TEMPERATURE AND TIME INFLUENCE ON THE WASTE PLASTICS PYROLYSIS IN THE FIXED BED REACTOR

by

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Pyrolysis as a technique of chemical recycling of plastic materials is causing an increasing level of interest as an environmentally and economically acceptable option for the processing of waste materials. Studies of these processes are carried out under different experimental conditions, in different types of reactors and with different raw materials, which makes the comparison of different processes and the direct application of process parameters quite complex. This paper presents the results of investigation of the influence of temperature in the range of 450-525 °C, on the yield of the process of pyrolysis of waste plastics mixture, composed of 45% polypropylene, 35% low density polyethylene, and 25% high density polyethylene. Also, this paper presents results of the investigation of the effect of the reaction, at intervals of 30-90 minutes, on the yield of pyrolysis of the mentioned waste plastics mixture. Research was conducted in a fixed bed pilot reactor, which was developed for this purpose. The results of the research show that at a temperature of 500 °C, complete conversion of raw materials was achieved, for a period of 45 minutes, with a maximum yield of the pyrolysis oil of 32.80%, yield of the gaseous products of 65.75%, and the solid remains of 1.46%. A further increase of temperature increases the yield of gaseous products, at the expense of reducing the yield of pyrolysis oil. Obtained pyrolysis oil has a high calorific value of 45.96 MJ/kg and in this regard has potential applications as an alternative fuel.

Key words: *pyrolysis, fixed bed reactor, waste plastic, process temperature*

Introduction

As the result of the continuous increase in the consumption of plastic materials in most countries including Bosnia and Herzegovina, the trend of a continual increase of plastic waste is present too [1]. The annual production of plastic materials in 1950 was 0.35 million tons, and since then, there has been a continual increase trend. According to data from 2011, plastic materials production was 250 million tons [2]. Today in Europe, most types of plastic are polyolefin polymers, polypropylene, PP (19%), low density polyethylene, LDPE (17%), and high density polyethylene, HDPE (12%) respectively, with the largest use of the plastics being for packaging; around 39.4% [2]. According to the official European statistics, the EU member countries average an annual production of plastic at 159.4 kg per person, whereas the share of waste plastics in the total packaging waste is 19% [3]. According to domestic official statistics, the total quantity of the produced and collected communal waste in the Republic of

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Srpska in 2012 was 376 438 t, and 250 223 t, respectively, whereas packaging waste was 445 t or 0.2%, and detailed data about the quantities and the waste plastic types does not exist [4-6]. However, it is possible to say that as in the other countries, the most recyclable packaking waste available on the market consists of HDPE, LDPE, PP, polyethylene (PET), polyvinylchloride (PVC), and polystyrene (PS) [7].

Most of the plastic material is not biodegradable and has a low density, which makes its disposal in landfills, undesirable [8]. One of the chemical recycling techniques for the plastic materials is pyrolysis, which is causing increasing interest as an environmentally and economically acceptable option for waste materials treatment. Pyrolysis is defined as a thermochemical process of the organic material degradation due to heating in an inert atmosphere. Depending on the applied technology, the process can be guided in a way to get a synthetic fuel, or to produce gaseous and liquid products which can be used in the petrochemical industry and coke production as a raw material for gasification [9].

Research of plastic pyrolysis processes are carried out in different experimental conditions as well as with different reactor types, different types of plastic materials, pure or waste materials, with the aim to get optimal content and quantity of liquid products. Experiments are mostly related to pyrolysis of the specific types of plastic materials or their mixtures, different shares of the materials as well as different raw material particle granulations. [10-16]. All of this makes the comparison of the processes complicated, and causes variations in the published results. A review of the variations in the published results was given by Jung and Fontana [17].

Experiments were frequently provided by using small samples, in autoclaves or specially dedicated devices predicted for thermo-gravimetric (TG) analysis, in conditions which do not have limitations in heat transfer to sample particles in the implementation of TG analysis. In the study of synthetic polymers and waste plastics pyrolysis on samples of 15-75 mg, it was mentioned that the obtained results should be carefully implemented in the industrial processes [18]. The result of the experiment with a mixture of PE, PP, and PS in the batch micro reactor with a volume of 30 mL, showed that the maximum yield of liquid phase was achieved at the temperature 750 K (477 °C), which suggested that there was the need for additional investigations on bigger pilot experimental set-ups, particularly in a case of work with the mixtures of waste plastics [19]. In other research, provided by Kaminsky and Zorriqueta [20] a batch micro reactor with a volume of 100 mL, it was found that at 400 °C, more than 40% of the PP samples did not react, while at 500 °C, 98% of the samples passed the pyrolysis process. Adrados *et al.* [15] were investigating pyrolysis of the waste plastics mixtures at a fixed temperature of 500 °C at a time of reaction of 60 minutes, in the fixed bed reactor with volume of 3.5 L and with a typical method of the plastic mixture heating in the reactor, through the reactor wall.

Thus one can conclude that additional investigation of pyrolysis in the fixed bed reactor exists, especially in the pilot reactors having additional limitations, compared to the laboratory micro reactors, in which the influence of heat transfer to raw material can be disregarded. It should be mentioned, beside this paper dial with pyrolysis in fixed bed reactor that the fluidized bed reactors are one of the most used reactors types for the pyrolysis of plastic materials, which is particularly interesting due to possibilities of obtaining continuous and isothermal process conditions [20-23].

In this paper are the results of the investigations of the temperature and time of the reaction on the yield of the pyrolysis on the mixtures of waste plastics (PP, LDPE, and HDPE), in the pilot fixed bed reactor, particularly developed for this purpose. The results determine the initial temperature and time intervals in which investigations were carried out.

Most of the researchers in choosing the temperatures for providing experiments start from TG results, respectively derivative TG (DTG) analysis, where it is possible on the base of obtained results to notice the temperature intervals of thermal decompositions. Regarding the reaction time, commonly a long enough interval is chosen, in order to expect maximum plastic degradation on selected temperatures. In available literature it is possible to find a lot of published TG and DTG analysis of the plastic materials pyrolysis process, which differs according to different experimental conditions [15, 16, 18-20, 24, 25]. Investigations provided by Norway University for Science and Technology of pyrolysis of the individual plastic types (HDPE, LDPE, PP, and PS) were carried out in temperature intervals 350-500 °C with a maximum rate in the interval of 413-479 °C [26].

Similar results were published by other authors, as in the investigation of Sharypov *et al.* [27] it was quoted a temperature of 500 °C as a finish of the thermal degradation of PE, and temperatures 488 °C, and 494 °C for PP (atactic PP), respectively, i-PP (iso-atactic PP). Also, DTG curves presented in the paper of Lopez *et al.* [16] suggested similar temperature intervals for individual types of plastic materials, and also additionally analysed plastic waste mixtures (PP, PE, PS, PVC, and PET) and it was quoted that the total pyrolysis of this mixture finished at 500 °C. According to the TG pyrolysis curves of individual plastic samples (HDPE, LDPE, and PP), provided on 5 mg samples and during a heating rate of 20 K per minute, pyrolysis of HDPE takes place in the interval of 438-509 °C, with a maximum rate on 492 °C and pyrolysis of PP taking place in the interval 447-503 °C, with a maximum rate on 496 °C [28].

These analyses were used as a basis for the setting of the experiments in the fixed bed laboratory reactor.

Experiments

Selection and preparation of the samples

As a material for the investigation, the three most common waste plastic types were used (PP, LDPE, and HDPE), their characteristic composition in the municipal waste: PP 40%, LDPE 35%, and HDPE 25%, respectively. Official statistics do not present data about waste plastic composition in the municipal waste, so that for the determination of mass ratios in the mixture of plastic waste, average values from EU Counties were used [2]. According to these statistics, the three most common plastic types are: PP 19%, LDPE 17%, and HDPE 12%, respectively, in percentages for the mixture PP+LDPE+HDPE: PP 40%, LDPE 35%, and HDPE 25%. For the PP and HDPE samples packaging waste was used, while for the LDPE sample, plastic bag production granules were used. Packaging waste was washed first, and then fragmented and milled in a laboratory mill and after that a PP and HDPE mixture was prepared. Prepared mixture was analysed for granulometric composition and an average particles diameter was determined, which was 1.40 mm. After that, a prepared mixture of PP and HDPE was mixed with LDPE granules of cylindrical shape (2.20 × 5.03 mm), acceding to above determined mass ratios.

Investigation methodology and experiments description

Pyrolysis process investigations were carried out on the pilot experimental set-up with the fixed bed reactor in the Laboratory for Ecological Engineering at Faculty of Technology Banja Luka. Schematic description of the set-up is presented in fig. 1.

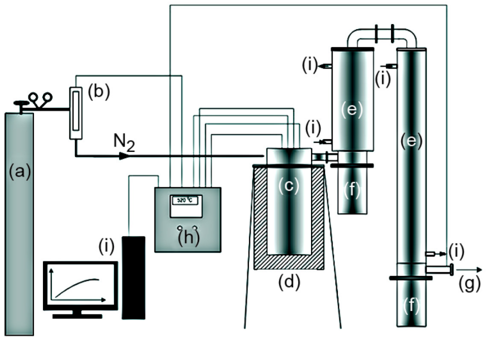

Figure 1. Schematics of the laboratory pilot set-up for pyrolysis process investigation; *(a) nitrogen, (b) gas flow meter, (c) pyrolysis reactor, (d) thermal insulation, (e) system for the vapours condensation, (f) separation system – vessels for condensate acceptance, (g) non-condensable gases outlet in the gases washing system, (h) distribution cabinet for regulation system, (i) PC*

A previously prepared and weighted sample was immersed in the reaction vessel (*c*), after that nitrogen as carrying gas and inert media was let into the system (*a*), which has a role of establishing an inert atmosphere and role of carrier gas. By using measuring-regulator (*b*) gas flow was adjusted to 100 mLn per minute, and after 10 minutes an inert atmosphere was achieved. By using PC (*i*) and adequate program package automatization and regulation of the system (*h*) switching on electric heaters system (*c*), which heats the reaction mixture. For all implemented experiments thermocouple, T_1, which measured temperature in the bottom part of the reactor was a control sensor for the regulation of the electric heaters. At achieving the previously defined reactor temperature, the time which raw material spent on a defined temperature represents the time of the reaction. After a defined time, the regulation system is switched off and after the reactor's temperature dropped below 100 °C, the reactor was taken apart, the reaction dish was disconnected from the reactor (*c*), after that the dish was weighed and solid residue was determined. The vessel for condensate acceptance (*f*) was disconnected too, and weighed in order to determine mass of condensable products, including a part of the condensate products mass from internal walls (*e*) of the condensate vessel. Small amounts of condensate could be left in the pipe system between two condensers (e), and between condenser and the reactor, but due to relatively large sample of row material (200 g), this could be neglected.

The gas phase yield, $m_{G,}$ has been determined from the mass balance as a difference between the mass of raw material, $m_{R,}$ and the summary mass of the liquid phase, m_L, and the mass of the solid residues, m_S:

$$m_G = m_R - m_L + m_S \tag{1}$$

All measurements were repeated three times, and the results presented in the table are average, arithmetic values of those three measurements.

Reactor temperature changes can be traced in three characteristic points. All temperatures were measured by using thermocouples K-type and recorded by using Omron's package *CX-Thermo*. The regulation of electric heaters work, respectively temperature control, was solved by use of Omron's temperature controller CelciuX (EJ1N-TC4A-QQ),with preciously adjusted PID constants, and definition of mentioned constants as well as other characteristic parameters in the regulation system, also by using package *CX-Thermo*. Inert gas flow was measured by using mass flow meter *Brokkhorst*, model MASS-VIEW MV-304, which has an additional option of fine adjustment of the gas flow in the range 0.04-20 Ln per minute. Pure, 99.9% nitrogen (N_2) was used as a carrier gas. The heat content of the produced fuels was measured by using calorimeter *Parr Instrument Company*; *model 6400 Automatic Isoperibol Calorimeter*, by use of dynamic method of measurement. Qualitative analysis of the produced fuels was carried out by using FTIR spectroscopy (*FTIR 1600 Perkin Elmer*), method: CEI IEC 590.

Results and discussion

Initial selection of temperature and time of the reaction

For the initial experiments, temperatures of 400 °C and 500 °C were chosen, taking into consideration results TG and DTG analysis that maximum velocities of thermal degradation can be expected between these mentioned temperatures [19, 20, 24]. Regarding reaction time; for the initial experiment a time of 60 minutes was selected, considering that this given time is enough to enroll full thermal degradation at the chosen temperature. In the further experiments reaction time was varied between 30 and 90 minutes with the aim to achieve optimum values in a sense of maximum yield of liquid phase (pyrolysis oil) and maximal conversion of the raw material.

Figure 2 shows the results of the initial experiments. It can be noted that on the initial selected temperature of 400 °C, a large part of the raw material stayed unreacted (39.86%), while at the temperature of 500 °C practically all raw material was reacted (only 1.43% of solid residue stayed in reactor), which is adequate to the results of the individual waste plastic samples technical analysis (annealing on 750 and 900 °C), which shows residue in the form of ash, 0.8% for PP, and HDPE 0.54% [29]. This solid residue in the reactor is a bit higher value than ash from technical analysis, but it should be taken in to consideration that in this case, waste plastics samples can have different quantities of inorganic additives.

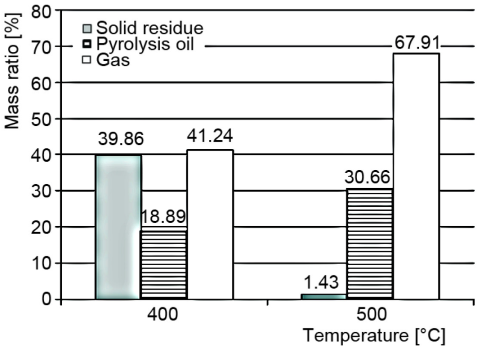

Figure 2. Pyrolysis of plastic mixture during reaction time of 60 minutes (N_2 flow is 0.5 Ln per minute, heating velocity 12 K per minute)

Temperature influence on the plastic pyrolysis

To investigate the influence of the reactor temperature on the pyrolysis process yield, temperature intervals of 450-525 °C, were selected. A temperature of 450 °C was selected as an initial value, because from this value, higher rates of degradation can be expected. It was shown, from the previous experiments, that at a temperature of 400 °C and a time of 60 minutes, a relatively low ratio of the raw material conversion was achieved, with a solid residue of 40% (39.86%). For the final temperature of the process, a temperature of 525 °C was chosen, because the thermal degradation process of all plastic materials ended below that value. This choice of temperature interval is in accordance with the results of numerous TG and DTG analysis of the maximal rate of thermal degradation of the investigated polymers [26-28]. Figure 3 shows the influence of temperature on pyrolysis process yield from the reactor on the investigated samples.

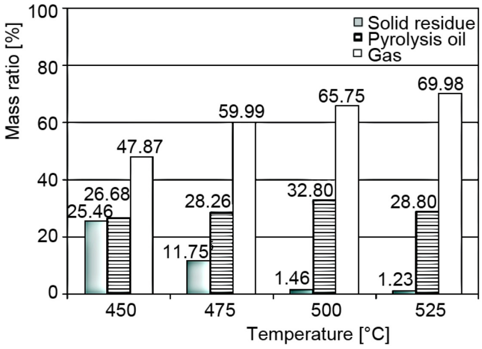

Figure 3. Influence of the reactor temperature on the plastic pyrolysis during a time of 45 minutes (N_2 flow was 0.5 Ln per minute, heating rate 12 K per minute)

Figure 3 shows that also at a temperature of 450 °C, a significant amount of the raw material stays unreacted (25.46%), and due to that, experiments on lower temperatures were not carried out.

An increase of raw material conversion with a temperature increase is obvious, while a maximum yield of liquid phase (pyrolysis oil) is obtained at 500 °C. There is a negligibly small increase of raw material conversion at 525 °C compared to conversion at 500 °C, simultaneously reducing the yield of pyrolysis oils in favour of increasing the yield of gaseous products. This can be explained, as on higher temperatures secondary reactions start to dominate reactions during which further cracking of molecular chains appears, and during this process shorter molecular emerge, respectively non-condensable gases. Similar behaviour was noticed by the other authors. Demirbas [19] in his work has quoted that with the increase of temperature in the investigated interval 550-900 K gaseous products yield also increases, from 12.3-42.4%, in the investigated plastic mixture (PP, PE, and PS). Liquid products yield also increased up to 750 K (477 °C), and after that slightly declines (up to temperature 900 K). This trend is slightly different to the results shown in fig. 3, due to the different nature of raw material. Achilias *et al.* [30] in their paper, dealing also with pyrolysis of individual plastic types (PP, LDPE, and HDPE) in the reactor with a fixed bed, but with a relatively small sample of 0.7 g, were shown that on an investigated temperature of 450 °C, during a time period of 17 minutes, a relatively small conversion was achieved (LDPE 76.4% solid residue, HDPE 76.7% solid residue, and PP 46.6%). This is significantly small compared to the achieved results from this investigation of the mixture at 450 °C (fg. 3), where the solid residue was 25.46%, but in a time period of 45 minutes. One can assume that such distinction in achieved degree of conversion is as a consequence of different reaction times. The results of the pyrolysis of synthetic and waste PP investigation in the laboratory batch fixed bed reactor, shows that at 500 °C, a yield of approximate 80% condensable products was achieved, but these results were achieved also in the experiments with relatively a small mass of the samples (20 g of raw material) [31]. In a study performed in a half-batch reactor of the HDPE plastics in non-isothermal conditions, it was mentioned that with the decrease of reactor temperature from 495 °C to 450 °C activation energy decreases for 20% [32]. Adrados *et al.* [15] and Lopez *et al.* [16] in the already mentioned pyrolysis reactor, investigated a mixture of pure synthetic polymers (PP 40%, PE 35%, PS 18%, PVC 3%, and PET 4%) and noticed that total conversion was achieved already at 460 °C, but due to better quality products, a temperature of 500 °C was recommended as the one at which a liquid products yield of 65.2% is achieved. Also, the same group of authors were investigating pyrolysis of waste plastic mixture at a fixed temperature at 500 °C within a reaction time of 60 minutes, and during this process a yield of 40.9% liquid product was achieved [15]. This is approximately the same as the achieved result at 500 °C which is 32.8% of liquid phase (fig. 3), and it is necessary to emphasize that samples of plastic material pure-synthetic or waste can produce different results under the same process condition which was also mentioned by some other authors [13, 15]. Thus *e. g.* some data shows that at a fixed temperature of 500 °C, and at a fixed time of 60 minutes, during pyrolysis of the mixture of pure, clean synthetic plastics (HDPE, PP, PS, PET, and PVC), 48.7% of liquid products was yielded, while the mixture of the same composition, but waste plastics obtained from German DSD recycling system, liquid phase yield was 32.5%, while from the same plastic waste mixture from Belgian system *Fros Plus*, liquid products yield was 64.1% [13]. Influence of the plastic mixture composition on the liquid products yield is specifically expressed in the presence of PS. During pyrolysis of PS due to a structure within a stable benzene ring, a higher yield of liquid products can be achieved and at the same time a lower yield of gaseous products during pyrolysis of poly-olefin polymers (PE, PP) with a plain carbon structure, without a benzene ring. Macromolecules of PS were less cracked in to gaseous products with five or less C atoms, so distribution of the products is dependent on the plastic type [33].

It can be concluded that liquid products yield, as well as the conversion of raw material, depends on: experimental conditions (process parameters), raw material type (waste or clean, synthetic plastics), the content of raw material (mixture or individual plastic types), mixture content, pyrolysis reactor type, size of the sample's particles, and the time of the reaction. Due to that, for each individual system or pyrolysis plant, it is necessary to clearly define the previous mentioned parameters, and investigate adequate yield.

In the investigated laboratory pyrolysis set-up, with a fixed bed and characteristic heating of plastic material mixture, optimal temperature of the reactor in a sense of maximum liquid products yield was 500 °C within a time of 45 minutes.

Influence of the reaction time on the waste plastic pyrolysis process

Considering the results of the previous experiments, respectively a maximum conversion of the raw material at temperature of 500 °C, for the study of reaction time influence on the investigated plastics pyrolysis process, a fixed temperature of 500 °C was selected. Also in a research of Adrados *et al.* [15] and Lopez *et al.* [16] it was mentioned that a fixed temperature of 500 °C, is optimal for the study of time of the reaction influence on the pyrolysis of plastic materials. The time of the reaction was varied between 30-90 minutes, during a fixed nitrogen flow of 0.5 Ln per minute and a fixed heating rate of 12 K per minute. The results of provided experiments are shown in fig. 4.

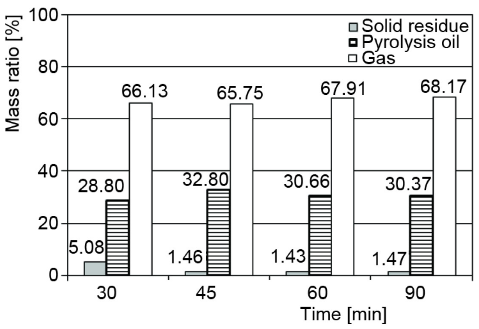

Figure 4. Reaction time influence on the plastic waste pyrolysis at a temperature of 500 °C (N_2 flow 0.5 L_N per minute, heating rate 12 K per minute)

Figure 4 shows that during the reaction time of 45 minutes, a total conversion of plastic material was achieved with a release of gaseous and liquid – condensable products. During the defined experiment conditions, a negligible change of solid residue mass, which was 1.46% in 45 minutes, and 1.47% in a time of 90 minutes, was noticed. Maximum yield of condensable products (pyrolysis oil) was also noticed, 32.80% in the reaction time of 45 minutes. With further increases of reaction time, no significant changes in a raw material conversion and gas and liquid products yield were noticed. Thus, it is possible to conclude that a reaction time of 45 minutes is sufficient for the total conversion of the raw material at a temperature of 500 °C, in this characteristic reactor system. Other authors mentioned different times, *e. g.* in the fixed bed reactor with a volume of 3.5 L and typical plastic mixture heating trough reactor wall, that for investigated mixture (PP, PE, PS, PVC, and PET) a sufficient time for total conversion is 30 minutes [16]. In some other typical laboratory reactors (Parr Mini Bench Top Reactor, Type 4561 m), autoclave with volume 300 ml, with mixer and under pressure of 19.5 MPa waste plastic mixture was investigated (HDPE, PP, PS, PET, and PVC), at a fixed temperature of 500 °C, and a fixed reaction time of 60 minute, but the eventual influence of the reaction time change was not investigated [13]. It is obvious that the need for additional investigations exists, particularly in the pilot reactors, which have additional limitations compared to the laboratory micro reactors in regard to the influence of heat transfer mechanisms on raw material, taking into consideration that this kind of reactor is dealing with small samples.

In the most studied researches of the waste plastics pyrolysis, the reaction time influences were not investigated, instead of that, the usual approach was to take a period which is long enough, during which maximal decomposition at a chosen temperature was expected. This means, for each characteristic reaction system it is necessary to determine the optimal, *i. e.* minimal, time necessary for the total conversion of raw material. This is very important from the aspect of a reduction in energy costs for such a system.

Heating value of pyrolysis oil and possibility of use for energy purposes

Samples of pyrolysis oil produced form the experiments at selected optimal experimental conditions (reaction time 45 minutes, temperature 500 °C, and inert gas flow 0.5 Ln per minute, were analysed in a calorimeter in order to determine the heating value as well as FTIR spectroscopy analysis. Produced pyrolysis oil has a heating value of 45.9603 ±0.15 MJ/kg, which is a bit higher than heating values of high quality coals, as well as the heating value of crude oil (44 MJ/kg) [34]. The other authors dealing with the same subject, have cited similar heating values, for example heating value of the pyrolysis oil produced from a commercial, rotary kiln reactor is 44.832 MJ/kg [35], and 44.340 MJ/kg, respectively [36].

Analysis of pyrolysis oil

The results of FTIR spectroscopy analysis, shows the following content of carbohydrates in mass percentages: aromatic compounds 11.49%, paraffins 82.11%, and naphthens 6.40%. These results are different from other author's results that were analysed of waste plastic pyrolysis. Thus *e. g.* during pyrolysis of plastic mixture (40% PE, 35% PP, 18% PS, 4% PET, and 3% PVC) in the fixed bed reactor, it was mentioned that results of GC-MS indicates a significant share of aromatics, (aromatic compounds 73,9%, non-aromatic compounds 22.3%, and non-identified components 3.9%) [16]. It was mentioned that beside the fact that raw material comprises mainly from long saturated hydrocarbons (PE and PP), in obtained liquid products there were no paraffin, differing to the results presented in this paper where a high yield of paraffin of 80.32% in pyrolysis oil were observed. This absence of paraffins can be explained by this, in that during polymers macro-molecules cracking, a large number of radicals were formed that have to be stabilized, which happens by: (1) the forming of double bond generating olefins; (2) combining each other with the emergence of cyclic structures *i. e.* naphthenes; (3) releasing of hydrogen being later transformed into highly unsaturated products or aromatics. It is also necessary to emphasize that at the same time other authors mentioned the occurrence of aliphatic compounds and naphthenes as dominant products [37, 38], cited in [16].Thus, it can be assumed that in a developed pilot reactor, after the initial decomposition of waste plastics, *i. e.* the primary cracking reactions of macro-molecules chains, products leave the reactor relatively quickly and enter into the area with low temperatures (condensation system) together with carrier gas, and due to that, there is no time for the occurrence of the reaction according to above presented mechanism, in a larger extent. This is in accordance with earlier ascertainment, that the process is strongly dependent on the reactor design and the applied parameters.

Conclusions

On the basis of provided research of the waste plastics mixture pyrolysis (PP 40%, LDPE 35%, and HDPE 20%) in a developed pilot fixed bed reactor, the following can be concluded.

- By careful selection of the process parameters, temperature and reaction time, it is possible to achieve total conversion of the waste plastics mixture in to the liquid and gaseous products.
- Selection of an adequate time for total conversion of raw material primarily depended on the design of the reactor and due to that it is necessary for every investigated system to determine its optimal time as a process parameter.
- The optimal temperature to achieve the total conversion of investigated raw material and a maximal yield of pyrolysis oil is 500 °C, over a duration of 45 minutes and a flow of inert gas (N_2) of 0.5 Ln per minute, to give a yield of 65.75% of gaseous products and 32.80% of liquid product (pyrolysis oil).
- With an increase of temperature over 500 °C yields of gaseous products increase up to a maximal 69.98% at a temperature 525 °C, and yield of pyrolysis oil decreases.
- Produced pyrolysis oil has a potential for energy purposes use due to its high heating value (45.9603 ± 0.15 kJ/kg), which is close to the heating value of high quality coals (43 MJ/kg), and heating value of crude oil (44 MJ/kg).
- Produced pyrolysis oil contains: 11.49% of aromatic 82.11% of paraffins, and 6.40% naphthenes, and has a lower level of aromatics then expected values. According to the other authors citations, this be explained by the fact that primary pyrolysis products leave the reactor relatively quickly, together with carrier gas, and due to that there is not enough time for the further reaction development, ensuring aromatic compounds production.

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