

The effect of temperature, heating rate and zeolite based catalysts on the pyrolysis of high impact polystyrene (HIPS) waste to produce the fuel like products

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Doi: 10.22063/poj.2018.2189.1114

Received: 4 May 2018 Accepted: 18 August 2018

ABSTRACT

The pyrolysis of high impact polystyrene (HIPS) waste has been studied under different process parameters such as temperature, heating rate and different zeolitic catalysts to produce the valuable liquid products. Liquid, gas and coke as pyrolysis product besides aromatic, naphthene, olefin and paraffin as liquid components and their molecular weight distributions were compared as function of the studied parameters in the stirred reactor. Aromatic-rich hydrocarbons within the gasoline range were the main pyrolysis product while the zeolitic catalysts, temperature and heating rate had significant effects on the products quality and quantity. Meanwhile, the non-isothermal mass losses of high impact polystyrene were measured using a thermo-gravimetric analyzer (TGA) at heating rates of 5, 15, 30, 45 and 90°C min⁻¹ until the furnace wall temperature reached to 600°C. The study of DTG (Differential thermal gravimetric) curves showed that heating rate had no obvious effect on the degradation trends in the studied range and increasing the heating rate decreased activation energies obviously (222.5-183.6 kJ mol⁻¹).

Keywords: High impact polystyrene; Temperature; Heating rate; catalyst; TGA.

INTRODUCTION

High impact polystyrene (HIPS) is the copolymer of polystyrene and butadiene rubber with improved toughness in comparison with polystyrene. Butadiene rubber as dispersed rubber phase in the polystyrene media with great increase in impact strength and environmental stress cracking resistance (ESCR) has led to a considerable growth in the range of applications for this polymer [1-2], including refrigeration cabinets, general packaging, electronics, toys, household appliances and disposables.

The increasing growth of HIPS waste can cause a lot of environmental problems in the related industries. On the other hand, HIPS waste has high volatile, fixed carbon and aromatic enriched content with heating value greater than the classic fuels. The understanding of effective parameters on the thermal degradation processes especially pyrolysis and gasification of various HIPS wastes can play an important role from the view of protecting environment and it allows to produce the valuable materials and energy [3-6].

The thermal degradation of natural and synthetic polymers at high temperatures in the absence of oxygen as pyrolysis can be a reliable solution to dispose the polymeric wastes [7-8]. In the pyrolysis process under high temperatures, the high molecular weight chains are broken down into low molecular weights. Depending on the polymer type with acceleration of the secondary reactions and the formation of hot spots, some coke are also produced. Coke, liquid and gas content and composition in the pyrolysis products depend on the different structural and process parameters such as polymer type, temperature, catalyst, reactor, carrier gas and maybe some other unknown parameters [8-11].

The degradation mechanisms containing chain-stripping, cross-linking, un-zipping and chain scission are the known mechanisms for the thermal degradation of polymers. It appears that all of the presented mechanisms happen in the pyrolysis process with different shares. The share of each mechanism depends strongly on the

polymer type though the process parameters such as temperature, heating rate and catalyst type and ratio can affect the degradation mechanism perfectly [12-15].

The catalytic degradation of polymeric materials can control the degradation mechanisms and the used catalyst can be a key parameter in determining the type and size of the final pyrolysis products. The catalytic products of the hydrocarbonic polymers like HIPS are highly useful and can be utilized as fuels or chemicals in the various applications. The zeolitic catalyst in the pyrolysis, lowers the required energy and time obviously. A narrow variety of products depending on the pore size of the catalyst is another advantage of catalytic pyrolysis in comparison with the thermal cracking [16-18].

Temperature as a critical and key parameter of pyrolysis plays an important role in determining the pyrolysis products and the high pyrolysis temperatures can decrease the catalyst role in the pyrolysis. In total, a review of the literature shows a strong dependence of carbonization products to process parameters such as temperature, catalyst type and polymer/catalyst ratio, heating rate and residence time [19-20].

Thermogravimetric analysis (TGA) is one of widely used techniques to consideration of the degradation trend under different process parameters such as temperature, heating rate and etc. The consideration of TGA results can show the effective parameters on the degradation mechanisms and activation energy. It is especially useful for the study of polymeric materials degradation including homo-polymers, copolymers and etc [13-15].

The goal of this paper is to elucidate the effect of temperature, heating rate and different zeolite based catalysts on the high impact polystyrene pyrolysis to produce the valuable products. Hence, we have reported the effect of zeolitic catalysts such as used FCC (Fluid catalytic cracking), HZSM-5 (Hydrogen form Zeolite Socony Mobil-5) and Ga/used FCC, temperature and heating rate on the pyrolysis yield and the composition of the condensed products plus the effect of heating rate on the degradation trend of HIPS using TGA method. The results show that the studied parameters have a significant effect on the residence time, amount of produced styrene, the distribution of molecular weight, and the composition of condensed product. Also, the trend of degradation of HIPS does not change significantly in the range of studied heating rates.

EXPERIMENTAL

Material

The shredded parts produced from HIPS 7240 grade (Tabriz Petrochemical Company), Nitrogen gas (purity 99.99%) by Roham Co and spent FCC catalyst by Abadan FCC Refinery. The $\text{Ga}(\text{NO}_3)_2$ was purchased from Merck chemical and HZSM-5 catalyst was supplied by Sudchemi Company.

Instruments and methods

Catalyst preparation

The spent FCC catalyst regenerated at 650°C and mild steaming for 4 hours. 0.78g $\text{Ga}(\text{NO}_3)_2$ was dissolved in distilled water (100g) under slow stirring at 90°C . The Ga/used FCC catalyst was prepared by wetness incipient method. The Ga solution was added to the regenerated used FCC (30g) at a lab rotary (RV8 model). The rotary temperature and rotation speed were raised step by step up to reach the dried mixture. After wetness incipient, the Ga/used FCC is dried in an oven at 120°C for 16 hours. Then calcined for another 4 hours at 650°C prior to the experiment.

EDX

The initial spent FCC with attention to varied metals in the naphtha had minor content of different metals on the surface. Quantax 200 energy dispersive X-ray spectroscopy (EDX) system at a WD of 23.00 and 15 KV was used to detect the metals on used FCC, Ga/used FCC and HZSM-5 catalysts. Meanwhile Si/Al ratio was calculated after Al and Si detection using EDX.

BET

BET (Brunauer–Emmett–Teller) method using Quantachrome Corp. Nova2200, Version 7.11 was used to calculate the Surface area of the catalysts from adsorption isotherms of nitrogen at 77K.

TGA

The thermo-gravimetric analysis was performed with a Netzsch TG 209 thermo balance. The initial mass of all the samples was 12.0-13.0 mg at same sizes. The experiments were carried out in a nitrogen atmosphere (99.99% minimum purity) with a flow rate of 30 ml min⁻¹.

Generally for polymer degradation, it is assumed that the rates of conversion are proportional to the concentration of reacted material. The rate of conversion can be expressed by the following basic rate equation:

$$\frac{\partial x}{\partial t} = \beta \frac{\partial x}{\partial T} = K(T)f(x) \quad (1)$$

Where " β " is the heating rate and " x " the degree of advance defined by

$$X = \frac{W_0 - W}{W_0 - W_f} \quad (2)$$

Where W is the weight of the sample at a given time t , W_0 and W_f , refer to values at the beginning and the end of the weight loss event of interest respectively. $f(x)$ and $K(T)$ are functions of conversion and temperature, respectively.

For each heating rate, the kinetic parameters, activation energy (E_a) and pre-exponential factor (A) of HIPS pyrolysis were determined by the integral method [21]. Many investigators assumed that solid fuel pyrolysis is a first order reaction [22–24].

GC/MS

Identification of varied compounds in the condensed products was carried out by a gas chromatograph mass spectrometry (GC/MS) of model GC-MS-QP5000. The analysis was performed on a 60 m*0.32 mm capillary column coated with a 1 μm film of DB⁻¹. The oven temperature was programmed, 40 °C hold for 10 min to 300 °C at 5 °C min⁻¹ hold for 10 min. The pure helium was used as the carrier gas at a rate of 1.4 ml min⁻¹. The injector/transfer line/trap temperatures were 220/250/200°C, respectively. Compounds were identified by means of the NIST12 and NIST62 library of mass spectra and subsets HP G1033A.

Pyrolysis process

Pyrolysis experiments were carried out in a 1 L stirred semi-batch reactor (buchi pilot plant with a custom built pressure reactor, Powerful cyclone stirrer drives with magnetic couplings, Temperature control by K type thermostat with electrical heating and special paddle stirrer) under atmospheric pressure and the schematic diagram is shown in Fig. 1. The fixed experimental conditions are as follows: 100g of shredded HIPS in the reactor, Nitrogen as carrier gas stream (300 ml min⁻¹) and agitator speed (50 rpm). At first, the mixture of HIPS and catalyst was added to the reactor and then reactor heater was turned on. Under nitrogen atmosphere as carrier gas, the evaporable products passed through three condensers containing an air condenser and two water condensers (the mixture of ice and water, 0°C).

The share of gaseous product that condensed in the water condensers and stored in the glass sampling bottles as the condensed product and the non-condensable product vented from the last condenser. The non-condensable products without any analysis were vented after cooling through three condensers and the condensed hydrocarbons products stored in glass sampling bottles. The components of total condensed hydrocarbons (residue in the condensers contained C₄ to C₁₀⁺) were quantified by GC/MS and the non-condensable products not analyzed. The solid char yield was determined gravimetrically after completion of the reaction and the non-condensable yield calculated by subtracting the weight of the condensed hydrocarbons and solid products from the sample weight.

RESULTS AND DISCUSSION

According to the previous studies [7-10], temperature, catalyst and heating rate as the key process parameters was considered to reach the optimal points on the pyrolysis of high impact polystyrene. By using a laboratory semi-batch stirred reactor, the effect of temperature (420–510°C), heater power (1000-4000 W) as function of heating rate and the different zeolite based catalysts containing used FCC, Ga/used FCC and HZSM-5 were considered on the pyrolysis products. To determine the mass balance and residue (char and the catalyst) calculation, the reactor vessel was weighted before and after the runs. The pyrolysis products are grouped together as the non-condensable product (gas), the condensed products (liquid) and char.

The effect of temperature

Temperature as key process parameter plays an important role in the thermal degradation [7-9]. Table 1 shows the different product yield plus the condensed liquid composition of high impact polystyrene pyrolysis under different degradation temperatures. In the studied range, the condensed liquid like the other hydrocarbonic polymers [7-9] showed a maximum yield at 450°C (94.9%) though the char yield increased with temperature increasing (0.3-1.1%) and gas had no obvious trend with the temperature (4.7-7.1%). The temperature of 450°C can be used as key and applied temperature in the pyrolysis conditions with suitable heat transfer such as stirred reactors. The increase of char can be related to the enhancement of Diels-Alder reactions and polycyclic production with the temperature [25]. The pyrolysis of high impact polystyrene produced the acceptable liquid shares (91.8-94.9%) in the studied temperature range as the applied range for the pyrolytic liquid production [7-9].

The composition of condensed pyrolysis products was identified using GC/MS as a function of temperature and the obtained results are given in Tables 1 and 2. Naphthenes (cycloalkanes), paraffins (alkanes), olefins (alkenes) and aromatics as the main structural components of hydrocarbons and the carbon numbers, molecular weight and gasoline range are shown in the mention tables. Aromatics (93.4–95.2%), Olefins (2.9–3.6%), paraffins (2.3–0.8%), naphthenes (1.4–0.4%) as components of the pyrolytic condensed liquid were affected by degradation temperature obviously. The results indicated that the aromatics with higher than 90% was the main component and in this regard, the structural parameter can limit the role of temperature in the studied range [19] though aromatics increased with increasing temperature moderately. The results showed that the dehydrogenation was accelerated with temperature and paraffins decreased moderately [7-9]. Temperature had no obvious effect on the polystyrene segments and aromatics was almost the only pyrolytic product while the pyrolysis of polybutadiene segments showed the reduction in aliphatic yield and increase in the cyclic products with temperature increasing and it can be related to the enhancement of Diels-Alder reactions and cross-linking mechanism with temperature increasing [8-9]. As a result, the un-zipping mechanism had a key role in the thermal degradation of HIPS and styrene had significant share in the condensed products though styrene decreased with temperature increasing (39.8-33.9%).

Table 2 shows the distribution of $C_4-C_{10}^+$ condensed hydrocarbon products, molecular weight and gasoline range with pyrolysis temperature. With temperature increasing, more chain scission occurred and the products tended toward low molecular weights (127.4-116.7 g $gmol^{-1}$) and also less share of C_{10}^+ (19.8-11.8%). Like polystyrene pyrolysis [19], although temperature had no clear effect on the product components but the carbon number distribution of the products showed the obvious difference under the studied temperature range. Meanwhile the gasoline range yield showed a significant increase with temperature increasing (75.1-83.3%). The pyrolysis of HIPS could produce the aromatic enriched liquid with acceptable gasoline range as auxiliary fuel to enhance the octane number in the studied temperature range [26]. The results also indicated that like the other polymers [7, 9], the residence time of HIPS in the reactor decreased obviously with increasing temperature (56-36 min).

The effect of different catalysts

The structural information of different zeolite based catalysts was identified using Energy Dispersive X-ray spectroscopy (EDX) analysis and BET test method (Table 3). The results showed a little difference between the Si/Al atomic ratio of Ga/used FCC and the used FCC. It has been reported that the residue metals on the used FCC can affect the polymer degradation and pyrolysis products [27].

The effects of different zeolitic catalysts (catalyst/HIPS: 0.15 w/w) on the condensed liquid, non-condensables and coke as the pyrolysis products and components of the condensed liquids in comparison with the thermal degradation are shown in Table 4. Table 5 shows the carbon number distribution of C₄ to C₁₀ and C₁₀⁺, molecular weight and gasoline range as function of catalytic and thermal pyrolysis of HIPS.

Like the other hydrocarbonic polymers [7-9], condensed liquid was the main fraction of HIPS pyrolysis (93.5-90.2%). The volatile products of the catalytic pyrolysis products had narrower molecular weight distribution and less viscosity in comparison with the thermal degradation. In the catalytic pyrolysis, used FCC had better operation in the liquid production (93.5%) and HZSM-5 with attention to the small size channel [9-10, 15] produced the lower amount in comparison with the others (90.2%).

Hot spots, the enhancement of secondary reactions such as Diels-Alder reactions, the tight place like catalyst pores can increase the coke production and the catalyst channels can be a good place to coke formation. The catalytic pyrolysis of HIPS produced the higher coke (0.7-1.2%) in comparison with the thermal degradation (0.4%). HZSM-5 with smaller channel size is more prone to coke formation [9-10] and also with 19.3% showed the significant difference with the other conditions in the gas production.

The catalytic pyrolysis of HIPS showed the acceptable operation in gasoline range (83.7-91.3%) and the yield of C₁₀⁺ as non-desirable product (12.8-6.1%) decreased using the catalysts in comparison with the thermal degradation (18.7%). The catalysts were less likely to follow the un-zipping mechanism and styrene production (34.1-32.2%) in comparison with the thermal degradation (38.5%).

The results also showed that the catalyst decreased the residence time significantly and HZSM-5 with 29 min had the best performance in comparison with the thermal degradation (47 min).

The composition of produced condensed liquid using thermal degradation system contained cyclic hydrocarbons (aromatics at 94.1% and naphthenes at 1.1%) and aliphatic hydrocarbons (olefins at 3.2% and paraffins at 1.6%). The condensed product distributions using Ga/used FCC were aromatics (98.1%), olefins (0.8%), paraffins (0.4%) and naphthenes (0.7%). The results also showed that the zeolite based catalysts had no different effect on the degradation mechanisms in comparison with the thermal degradation and it can be related to the special structure of HIPS [3] while the zeolite catalysts can affect strongly the non-aromatic hydrocarbonic polymers [7-9].

Also with used FCC catalyst, the results were little different from Ga/used FCC. The condensed product yield is 90.4% containing aromatics (95.3%), olefins (2.9%), paraffins (1.0%) and naphthenes (0.8%). While with HZSM-5 catalyst, the condensed hydrocarbons decreased in comparison with the other catalysts and reached a yield of 90.2%. Aromatics (95.9%), olefins (1.6%), paraffins (0.9%) and naphthenes (1.6%) are the main components of the condensed product respectively for this catalyst.

The effect of heating rate

The element heaters with different powers were used to study the HIPS degradation under different heating rates. The effects of heater powers from 1000 to 4000 W on the pyrolysis products containing condensable, non-condensable and coke plus the composition of liquid products are shown in table 6. The results show that the condensed (91.9-94.9%) as the main product and non-condensable products (4.7-7.4%) had a peak with increasing heater power while the coke yield decreased with increase of heater power in the studied range (0.7-0.2%).

The results showed that styrene as construct unit had significant share in the condensed products and the degradation tended to follow the un-zipping mechanism though styrene decreased with heating power in the studied range (40.6-35.6%). Aromatics containing styrene as the main and also only component decreased with increasing heating power (95.2-92.8%) while the other components with less than 10% share acted as raffinate and had no significant role in the products. The results indicated that the residence time decreased with heating power obviously (62-33 min).

The carbon number distribution, molecular weight and gasoline range of the condensed product under different heating power are shown in table 7. The results showed that the molecular weight of the liquid products was decreased with increasing of heating power obviously.

TG study of HIPS pyrolysis

Fig. 2 shows the non-isothermal mass losses of HIPS using a thermo-gravimetric analyzer (TGA) at heating rates of 5, 15, 30, 45 and 90°C min⁻¹. The results showed that the sample tended to degrade at higher temperatures with increase in heating rate. Fig. 3 shows the related DTG graphs with the TGA curves at the previous Figure. The DTG curves almost showed a unimodal degradation curve though the next peak tended to eliminate with heating rate increasing.

The typical plots of $\ln [-\ln (1-x) / T^2]$ versus $1/T$, indicating that for all of the heating rates, single first order reaction should be used to describe the pyrolysis process (Fig. 4). The integral method [22-24] was applied separately to each of the stages. To do so, the conversion x was recalculated for each reaction. From the slope of each line, the value of E_a and A could be obtained for different stages.

Table 8 lists the activation energies and pre-exponential factors are obtained by different heating rates using integral method. The results indicated that activation energy was decreased with increase of heating rate obviously (222.5-183.6 kJ mol⁻¹). The kinetic parameters were calculated in the range of $x=5$ to 95%, which represented the main pyrolysis region. The good correlation coefficient indicated that the corresponding independent first order reaction model fitted the experimental data very well. Table 11 also indicates the temperature interval for the decomposition of the HIPS defined between the temperatures T_5 and T_{95} and their difference. These two temperatures are defined respectively as the temperature at which the conversion starts (T_5 at 5% conversion) and T_{95} (close to the end of conversion, at 95%). The results indicated that the difference between T_5 and T_{95} as function of DTG breadth, decreased moderately with heating rate increasing. It can show that the heating rate had no obvious effect on the degradation mechanism in the studied range.

It seemed that the related effective pyrolysis mechanisms (i.e. chain scission, un-zipping and a little cross-linking) and their shares in the degradation were changed under different heating rates and degradation temperature. According to the results using the pyrolysis reactor along with the results using TGA instrument showed that unzipping and chain scission were the effective mechanisms though un-zipping over chain scission decreased with temperature and heating rate increasing. The cross-linking mechanism had a little role in the degradation and with attention to the results, the cross-linking mechanism role was increased with temperature and decreased with the heating rate.

CONCLUSION

A laboratory stirred reactor and TGA instrument have been used to consideration of HIPS degradation and the pyrolytic products under temperature, heating rate and zeolitic catalysts. The fuel like and aromatic enriched products in the gasoline range can be produced under catalytic degradation of high impact polystyrene over zeolite based catalyst. According to this study, the pyrolysis products were changed under different heating rates, temperatures. The results showed that the faster pyrolysis and high degradation temperatures tended to decrease the molecular weight in the gasoline range. Styrene was the main product of high impact polystyrene pyrolysis up to 40% while the studied catalysts, heating rate and temperature tended to decrease styrene production and un-zipping mechanism role obviously. In the studied heating rate range, DTG curves of the degradation were almost like each other and it is due to the structural similarity between the linear scission performance of chain scission and un-zipping as main degradation mechanisms and a little role of cross-linking mechanism with non-linear scission performance in the pyrolysis. The activation energy of degradation was decreased with increase of heating and temperature. Thus, the catalytic pyrolysis of high impact polystyrene using the zeolitic catalyst under higher pyrolysis heating rates and temperature appeared to be the more economically favorable in terms of cost efficient operation.

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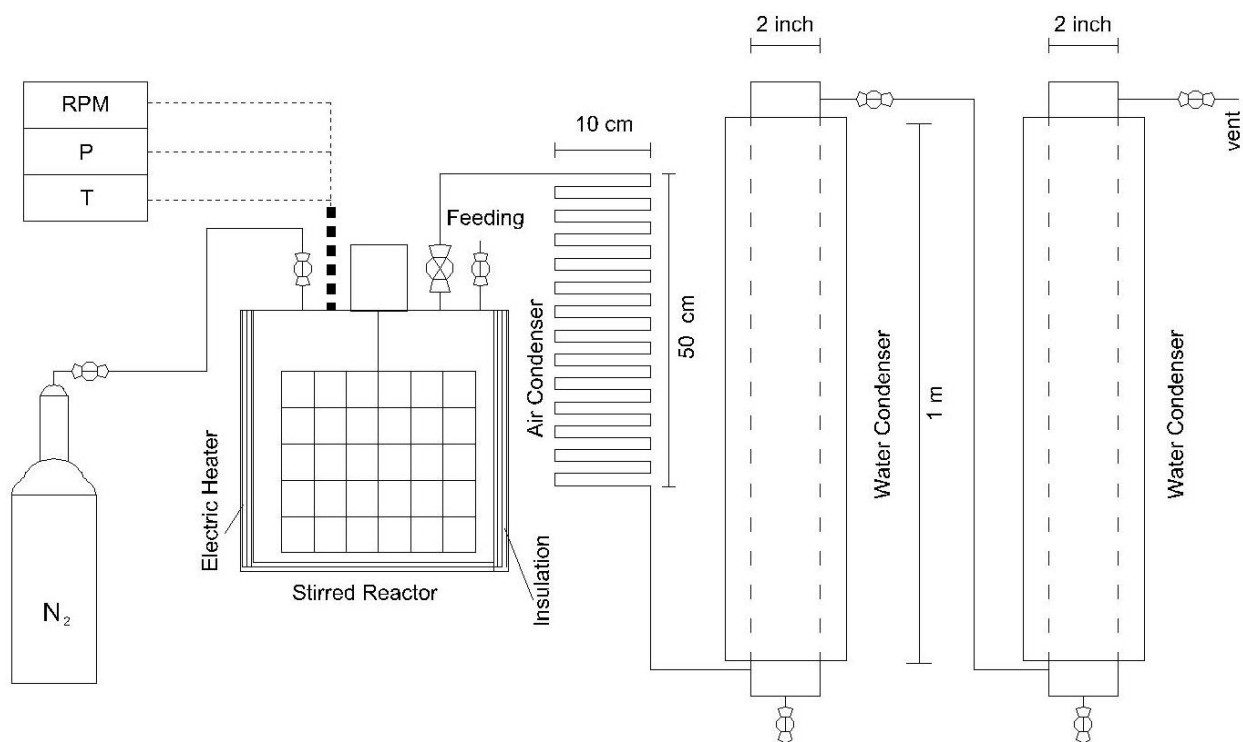


Figure 1. Flow scheme of the pyrolysis system.

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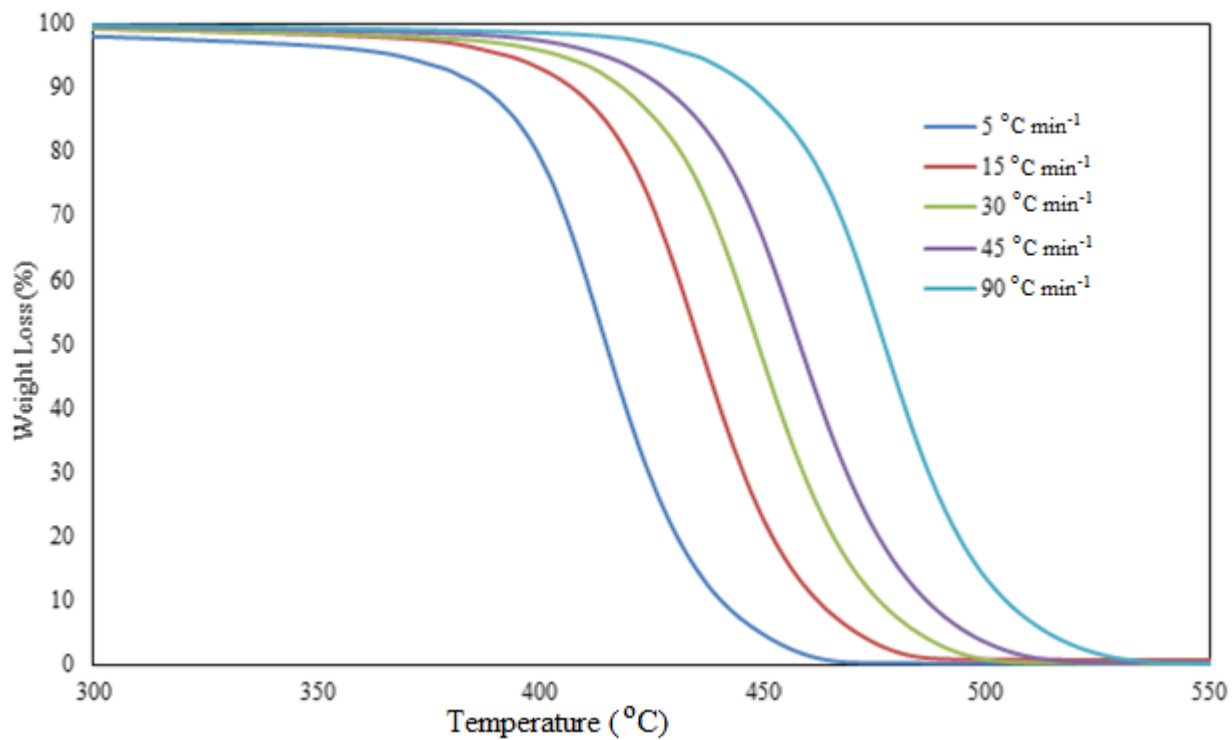


Figure 2. TGA curves of HIPS at different heating rates (5, 15, 30, 45 and 90 °C min⁻¹).

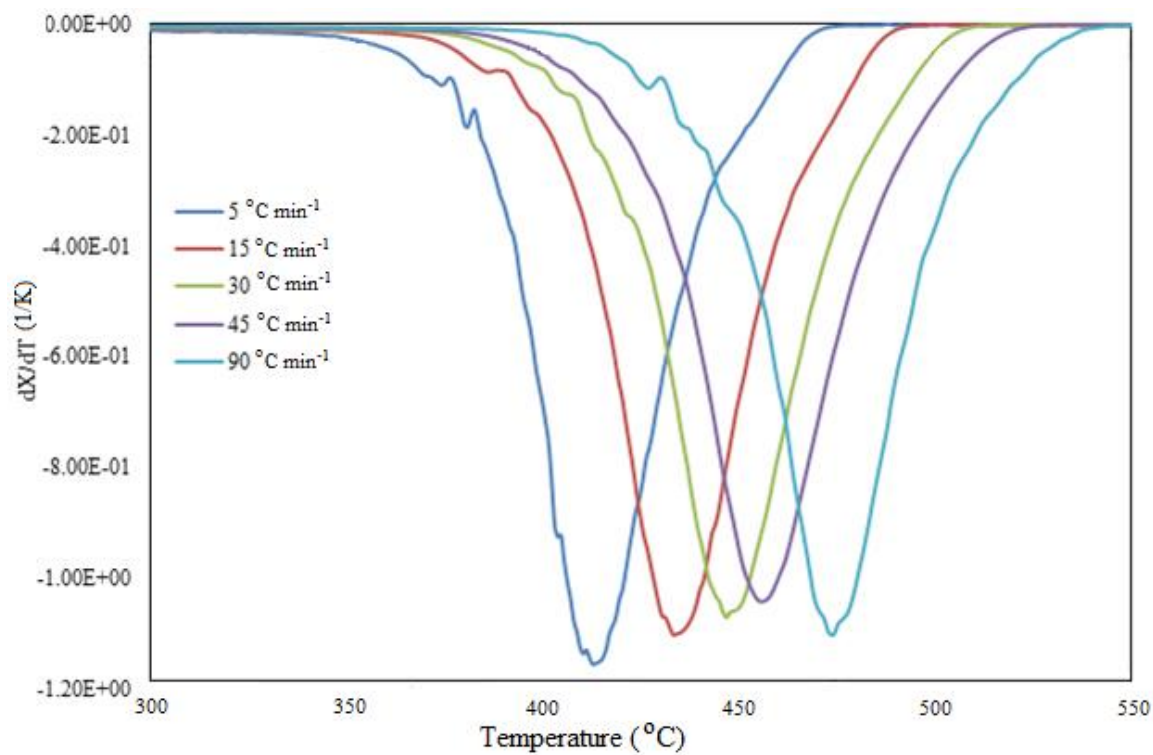


Figure 3. DTG curves of HIPS at different heating rates (5, 15, 30, 45 and 90°C min⁻¹).

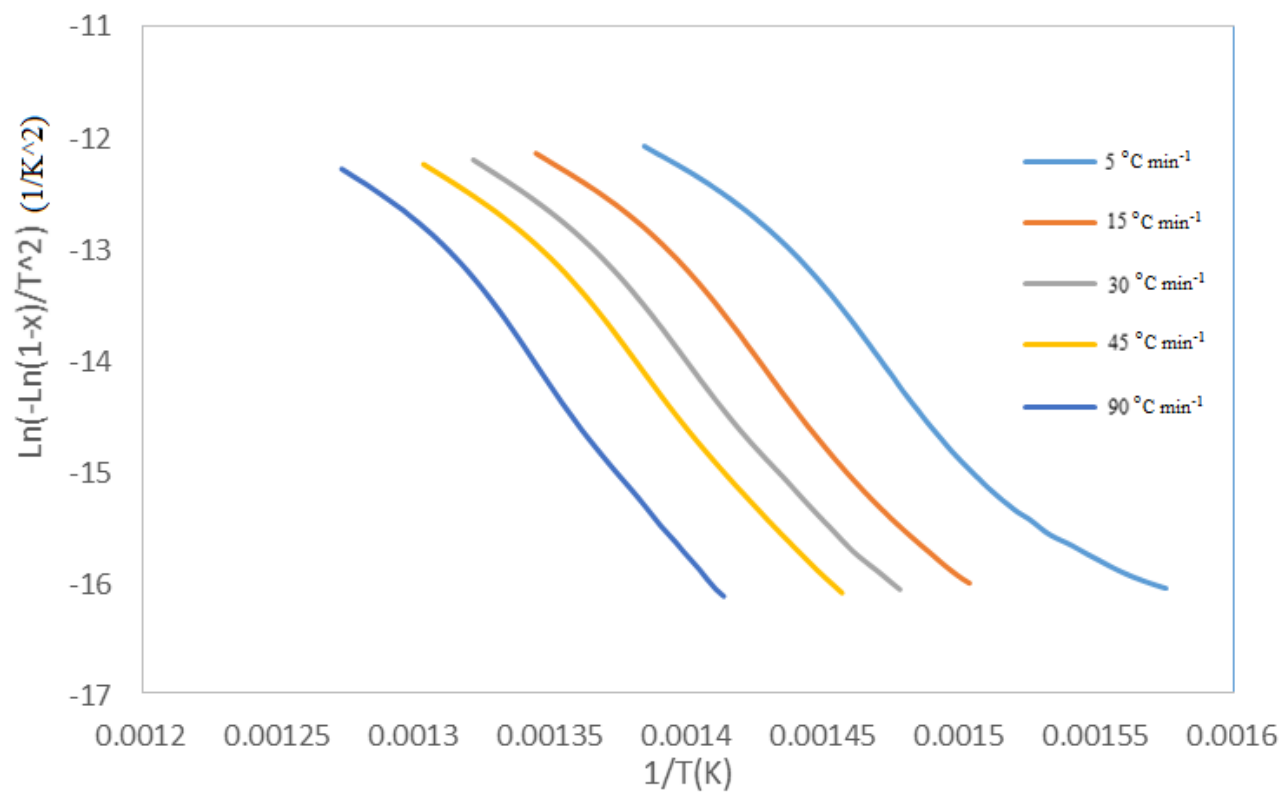


Figure 4. Plot of $\ln(-\ln(1-x)/T^2)$ vs $1/T$ of HIPS at different heating rates.

Table 1. The effect of temperature on the HIPS product yield and liquid composition.

T (°C)	Liquid (%)	Gas (%)	Coke (%)	olefins (%)	paraffins (%)	naphthenes (%)	aromatics (%)	Styrene (%)	residence time (min)
420	93.2	6.5	0.3	2.9	2.3	1.4	93.4	39.8	56
450	94.9	4.7	0.4	3.2	1.6	1.1	94.1	38.5	47
480	92.9	6.4	0.7	3.4	1.4	0.6	94.6	36.2	41
510	91.8	7.1	1.1	3.6	0.8	0.4	95.2	33.9	36

Catalyst/HIPS: 0, Carrier gas: Nitrogen, Agitator speed: 50 RPM, Heating Power: 2000W

Table 2. The effect of temperature on the carbon number distribution of the HIPS condensed product composition.

Temperature(°C)	420	450	480	510
Carbon Number				
C ₄	0.2	0.1	0.1	0.2
C ₅	0.5	0.4	0.8	1.6
C ₆	3.4	4.2	5.4	6.4
C ₇	3.5	4.3	5.7	7.3
C ₈	65.2	64.5	63.1	61.2
C ₉	2.5	3.2	4.2	6.8
C ₁₀	4.9	4.6	4.8	4.7
C ₁₀ ⁺	19.8	18.7	15.9	11.8
Sum(C₅-C₉)	75.1	76.6	79.2	83.3
Ave. Molecular Weight	127.4	124.5	121.0	116.7

Catalyst/HIPS: 0, Carrier gas: Nitrogen, Agitator speed: 50 RPM, Heating Power: 2000W

Table 3. The specification of different catalysts used in the catalytic degradation of HIPS.

Catalyst	Used FCC	Ga/FCC	HZSM-5
Surface Area (m ² g ⁻¹)	235.0	215.2	381.3
Si/Al	6.0	5.9	20.0
Ga (%)	0.00	0.82	0.00
Na (%)	0.30	0.29	0.18
Ca (%)	1.54	1.52	0.00
Fe (%)	0.20	0.19	0.00
V(ppm)	450	435	0
Ni(ppm)	180	175	0

Table 4. The effect of different catalysts on the HIPS products yield and the condensed product.

Catalyst	Liquid (%)	Gas (%)	Coke (%)	olefins (%)	paraffins (%)	naphthenes (%)	aromatics (%)	Styrene (%)	residence time (min)
no catalyst	94.9	4.7	0.4	3.2	1.6	1.1	94.1	38.5	47
used FCC	93.5	5.8	0.7	2.9	1.0	0.8	95.3	34.1	35
Ga/FCC	93.3	5.8	0.9	0.8	0.4	0.7	98.1	33.9	33
HZSM-5	90.2	8.6	1.2	1.6	0.9	1.6	95.9	32.2	29

Catalyst/HIPS: 0.15 w/w, Carrier gas: Nitrogen, Agitator speed: 50 RPM, Temperature: 450°C, Heating Power: 2000W

Table 5: The effect of different catalysts on the carbon number distribution of the HIPS condensed product composition.

	no catalyst	used FCC	Ga/used FCC	HZSM-5
Carbon Number				
C₄	0.1	0.1	0.1	1.2
C₅	0.4	0.7	0.7	3.3
C₆	4.2	4.7	5.2	5.9
C₇	4.3	5.3	5.8	6.2
C₈	64.5	69.1	70.1	68.8
C₉	3.2	3.9	3.7	7.1
C₁₀	4.6	3.4	3.1	1.4
C₁₀⁺	18.7	12.8	11.3	6.1
Sum(C₅-C₉)	76.6	83.7	85.5	91.3
Ave. Molecular Weight	124.5	119.8	118.4	112.9

Catalyst/HIPS: 0.15 w/w, Carrier gas: Nitrogen, Agitator speed: 50 RPM, Temperature: 450°C, Heating Power: 2000W

Table 6. The effect of heater power on the products yield, the condensed product composition and residence time.

Heating power (w)	Liquid (%)	Gas (%)	Coke (%)	olefins (%)	paraffins (%)	naphthenes (%)	aromatics (%)	Styrene (%)	residence time (min)
1000	91.9	7.4	0.7	2.7	1.7	0.4	95.2	40.6	62
2000	94.9	4.7	0.4	3.2	1.6	1.1	94.1	38.5	47
3000	93.5	6.2	0.3	3.9	1.4	1.5	93.2	37.2	39
4000	93.1	6.7	0.2	4.1	1.1	2.0	92.8	35.6	33

Catalyst/HIPS: 0, Carrier gas: Nitrogen, Agitator speed: 50 RPM, Temperature: 450°C.

Table 7. The effect of heater power on the carbon number distribution of the condensed products.

	1000 W	2000 W	3000 W	4000 W
Carbon Number				
C ₄	0.4	0.1	0.2	1.2
C ₅	0.6	0.4	4.3	4.3
C ₆	1.2	4.2	6.1	8.1
C ₇	1.5	4.3	6.7	7.2
C ₈	66.1	64.5	62.7	61.1
C ₉	3.9	3.2	2.3	3.2
C ₁₀	3.1	4.6	2.9	2.8
C ₁₀ ⁺	23.2	18.7	14.8	12.1
Sum(C₅-C₉)	73.3	76.6	82.1	83.9
Ave. Molecular Weight	128.1	124.5	118.6	115.7

Catalyst/HIPS: 0, Carrier gas: Nitrogen, Agitator speed: 50 RPM, Temperature: 450°C

Table 8: The effect of heating rates on the kinetic parameters and characteristic temperatures.

β (°C min ⁻¹)	Conversion range (%)	E _a (KJ mol ⁻¹)	A (min ⁻¹)	R ¹	T ₅ (°C)	T ₉₅ (°C)	ΔT (°C)
5	5-95	222.5	3.4*10 ¹³	0.989	367.8	449.4	81.6
15	5-95	215.4	6.7*10 ¹²	0.998	391.1	471.2	80.1
30	5-95	206.1	4.6*10 ¹²	0.994	404.3	484.7	80.4
45	5-95	199.7	1.9*10 ¹²	0.993	415.2	494.9	79.7
90	5-95	183.6	2.2*10 ¹¹	0.993	434.7	512.8	78.1