Chemical recycling of plastic wastes made from polyethylene (LDPE and HDPE) and polypropylene (PP)

D.S. Achilias [a,*], C. Roupakias [a], P. Megalokonomos [a], A.A. Lappas [b], E.V. Antonakou [b]

[a] Laboratory of Organic Chemical Technology, Department of Chemistry, Aristotle University of Thessaloniki, 541 24 Thessaloniki, Greece
[b] Laboratory of Environmental Fuels and Hydrocarbons, Chemical Process Engineering Research Institute, 570 01 Thessaloniki, Greece

Abstract

The recycling of either model polymers or waste products based on low-density polyethylene (LDPE), high-density polyethylene (HDPE) or polypropylene (PP) is examined using the dissolution/reprecipitation method, as well as pyrolysis. In the first technique, different solvents/non-solvents were examined at different weight percent amounts and temperatures using as raw material both model polymers and commercial products (packaging film, bags, pipes, food-retail outlets). The recovery of polymer in every case was greater than 90%. FT-IR spectra and tensile mechanical properties of the samples before and after recycling were measured. Furthermore, catalytic pyrolysis was carried out in a laboratory fixed bed reactor with an FCC catalyst using again model polymers and waste products as raw materials. Analysis of the derived gases and oils showed that pyrolysis gave a mainly aliphatic composition consisting of a series of hydrocarbons (alkanes and alkenes), with a great potential to be recycled back into the petrochemical industry as a feedstock for the production of new plastics or refined fuels.

Keywords: Polymer recycling; Polyethylene; Polypropylene; Dissolution/reprecipitation; Pyrolysis

1. Introduction

During last decades, the great population increase worldwide together with the need of people to adopt improved conditions of living led to a dramatical increase of the consumption of polymers (mainly plastics). Materials that appears interwoven with the consuming society where we live.

Current statistics for Western Europe estimate the annual total consumption of plastic products at 48.8 million tonnes for 2003 corresponding to 98 kg per capita. The same quantity a decade before, i.e. in 1993 was approximately 64 kg/capita [1,2].

Over 78 wt.% of this total corresponds to thermoplastics (mainly polyolefins, low density polyethylene, LDPE-17%, high density polyethylene, HDPE-11%, polypropylene, PP-16%) and the remaining to thermosets (mainly epoxy resins and polyurethans). Plastics consumption in Greece in 2002 was 515,000 tonnes with an increasing trend from 2001 to 2002 equal to 10.9% [1,2].

Since the duration of life of plastic wastes is very small (roughly 40% have duration of life smaller than 1 month), there is a vast waste stream (approximately 21.2 millions tonnes for 2003) that reaches each year to the final recipients creating a serious environmental problem. Despite significant advances in recent years, 61% of the plastic waste generated in W. Europe is still disposed of to landfill. The rest 39% recovered mainly with three methods. The bigger percentage was been disposed for energy recovery (4.75 million tonnes, percentage 22%), while 15% was mechanically recycled (3.13 million tonnes), with only 2% recycled chemically (0.35 millions tonnes) [1]. From the total 370,000 tonnes of plastic wastes in Greece in 2002, the percent amount recovered and recycled was approximately 2.2% [2].

Disposing of the waste to landfill is becoming undesirable due to legislation pressures (waste to landfill must be reduced by 35% over the period from 1995 to 2020), rising costs and the poor biodegradability of commonly used polymers. The approaches that have been proposed for recycling of waste polymers include [3,4]: *Primary recycling* referring to the "in-plant" recycling of the scrap material of controlled history. *Mechanical recycling*, where the polymer is separated from its associated contaminants and it is reprocessed by melt extrusion. *Chemical recycling* leading in total depolymerization to the monomers, or partial degradation to other secondary valuable materials. *Energy recovery* as an effective way to reduce the volume of

---

* Corresponding author. Tel.: +30 2310 997822; fax: +30 2310 997769.
E-mail address: axilias@chem.auth.gr (D.S. Achilias).

0304-3894/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhazmat.2007.06.076

organic materials by incineration. Among the recycling techniques, incineration meets with strong societal opposition and mechanical recycling can be carried out only on single-polymer waste streams. However, the most attractive method, in accordance also with the principles of sustainable development is chemical recycling also called as feedstock or tertiary recycling. According to this method, waste polymers can be either converted to original monomers or other valuable chemicals. These products are useful as feedstock for a variety of downstream industrial processes or as transportation fuel.

Polyolefins (LDPE, HDPE, PP) are a major type of thermoplastic used throughout the world in such applications as bags, toys, containers, pipes (LDPE), housewares, industrial wrappings and film, gas pipes (HDPE), film, battery cases, automotive parts, electrical components (PP). In Western Europe alone approximately 21.37 million tonnes of these three polymers are consumed each year (data of 2003), representing an amount of 56% of the total thermoplastics [1]. Addition polymers (like polyethylene) in contrast to condensation polymers (i.e. poly(ethylene terephthalate) (PET)) cannot be easily recycled by simple chemical methods [5]. Instead, thermochemical recycling techniques like pyrolysis have been proposed as process producing a series of refined petrochemical products and particularly of a liquid fraction similar with that of commercial gasoline [3].

Thermal cracking of polyethylene and polypropylene is usually carried out either in high temperatures (>700 °C), to produce an olefin mixture (C_1–C_4) and aromatic compounds (mainly benzene, toluene and xylene) or in low temperature (400–500 °C) (thermolysis) where three fractions are received: a high-calorific value gas, condensable hydrocarbon oil and waxes [6,7]. In the first case, the objective is to maximize the gas fraction and to receive the olefins, which could be used after separation as monomers for the reproduction of the corresponding polyolefins [8]. Cracking in lower temperatures leaves a waxy product in the reactor that mainly consists of paraffins together with a carbonized char. The gaseous fraction can be used for the supply of the energy required for the pyrolysis after burning. The liquid fraction mainly consists of linear olefins and paraffins with C_{11}–C_{14} carbon atoms with only traces of aromatic compounds [6]. Thermal cracking of polyolefins proceeds through a random scission mechanism in four steps: initiation, depropagation, inter- or intra-molecular hydrogen transfer followed by b-scission and termination. In general, thermal cracking is more difficult in HDPE followed by LDPE and finally by PP [9]. Due to the low thermal conductivity of polymers together with the endotherm of cracking, thermal pyrolysis consumes large amounts of energy. Thus, catalytic technologies have been proposed to promote cracking at lower temperatures, resulting in reduced energy consumption and higher conversion rates [10]. Furthermore, use of specific catalysts allows the process to be directed towards the formation of a narrower distribution of hydrocarbon products with a higher market value [6]. Heterogeneous catalysis has been investigated extensively using solids with acid properties. Zeolites of the kind employed in the catalytic cracking of hydrocarbon feedstocks (Y, ZSM-5, Beta) as well as other well-known acid solids like silica–alumina, alumina and clays are being the most studied [10]. Mixtures of these catalysts like SAHA/ZSM-5, MCM-41/ZSM-5 have been also used. Cracking with acid catalysts takes place through the formation of carbocations, which requires the presence of strong acidic regions. Acid strength and textural properties are the main parameters dictating the performance of acid solids in the catalytic conversion of polymers. Porosity, surface area characteristics and particle size determine to a large extent the accessibility of bulky polymeric molecules to the internal catalytic acid sites of the solids. Thus, while catalyst HZSM-5 presents bigger reactivity from HMCM-41 in the cracking of HDPE and LDPE, at the decomposition of the large molecules of PP the transformation is almost the same with that of thermal cracking, because cross-section of polymer is very big in order to enter in catalysts' micropores [11].

In the present investigation, the recycling of model and waste products based on LDPE, HDPE and PP was examined using two different methods: the traditional method of dissolution/reprecipitation and the more challenging technique of pyrolysis. The first belongs to the mechanical recycling techniques while the second to the chemical/feedstock recycling. During the first technique, the polymer can be separated and recycled using a solvent/non-solvent system. For this purpose, different solvents/non-solvents were examined at different weight percent amounts and temperatures using either model polymers as raw material or commercial waste products (packaging film, bags, pipes, food-retail products). This technique has been widely used by Papaspyrides et al. [12–14] and other researchers [15]. Furthermore, catalytic pyrolysis was carried out in a laboratory fixed bed reactor using as raw materials either model LDPE, HDPE and PP or waste products based on these polymers. All compounds in the gaseous and oil fractions from pyrolysis were identified. Conclusions are very encouraging concerning alternative techniques of waste polymer recycling.

2. Materials and methods

2.1. Materials

Model polyethylene (LDPE and HDPE) and polypropylene (PP) obtained from Aldrich were used in this study, together with different commercial waste products (packaging film, bags, pipes, food-retail outlets) made from these polymers. The solvents used (toluene, xylene, *n*-hexane) were reagent grade. In all pyrolysis experiments, an FCC catalyst was used with the following characteristics: total surface area: 178.4 m^2/g, zeolite area: 58.5 m^2/g, Z/M: 0.49, UCS: 24.26 Å, Ni 150 ppm and V 367 ppm.

2.2. Dissolution/reprecipitation technique

The experimental procedure comprised: the polymer (1 g) and the solvent (20 mL) were added into a flask equipped with a vertical condenser and a magnetic stirrer. The system was heated for 30 min to the desired temperature. Then, the flask was cooled and the solution of the polymer was properly poured into the non-solvent. The polymer was re-precipitated, washed, filtrated

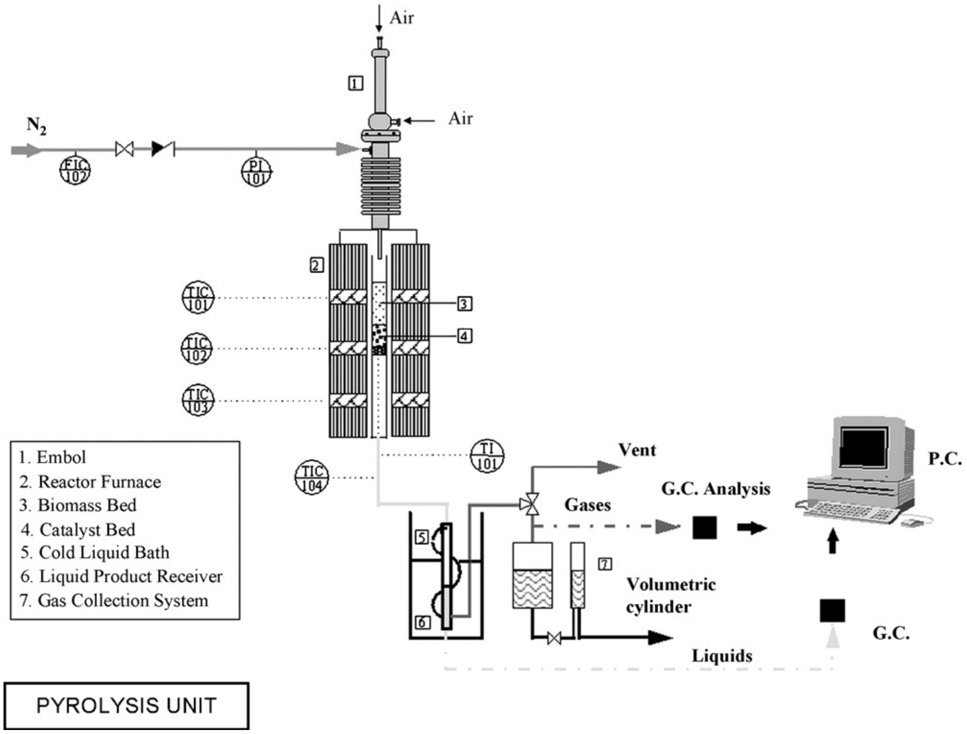

Fig. 1. The fixed bed reactor system.

and dried in an oven at 80 °C for 24 h. The recycled polymer was obtained in the form of powder or grains. Xylene and toluene were used as solvents, while *n*-hexane as non-solvent. Some other parameters include solvent/non-solvent volume ratio: 1/3, dissolution temperatures below the boiling point for each solvent (140 °C for xylene and 110 °C for toluene) and various polymer concentrations.

2.3. Measurements

2.3.1. Fourier-transform infra-red (FT-IR)

The chemical structure of the model polymers and waste plastics, before and after the recycling technique was confirmed by recording their IR spectra. The instrument used was an FT-IR spectrophotometer of Perkin-Elmer, Spectrum One. The resolution of the equipment was 4 cm^{-1}. The recorded wavenumber range was from 450 to 4000 cm^{-1} and 16 spectra were averaged to reduce the noise. A commercial software Spectrum v5.0.1 (Perkin-Elmer LLC 1500F2429) was used to process and calculate all the data from the spectra. Thin polymeric films were used in each measurement, formed by a hydraulic press Paul-Otto Weber, at a temperature 20 °C above the melting point of each polymer.

2.3.2. Tensile measurements

The tensile mechanical properties were studied on relatively thin films of the polymers. Dumbbell-shaped tensile-test specimens (central portions, 5 mm × 0.5 mm thick, gauge length 22 mm) were cut from the sheets in a Wallace cutting press and conditioned at 23 °C and 55–60% relative humidity for 48 h. The stress–strain data were obtained with an Instron model BlueHill 2 tensile-testing machine, which was maintained under the same conditions and operated at an extension rate of 5 mm/min. The values of the yield stress, tensile strength and elongation at break were determined according to ASTM D 1708–66. At least five specimens were tested for each sample, and the average values are reported.

2.4. Pyrolysis

A laboratory-scale fixed bed reactor, illustrated in Fig. 1, was used in all pyrolysis experiments. The reactor was filled with 0.7 g of the FCC catalyst and the piston was filled with the polymer (1.5 g). Glasswool was placed in the bottom of the reactor, the top of the piston and inside the bed in order to separate the catalyst and the polymer bed. The system was always heated in the presence of N_2 (30 mL/min) and, by using a temperature controller the temperature of each zone of the furnace was controlled. As soon as the reaction temperatures were achieved, polymer entered the reactor and the experiment started. The time of the experiment was 17 min and the reaction temperature 450 °C. At the end of the experiment purging (30 min) was performed. Both the experiment (100 mL/min) and purging (30 mL/min) were performed in the presence of N_2. The pressure was controlled, before and after the entrance of the piston into the reactor to identify potential blockage.

The liquid products were collected in a liquid bath (−17 °C) and quantitatively measured in a pre-weighed glass receiver. The gaseous products were collected and measured by water displacement. The liquid samples were analysed by GC/MS analysis in a HP 5989 MS ENGINE (electron energy 70 eV; emission 300 V; helium flow rate: 0.7 cm^3/min; column: HP-

5MS). The gaseous products were analysed in a HP 6890 GC, equipped with four columns (precolumn: OV-101; columns: Porapak N, Molecular Sieve 5A and Rt-Qplot and two detectors (TCD and FID)). The chromatograph was standardized with gases at known concentrations as standard mixtures.

3. Results and discussion

3.1. *Recycling of LDPE, HDPE and PP by the dissolution/reprecipitation technique*

Based on the principle that polymers, generally, can be dissolved in solvents with similar values of the solubility parameter, δ, two solvents were selected for the recycling process. These solvents were xylene [$\delta = 8.8$ (cal/cm^3)$^{1/2}$] and toluene [$\delta = 8.9$ (cal/cm^3)$^{1/2}$]. Polyolefins present a value of solubility parameter near to 8.0 (cal/cm^3)$^{1/2}$.

Two solvent/non-solvent systems, three dissolution temperatures and four initial polymer concentrations were investigated. The effect of these parameters on the % recovery of the three model polyolefins (LDPE, HDPE, PP) and several commercial products based on these polymers appears in Table 1.

It is obvious that at all different experimental conditions and for all commercial samples examined the polymer recovery was always high. Xylene was found to be a very good solvent for all polyolefins examined. An increase in dissolution temperature leads to increased polymer recovery values. In contrast, increasing the polymer concentration in the solvent leads to decreased recovery values mainly due to difficulties in stirring caused by the increased viscosity of the solution.

3.2. *Characterization of the samples*

Subsequently, the properties of the polymers before and after the recycling technique were investigated. Comparing the FT-IR spectra of the solid obtained after recycling of either model LDPE or a commercial sample based on LDPE with that of model polyethylene identified the polymer recovered with this technique. Indicative spectra of a plastic commercial product and model LDPE are presented in Fig. 2. It is obvious that all four spectra (i.e. model polymer and waste product before and after recycling) are almost identical. The same results were also obtained for HDPE and PP.

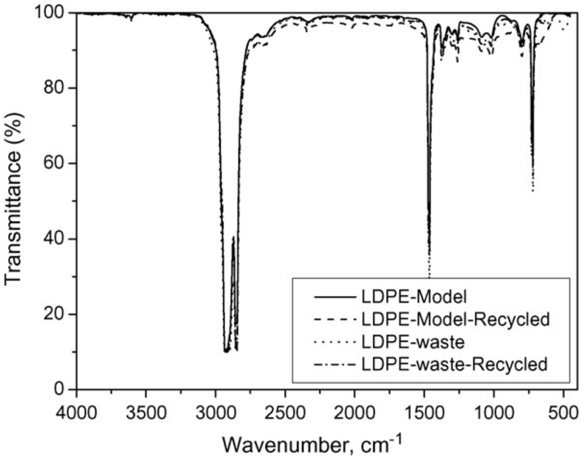

Fig. 2. FT-IR spectra of model LDPE and commercial plastic product based on LDPE before and after recycling.

In advance the tensile mechanical properties of the polymers before and after recycling were investigated. Results from tensile breaking measurements for the model and waste plastic products before and after recycling are presented in Tables 2 and 3, respectively. The data suggest that the recycled grades (either from model polymers or from waste products) exhibit tensile strength at maximum load levels competent to those of the virgin polymers. The same holds for the tensile stress at yield measurements. Even more, there is a clear indication that after recycling the elastic modulus increases possibly due to the influence of the fractionation phenomena encountered during the dissolution/reprecipitation process (i.e. some lower molecular weight fractions may remain soluble in the solvent/non-solvent phase),

Table 1
Polymer recovery (wt.%) by the dissolution/reprecipitation technique

Solvent/non-solvent	Temperature (°C)	Concentration (%, w/v)	LDPE	HDPE	PP
Toluene/*n*-hexane	110	5	97.7	96.7	98.2
Xylene/*n*-hexane	50	5	63.2	6.4	4.9
Xylene/*n*-hexane	100	5	98.9	98.3	75.5
Xylene/*n*-hexane	140	5	99.7	99.6	98.7
Xylene/*n*-hexane	140	10	99.8	99.7	99.7
Xylene/*n*-hexane	140	15	99.8	99.7	99.9
Xylene/*n*-hexane	140	20	95.9	99.4	97.4
Commercial waste products					
Xylene/*n*-hexane	140	5	98.6 packaging film		
Xylene/*n*-hexane	140	5	99.6 plastic bag		
Xylene/*n*-hexane	140	5		98.8 pipe	
Xylene/*n*-hexane	140	5		98.3 food bag	
Xylene/*n*-hexane	140	5		98.5 plastic bottle	
Xylene/*n*-hexane	140	5		99.0 plastic cap	
Xylene/*n*-hexane	140	5			98.2 plastic bottle
Xylene/*n*-hexane	140	5			99.0 plastic cup
Xylene/*n*-hexane	140	5			99.6 plastic cap

Table 2
Mechanical properties of model polymers before and after the recycling technique

	LDPE		HDPE		PP	
	Virgin	Recycled	Virgin	Recycled	Virgin	Recycled
Tensile stress at max load (MPa)	8.6	8.6	32.8	33.1	23.7	28.5
Elongation at break (%)	83	146	550	553	620	682
Tensile stress at yield (MPa)	8.6	8.6	14.4	14.9	18.5	21.3
Elastic modulus (MPa)	303	360	104	128	297	354

Table 3
Mechanical properties of waste plastic products before and after the recycling technique

	LDPE		HDPE		PP	
	Virgin	Recycled	Virgin	Recycled	Virgin	Recycled
Tensile stress at max load (MPa)	17.0	17.6	14.8	22.0	25.3	28.2
Elongation at break (%)	711	722	721	732	602	652
Tensile stress at yield (MPa)	8.8	8.9	14.8	17.2	23.3	25.0
Elastic modulus (MPa)	175	182	189	250	626	674

as well as to the role of the additives initially contained in the starting material [12–14].

3.3. *Recycling of LDPE, HDPE and PP by pyrolysis*

Thermal cracking or pyrolysis, involves the degradation of the polymeric materials by heating in the absence of oxygen (usually in a nitrogen atmosphere). During pyrolysis at increased temperatures, depending on polymer type, either end-chain or random scission of the macromolecules occurs. In the first case (occurring in poly(methyl methacrylate)), the monomer can be produced in a large amount, while in the second, occurring mainly in polyolefins (LDPE, HDPE, PP) the amount of monomer produced is very low. A review on the current trends in chemical recycling of LDPE, HDPE and PP can be found in ref. [7].

In this investigation, results are presented on the catalytic pyrolysis of model LDPE, HDPE and PP using an acid FCC catalyst, as well as on waste products based on these polymers. The values measured for the product yield appear in Table 4. It is seen that since pyrolysis temperature is rather low a small gaseous fraction was obtained from all polymers. It was also observed that the relative amounts of gas and liquid fraction are very much dependent on the type of polymer used as raw

Table 4
Product yield from the catalytic pyrolysis of LDPE, HDPE and PP

Polymer	Temperature (°C)	Gas (wt.%)	Liquid (wt.%)	Residue (wt.%)
Model polymers				
LDPE	450	0.5	46.6	52.9
HDPE	450	0.5	38.5	61.0
PP	450	6.2	67.3	26.5
Waste products				
LDPE	450	8.5	72.1	19.4
HDPE	450	3.3	44.2	52.5
PP	450	15.3	64.7	20.0

Table 5
Composition of the gaseous fraction from the catalytic pyrolysis of model LDPE, HDPE and PP and waste products based on these polymers (wt.% on polymer)

	Model polymers			Waste products		
	LDPE	HDPE	PP	LDPE	HDPE	PP
Hydrogen, H_2	0.001	0.001	0.002	0.02	0.00	0.01
Carbon dioxide, CO_2	0.000	0.000	0.000	2.90	0.00	0.64
Carbon monoxide, CO	0.000	0.000	0.000	0.00	0.00	0.00
Methane, CH_4	0.002	0.001	0.030	0.03	0.01	0.04
Ethane, C_2H_6	0.003	0.002	0.072	0.00	0.01	0.11
Ethylene, C_2H_4	0.004	0.002	0.026	0.03	0.02	0.05
Propane, C_3H_8	0.011	0.007	0.060	0.03	0.05	0.10
Propylene, C_3H_6	0.068	0.058	1.101	0.65	0.44	2.73
nC_4	0.190	0.176	2.565	1.76	1.25	6.21
nC_5	0.050	0.057	1.003	0.74	0.37	2.47
iC_5	0.080	0.119	0.664	1.28	0.69	1.52
C_6	0.047	0.062	0.717	1.11	0.44	1.45
Total	0.456	0.485	6.240	8.55	3.28	15.33

Table 6
Compounds identified in the liquid fraction of the catalytic pyrolysis of model LDPE, HDPE and PP (wt.% on liquid fraction)

Polymer	LDPE	HDPE	PP
i-C_6	–	2.9	1.6
C_7	0.8	1.9	–
i-C_7	1.4	2.9	1.0
$C_8^=$	3.9	2.0	3.4
i-C_8	0.3	1.8	2.1
C_9	1.4	4.3	2.6
C_{10}	8.0	5.7	5.2
C_{11}	6.4	2.5	4.1
C_{12}	8.1	4.7	9.1
C_{13}	3.7	2.9	1.8
C_{14}	7.9	6.1	6.3
C_{15}(+)	38.4	36.5	37.7
Naphthenes	7.1	21.4	7.9
Aromatics	2.9	0.8	0.6
Other compounds	9.7	3.6	16.6

Table 7
Compounds identified in the liquid fraction of the catalytic pyrolysis of HDPE waste product (wt.% on liquid fraction)

Carbon number	n-Alkanes	n-Alkenes	*iso*-Alkanes	*iso*-Alkenes	Naphthenes	Aromatics	Total
C_6				0.5	0.1		0.6
C_7	0.2	0.2	0.3	1.4	0.5		2.6
C_8		2.5	2.4	1.4	0.3	1.5	8.1
C_9	0.3	0.5	2.4	2.7	1.2	1.4	8.5
C_{10}	0.7	0.8	2.3	1.6	1.1	2.4	8.9
C_{11}		3.1	3.2	0.8	0.2	0.4	7.7
C_{12}	1.3	6.0	2.4	1.2	0.5		11.4
C_{13}	0.9	3.0	2.1	0.5	0.3		6.8
C_{14}	1.6	10.2	0.5		0.2		12.5
C_{15}	1.9	2.9	0.9		0.2		5.9
C_{16}	0.8	6.5	0.2				7.5
C_{17}	0.7	0.4					1.1
C_{18}	0.2	1.4	0.2				1.8
C_{19}	0.8	1.9					2.7
C_{20}	1.6	0.5					2.1
Total	11.0	39.9	16.9	10.1	4.6	5.7	88.2

Table 8
Compounds identified in the liquid fraction of the catalytic pyrolysis of LDPE waste product (wt.% on liquid fraction)

Carbon number	n-Alkanes	n-Alkenes	*iso*-Alkanes	*iso*-Alkenes	Naphthenes	Aromatics	Total
C_6				4.4	0.6		5.0
C_7		0.8	4.8	6.0	1.6		13.2
C_8		3.9	5.3	7.0	2.7	5.2	24.1
C_9	0.3	1.7	3.5	4.4	3.6	9.0	22.5
C_{10}	0.2	1.9	2.2	2.4	1.2	7.6	15.5
C_{11}		0.9	4.2	1.0	1.8	3.8	11.7
C_{12}	0.1	1.4	0.3	0.6	0.3	0.2	2.9
C_{13}	0.1		1.1	1.0			2.2
C_{14}		0.1		0.3			0.4
Total	0.7	10.7	21.4	27.1	11.8	25.8	97.5

material. Thus, higher decomposition was observed in PP, followed by LDPE and finally HDPE. It seems that less crystalline or more branched polymers are less stable in thermal degradation. Furthermore, since the employed waste product based on LDPE (i.e. a plastic bag) was very thin, its degradation was better and a high liquid yield was measured. The composition of the gaseous product is not so much dependent on the polymer type, as it is illustrated in Table 5. It was observed that cracking of all model polyolefins do not lead to the production of either CO or CO_2, since there are not any oxygen atoms in their

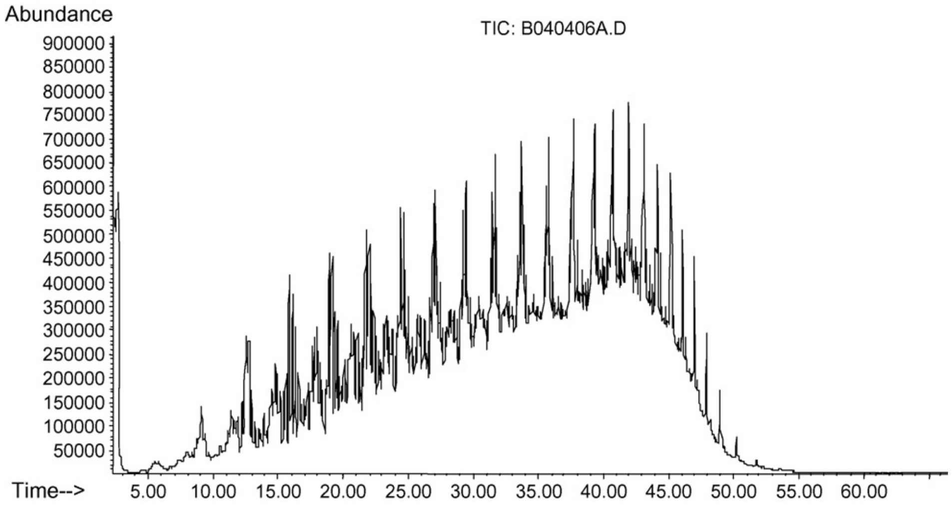

Fig. 3. GC–MS chromatogram of the liquid fraction obtained from model HDPE pyrolysis.

macromolecules. However, some quantities were measured in the waste products since they contain additives, which probably include oxygen atoms. Moreover, in all polymers examined a series of alkanes and alkenes were produced from C_1 to C_5 with the greater percentage for all samples observed at C_4.

Finally, the compounds identified in the liquid fraction from pyrolysis of model polymers appear in Table 6. A mixture of hydrocarbons was determined for all three samples in the region of commercial fuels. The main part consisted of aliphatic compounds (normal and *iso*-alkanes and *iso*-alkenes), with only a small proportion of aromatic substances. This again is due to the rather low pyrolysis temperature. Furthermore, a detailed list of all hydrocarbons detected in the liquid fraction of pyrolysis of waste products based on HDPE and LDPE appear in Tables 7 and 8, respectively. It was observed that pyrolysis of the plastic bag made from LDPE leads to a fraction mainly in the region of C_7–C_{12}, which is in the gasoline region. Also, the main components were *iso*-alkanes or *iso*-alkenes. In contrast, in the HDPE based waste product higher hydrocarbons were also detected and the main components were normal alkenes.

A typical GC–MS diagram for the liquid fraction taken from model HDPE pyrolysis is illustrated in Fig. 3. Characteristic lines for hydrocarbons with different number of carbon atoms appear. Also it is clear that these are not single lines, meaning the existence of alkanes, alkenes and alkadienes having the same number of carbon atoms.

4. Conclusions

The chemical recycling of LDPE, HDPE and PP was examined by both a dissolution/reprecipitation technique and pyrolysis. The first leads to high recovery of polymer with the disadvantage of using large amounts of organic solvents. From the FT-IR spectra of the samples before and after recycling and the measurements of the tensile mechanical properties it was found that the product recycled is almost identical to the virgin polymer. Furthermore, pyrolysis was investigated as a promising technique for thermochemical recycling of these polymers. The oil and gaseous fractions recovered presented a mainly aliphatic composition consisting of a series of alkanes and alkenes of different carbon number with a great potential to be recycled back into the petrochemical industry as a feedstock for the production of new plastics or refined fuels. Very interesting was the pyrolysis of plastic bags made from LDPE, were the liquid fraction consisted by hydrocarbons in the range of commercial gasoline. This research is continued further by examining mixtures of polyolefins, or other polymers.

Acknowledgement

This work was funded by the E.K.T./E.P.E.A.E.K. II in the framework of the research program PYTHAGORAS II, Metro 2.6. (Code 80922).

References

[1] http://www.plasticseurope.org.
[2] http://www.apme.org.
[3] J. Scheirs, Polymer Recycling, J. Wiley & Sons, W. Sussex, 1998.
[4] D.S. Achilias, G.P. Karayannidis, The chemical recycling of PET in the framework of sustainable development, Water Air Soil Pollut. Focus 4 (2004) 385–396.
[5] G.P. Karayannidis, D.S. Achilias, Chemical recycling of poly(ethylene terephthalate), Macromol. Mater. Eng. 292 (2007) 128–146.
[6] J. Aguado, D.P. Serrano, in: J.H. Clark (Ed.), Feedstock Recycling of Plastic Wastes, The Royal Society of Chemistry, Cambridge, 1999.
[7] D.S. Achilias, P. Megalokonomos, G.P. Karayannidis, Current trends in chemical recycling of polyolefins, J. Environ. Prot. Ecol. 7 (2006) 407–413.
[8] W. Kaminski, B. Schlesselmann, C. Simon, Olefins from polyolefins and mixed plastics by pyrolysis, J. Anal. Appl. Pyrol. 32 (1995) 19–27.
[9] A. Uddin, K. Koizumi, K. Murata, Y. Sakata, Thermal and catalytic degradation of structurally different types of polyethylene into fuel oil, Polym. Degrad. Stab. 56 (1997) 37–44.
[10] G. Manos, I. Yusof, N.H. Gangas, N. Papayannakos, Tertiary recycling of polyethylene to hydrocarbon fuel by catalytic cracking over aluminum pillared clays, Energy Fuels 16 (2002) 485–489.
[11] D. Serrano, J. Aguado, J. Escola, J. Rodriguez, G. San Miguel, An investigation into the catalytic degradation of LDPE using Py-GC/MS, J. Anal. Appl. Pyrol. 74 (2005) 370–378.
[12] C.D. Papaspyrides, J.G. Poulakis, P.C. Varelides, A model recycling process for low density polyethylene, Res. Conserv. Recycl. 12 (1994) 177–184.
[13] J.G. Poulakis, C.D. Papaspyrides, Recycling of polypropylene by the dissolution/reprecipitation technique: I. A model study, Res. Conserv. Recycl. 20 (1997) 31–41.
[14] J.G. Poulakis, C.D. Papaspyrides, The dissolution/reprecipitation technique applied on high-density polyethylene: I. Model recycling experiments, Adv. Polym. Techn. 14 (3) (1995) 237–242.
[15] G. Pappa, C. Boukouvalas, C. Giannaris, N. Ntaras, V. Zografos, K. Magoulas, A. Lygeros, D. Tassios, The selective dissolution/precipitation technique for polymer recycling: a pilot unit application, Res. Conserv. Recycl. 34 (2001) 33.