS, an increase in the value of microwave power, caused the slope or heating rate to shoot up rapidly. Similar behavior was observed in case of PP and LDPE. Results of variation in coil temperature at minimum and maximum microwave powers for each plastic are summarized in table 1.

Table 1. Variation in coil temperature at minimum and maximum microwave powers for each plastic.

| Plastic sample | Rise in coil temperature (°C) after 5 min of microwave exposure |
|----------------|---------------------------------------------------------------|
|                | 500 W (Min.) | 2500 W (Max.) |
| PS             | 154          | 937           |
| PP             | 365          | 748           |
| LDPE           | 253          | 796           |
Figure 2. Variation of coil temperature with reaction time and microwave power for (a) PS, (b) PP and (c) LDPE.
The significant variation in coil temperature at same power of microwave heating in different plastic samples can be attributed to interaction of microwaves with metallic probe (Type K thermocouple), in addition to microwave interaction with iron coil. This is caused due to trips and sparks commonly encountered in microwave-metal interactions [10].

Repeated study on different plastics was carried out under the same conditions of microwave power and reaction time to reveal the distribution of fluctuations in the heating process. The production of oil during the process confirmed that temperature attained by coil was sufficient to breakdown the plastic. The process of thermal pyrolysis was carried out in the range of 300 to 700 °C.

Variation in average coil temperature with microwave power is presented in Figure 3. Average temperature rise was calculated at different powers in the range of 500-2500 W for PS, PP and LDPE. It was observed that average temperature was directly proportional to microwave power in case of each plastic. Slopes of average temperature versus microwave power were estimated as: PS = 0.24 °C/W, PP = 0.20 °C /W, LDPE = 0.18 °C /W, which represented similar values with insignificant deviation showing consistency of heating process for each plastic, achieved by the current set-up. Further, it was inferred that nature of plastic pyrolyzed had insignificant influence on coil temperature. This is also obvious to the fact that plastic is not in direct contact with the coil but is heated inside the GI pipe used in the current set-up.

Figure 3. Variation of coil average temperature with different microwave powers and plastic samples.

4. Conclusions
The current investigation found that maximum heating occurred in the first 5 minutes of microwave exposure for entire range of microwave power between 500 to 2500 W for each plastic sample comprising PS, PP and LDPE. The average temperature directly proportional to microwave power for each plastic. Slopes of average temperature versus microwave power were estimated as: PS = 0.24 °C/W, PP = 0.20 °C /W, LDPE = 0.18 °C /W, which indicated consistency in heating process for each plastic achieved by the range of power rating 500 to 2500 W.

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