

Optimisation of Jet Fuel Production from Waste Polypropylene in Conical Reactor

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Abstract

Traditional liquid fuel, such as kerosene, is still the primary fuel in air transport for longer distances. Other types of propulsion, like electric batteries, fuel cells, or their combination with solar panels, are only practical for smaller aeroplanes designed for transportation purposes. In order to replace at least some fossil kerosene with waste raw materials, kerosene production from waste polyalkenes has become more important. This work investigates the possibility of using a laboratory continuous conical spouted bed reactor for the study of the production of jet fuel fraction from waste polypropylene. Optimal reaction conditions of cracking for producing high yields of hydrocarbon liquids were determined. Tested pyrolysis temperatures changed from 420 to 460°C, and CO₂ flow from 0.05 to 0.2 L.min⁻¹ at various polypropylene dosing speeds. Yields and composition of liquid and gaseous products were measured. Monomer propene dominated with almost 60 wt% in pyrolysis gases. The highest yield of jet fuel fraction, 34 wt%, was obtained at 420°C and 0.1 L.min⁻¹ of inert gas flow.

Keywords: Pyrolysis; Polypropylene; Optimization; Semi-continues; Jet fuel; Conical reactor.

1. Introduction

The amount of plastic waste is growing each year. In 2019, 53 million tons of new plastic production were estimated in the European Union [1]. Therefore, there is a high demand for suitable recycling solutions for plastic end-of-life products. Mechanical recycling represents one of the different recycling ways. The advantage of mechanical recycling is the low energy consumption and wide use for streams of one-type plastics [2-4]. Mechanical recycling also has a disadvantage [5], which is, in this case, a high demand for feedstock quality if the product wants to maintain its high value. There is mechanical recycling that can treat a mixed plastic feedstock. However, the products of this recycling have a lower value due to unpredictable properties, and they can only be used to produce lower-value products.

Pyrolysis is one of the plastic recycling methods that can handle feedstock of various plastic types and changes in quality. Pyrolysis has advantages and disadvantages, opposite to mechanical recycling. Pyrolysis is often less dependent on feedstock quality, but its energy consumption is significantly higher than mechanical recycling [5]. The composition and yields of chemical recycling products vary according to the conditions used in pyrolysis. They are gases, liquids, or solid products, or their combination [6]. The main goal of chemical recycling is to obtain valuable chemicals with high value. Some researchers are focused on obtaining monomers to produce new plastics [7-9]. Other researchers are focused on obtaining liquid products that can be used as fuels [10-14].

For pyrolysis, many types of reactors are used. Some have been used widely in the industry and also for other types of use for many years, such as mixed reactors [12], fluid beds [7], circulating fluid beds, and auger reactors [15]. Some, such as the ablative, cyclonic, rotary kiln [16] and the rotating cone reactor [17], were specially designed and optimised for plastic waste

recycling, considering their specific characteristics. Each reactor has its advantages and disadvantages. In some cases, it is preferable to have a simple design. In other cases, a more complex design can better solve problems connected with feedstock treatment, as can contamination or solid additives.

It is crucial to determine the optimal production parameters for every type of reactor. Many vital parameters include temperature, feedstock flow, feedstock temperature, and inert gas flow. Optimisation of these parameters is essential to obtain preferred products. This paper focuses on using our conical reactor to obtain plane jet fuel. This paper investigates the possibility of using a new laboratory continuous conical spouted bed reactor to produce a jet fuel fraction from waste polypropylene. Optimal reaction conditions of cracking to produce high yields of hydrocarbon liquids were determined using native polypropylene to ensure a feedstock of constant composition.

2. Experimental

2.1. Materials

Native polypropylene obtained from Slovnaft a.s., Slovakia, was used to ensure the constant composition of the plastic feedstock during experiments (Table 1). As an inert gas, carbon dioxide purity 99.5 vol% from Messer Tatragas, s.r.o. was used.

Table 1. Selected properties of native polypropylene.

Properties	Method	Measurement units	PP homopolymer native
Melt flow index (230°C/2.16kg)	STN EN ISO 1133-1	g/10min	3.73
Crystallization temperature	STN EN ISO 11357-3	°C	116.5
Melting temperature	STN EN ISO 11357-3	°C	164.5

Thermal decomposition of PP was investigated by thermogravimetry on a Perkin Elmer TGA 4000 Thermogravimeter. The measurement took place in the temperature range of 50 to 800°C (10°C/min) in a nitrogen atmosphere at a pressure of 3 bar in three repetitions. The thermogravimetric curves in Fig. 1 (weight loss of the sample as a function of temperature) show a rapid decomposition typical for polyolefins. The induction period was followed by one major decomposition step, with decomposition temperatures of (363.6, 373.4, 382.5) °C for

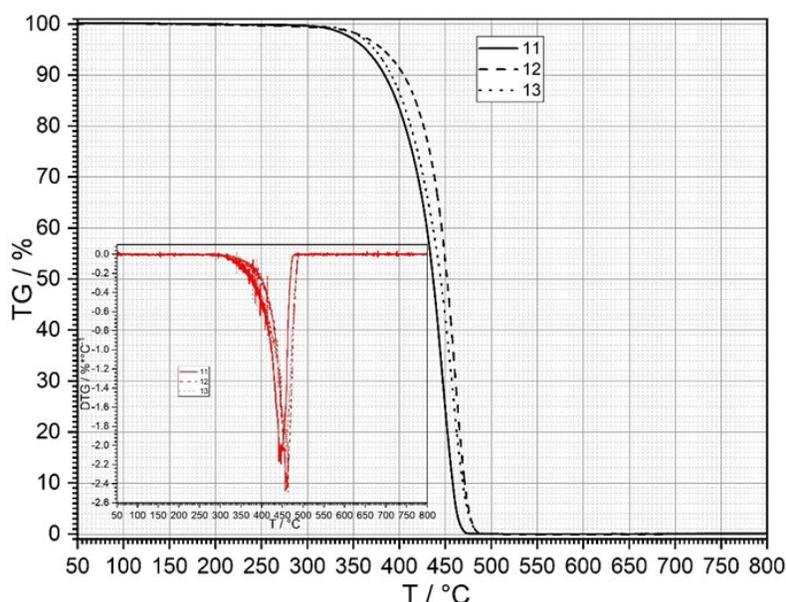


Fig. 1 TGA analysis of native polypropylene.

5 % mass loss and (383.7, 391.3, 404.8) °C for 10 % mass loss for three repeated measurements of the same sample. The rate of decomposition is highest at temperatures (446.5, 458.5, 460.5°C) and corresponding mass losses (68.8, 72.9, 68.7 wt%). The PP sample was completely decomposed into gases and volatile components above temperature 493 °C. Shifted thermogravimetric curves of the same indicate the effect of inhomogeneity on the thermal decomposition process.

2.2. Apparatus

A conical continuous reactor with an electric furnace was used for the experiments. The furnace had two heating zones regulated separately to obtain an optimal temperature profile inside the reactor. The reactor temperature decreased from the bottom to the top of the reactor. The temperature inside the reactor was controlled by three thermocouples placed inside the tube located in the reactor axis. The temperatures measured by the three thermocouples were recorded on a PC. The thermocouples reached the bottom, 100 mm from the bottom and 200 mm from the bottom. The inert gas was introduced through the bottom of the reactor through a thin jet and regulated by a Bronkhorst EL-FLOW Prestige gas flow regulator. The inert gas introduction had two purposes. First, mix the melted plastic inside the reactor. The second is to help carry out the cracking products of the pyrolysis. The gas products of pyrolysis were first condensed in a water cooler. The condensed products were collected in a round-bottom flask. Non-condensed gases proceeded to the Dimroth's cooler, cooled to -8°C. Then, non-condensed gases were introduced into two gas-washing bottles filled with sodium hydroxide solution (1 mol.L⁻¹) to capture carbon dioxide. The plastic feedstock was fed through the tube on top of the reactor, which was equipped with a ball valve that allowed the opening and closing of the reactor. The scheme of the apparatus is shown in Fig.2.

2.3. Measurement procedure

Two reaction conditions, temperature and inert gas flow, were optimised. On the basis of TGA measurement for PP thermal decomposition, pyrolysis temperatures 420, 440, 460°C were chosen. The maximum temperature in the centre and close to the bottom of the reactor was regulated at these levels. The inert gas flow was set at 0.2, 0.1, 0.05, and 0.02 L.min⁻¹. Inert gas was introduced into the reactor from the bottom.

The empty reactor was sealed and connected to the inert gas. 200 g of native polypropylene was added to the reactor. Inert gas was introduced into the reactor to expel all air from the reactor. Then, the heating of the reactor started according to the temperature regulator's program. The lower regulator, which regulated the thermal spiral in the bottom of the reactor, was programmed to reach the set temperature inside the reactor in two-hour intervals. The second regulator was programmed to reach 300°C for 60 minutes and then 450°C for the next 90 minutes. After the set temperature at the bottom of the reactor was achieved, a one-hour period was introduced, during which the plastic inside was pyrolysed and removed from the reactor. Then, plastics were continuously added 10 g every 5 minutes until 300 g of polypropylene was added summarily to the reactor. Two experiments were conducted during one day. A period of one hour was added between and after the second experiment, when the reactor remained at constant conditions, and all polypropylene was pyrolysed. After the experiments, the reactor was opened to check if all polypropylene was pyrolysed and to weigh potential residues from pyrolysis. In all experiments, the amount of coke placed on the inner reactor walls was insignificant and, therefore, neglected.

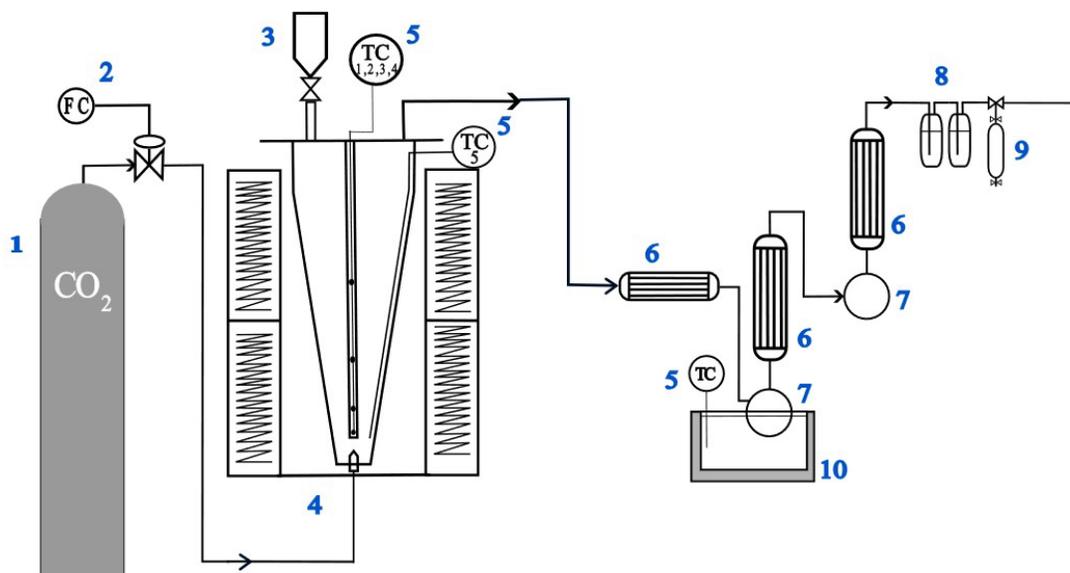


Fig. 2. Scheme of thermal/catalytic cracking apparatus of waste polyalkenes.

1 – CO₂ gas cylinder; 2 – Digital flow meter and flow regulator; 3 – Input of waste plastic pellets; 4 – Thermal cracking reactor; 5 – Thermocouples; 6 – Condensers; 7 – Glass tanks for liquid cracking products; 8 – CO₂ capturing; 9 – Gas for analysis; 10 – Cooling bath

2.4. Liquid products analysis

The pyrolysis oil was analysed using a Hewlett Packard HP 7890A gas chromatograph with a flame ionisation detector. A HP-5 column (5 % phenylmethylpolysiloxane) with dimensions 30 m × 320 μm × 0.25 μm was used, and the carrier gas was helium. The compounds were separated by the retention times of n-alkanes, and the fraction of gasoline, jet fuel, and residue was established as <nC₅ - nC₉, nC₁₀ - nC₁₇, and nC₁₇⁺, respectively. Simdist analysis was performed with the help of GC Agilent 7890B (on column system, nonpolar stationary phase, FID detector, temperature program 0°C, 20°C/min up to 350°C 13 min) and the bromine number was analysed according to the standard ASTM 1159 with accuracy 6 %. According to ASTM 1159, the bromine number represents grammes of bromine that react with 100 grams of the sample.

2.5. Gas products analysis

The gas sample was collected at 110-130 min. from the start of the experiment after initial stabilisation of the experiment temperature and analysed by gas chromatography with the help of Hewlett Packard HP 6890 chromatograph (TCD, FID detectors), multi columns system.

3. Results and discussion

3.1. Optimisation of reaction conditions

In the first two hours, the temperature inside the reactor rose until the pyrolysis process started, and the production of the first amounts of gasses and liquids was observed. This reduced the temperature of the reactor. This effect was compensated by the increased amount of heat from heat spirals. Approximately two hours later, the temperature at the bottom of the reactor reached the set value. The temperature at the bottom and 10 cm remained unchanged for one hour. The temperature at 20 cm slowly decreased. This was caused by the reduced amount of gasses from PP pyrolysis, which heated the upper part of the reactor.

After one hour, PP was added to the reactor as granules at laboratory temperature with the help of a feeding tube. Therefore, after we had added the plastic inside the reactor, the temperature at the bottom rapidly decreased. The input of the plastic batch significantly less

influenced the other two temperatures. Four different plastic additive rates (10g/5 min, 10g /3 min, 15g /5 min and 6g /3 min) were tested to eliminate the sudden decrease in reactor bottom temperature. The temperature at the bottom of the reactor reacted differently with each dosing method (Fig.3). As the optimal dosing rate, 10g/5 min was chosen because, in this case, the bottom temperature had enough time to return to the set temperature. The rates with fewer added plastics had lower waves (lower deviations from the required temperature). However, the temperature did not reach the set temperature between the two batches because of a short time.

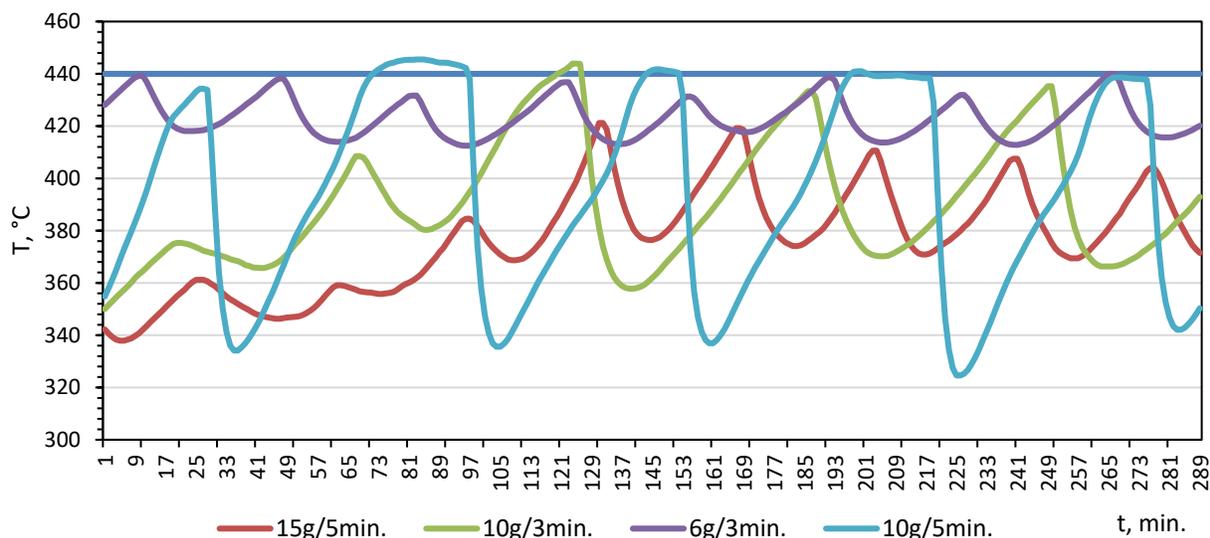


Fig.3. Temperature change in the centre near the bottom of the reactor for different dosing rates of polypropylene.

Once the plastic feed rate was optimised, the appropriate pyrolysis temperature and inert gas flow were tested to obtain a high yield of the kerosene fraction with a low C₂₂⁺ hydrocarbon content.

3.2. Material balance

Each experiment determined a mass proportion of the pyrolysis gas, liquid, and residue in the reactor. Differences between product yields for different experiments were slight but showed certain trends. The yield of gas increased, and the yield of liquid decreased with increasing maximal temperature in the reactor.

Table 2. Effect of temperature and inert gas flow on yield (Y, wt%) of gaseous and liquid products.

CO ₂ , L.min ⁻¹	0.2		0.1		0.05		0.02	
T, °C/Y, wt%	Gas	Liquid	Gas	Liquid	Gas	Liquid	Gas	Liquid
420	7.1	92.9	5.9	94.1	8.5	91.5	8.5	91.5
440	7.6	92.4	8.6	91.4	9.9	90.1	6.2	93.8
460	9.4	90.6	9.7	90.3	9.1	90.9	9.4	90.6

3.3. Liquid composition

With high inert flow for all three tested temperatures, the pyrolysis liquid has a higher average boiling point because of the reduced retention time of molecules formed from plastic pyrolysis in the reactor's hottest zone. On the other hand, at the lowest flow tested, 20 ml per minute, a problem with insufficient mixing of the reaction mixture occurred. Therefore, different parts of the reactor created an inhomogeneous temperature field. This led to a higher

average boiling point than obtained for liquids with inert gas flow 50 mL.min⁻¹ at temperatures 440 and 460°C (Fig.4).

At a temperature of 460°C, the highest value of the average boiling point of the liquids was observed for all inert gas flows tested. This observation seems to contrast with the expectation of better feedstock cracking with increasing reactor temperature. This observation can be explained by the extremely fast decomposition of polypropylene introduced into the hot reactor. The TGA measurement of the PP feedstock showed the average highest rate of decomposition at 455°C (Fig. 1). The initial stages of decomposition for a decrease of 5 wt% and 10 wt% were obtained already at 373 and 393°C, respectively (Fig. 1). It appears that the reactor temperature of 460°C was too high to allow sufficient time for the gradual breakdown of PP macromolecules and subsequent decomposition of primary cracking products. After dosing, the plastic quickly heated up from the hot walls of the reactor. Rapid gaseous products formed that dragged even less cracked molecules with them and carried them out of the reactor.

For this reason, larger hydrocarbon molecules are present in liquids from 460°C cracking, manifested in a high average boiling point. The bromine number is growing with a decrease in the average boiling point (Table 3). This means that the liquid contains more double-bond compounds.

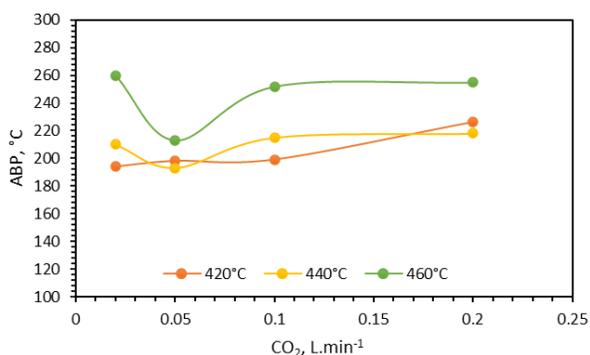


Fig. 4. Average boiling point (ABP) of pyrolysis liquids in dependence on CO₂ flow rate and reactor temperature.

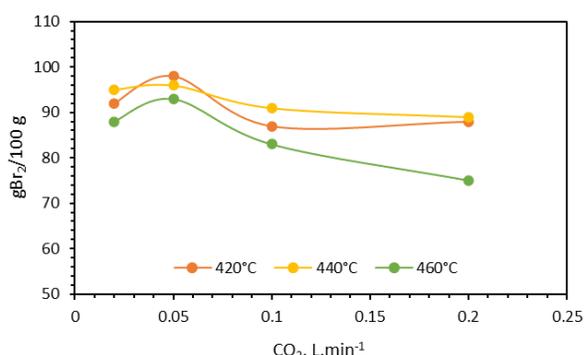


Fig. 5. Content of double bond in pyrolysis liquids, expressed as bromine number, in dependence on CO₂ flow rate and reactor temperature.

Table 3. Simdist, final boiling point, average boiling point, and bromine number of pyrolysis liquids in dependence on CO₂ flow rate and reactor temperature.

T, °C	420				440				460			
CO ₂ , L.min ⁻¹	0.2	0.1	0.05	0.02	0.2	0.1	0.05	0.02	0.2	0.1	0.05	0.02
Simdist, °C												
10 %wt.	77	64	64	64	77	64	63	64	80	63	62	62
30 %wt.	138	137	137	137	138	137	137	137	136	136	136	136
40 %wt.	174	140	139	138	163	144	138	138	190	174	137	148
50 %wt.	225	192	192	189	213	200	182	191	236	236	191	213
90 %wt.	393	341	345	334	407	390	341	384	483	485	397	470
FBP*, °C	514	418	443	423	524	510	431	510	545	545	531	545
ABP**, °C	226	199	198	194	218	215	193	210	255	252	213	260
BN***, gBr ₂ /100 g	88	87	98	92	89	91	96	95	75	83	93	88

* Final boiling point, ** Average boiling point, *** Bromine number

The liquids obtained from pyrolysis of polypropylene are multicomponent mixtures, especially of branched alkenes and alkanes [18-19]. It was not possible to identify individual compounds in the mixture. Therefore, the liquid products were analysed by GC, and the mass content of hydrocarbons eluted between retention times of individual n-alkanes was calculated

(Table 4, Fig.7). Based on the previous identification of the PP decomposition liquid, we found that the liquid contained a significant amount of dimer, trimer, tetramer and pentamer. We also confirmed the presence of these branched alkenes in our liquid samples (Fig. 6).

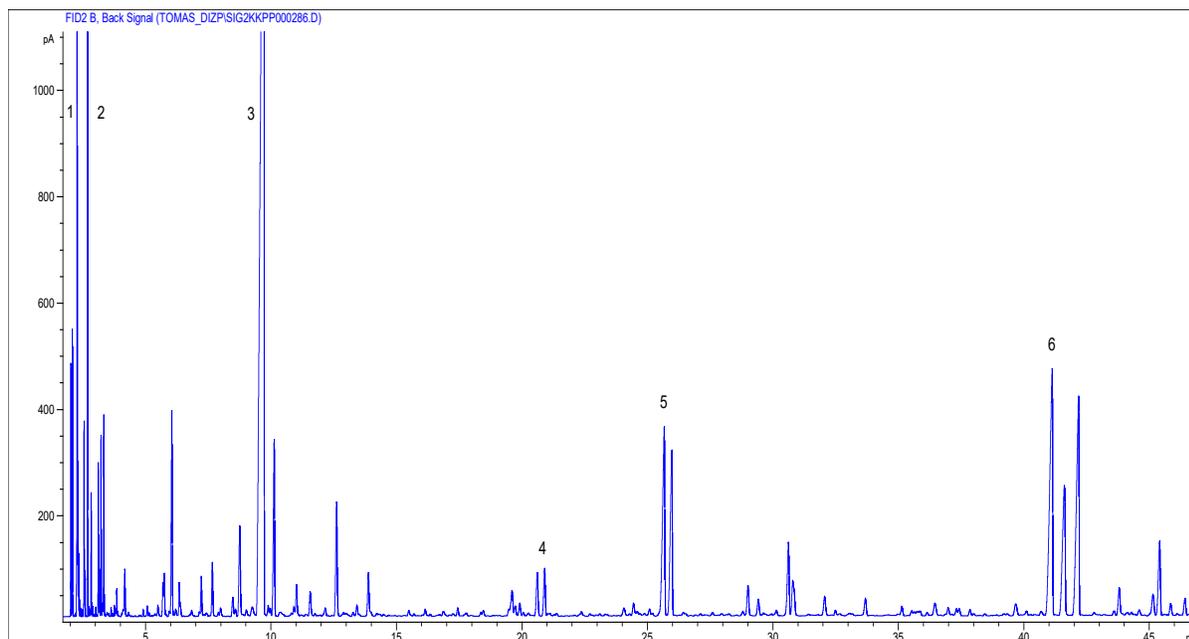


Fig.6. Part of gas chromatogram of pyrolysis oil.

1 Pentane; **2** 2-Methyl-1-Pentene; **3** 2,4-Dimethyl-1-Heptene; **4** 4,6-Dimethyl-1-nonene; **5** 2,4,6-Tri-methyl-1-nonene; **6** 2,4,6,8-Tetramethyl-1,8,-nonadiene

On the one hand, the rising content of some light hydrocarbons, especially nC_5 - C_8 and nC_8 - C_{10} , occurred with the reduction of the inert gas flow at a set temperature (Fig.7). This was probably caused by a longer residence time of PP pyrolysis products in the reactor, which resulted in their more significant splitting. On the other hand, decreasing content of larger hydrocarbons with lowering CO_2 flow was observed for hydrocarbons C_{16}^+ . A similar trend can also be seen at $420^\circ C$. The liquids from pyrolysis at $460^\circ C$ were not analysed using the GC-FID method used in this work because the liquids contained large amounts of heavier hydrocarbons.

Based on the content of hydrocarbons eluted between the retention times of individual n -alkanes, the yields of three fractions, gasoline, jet fuel and residue C_{17}^+ , were calculated. All hydrocarbons until n - C_9 were included in the gasoline fraction, and hydrocarbons between n - C_9 and n - C_{17} were summed up in the jet fuel. The residue comprised all hydrocarbons greater than n - C_{17} (Table 5). The gasoline fraction reached the highest yield in all experiments, followed by the jet fuel fraction in most cases. The highest yield of the 46 wt% of gasoline fraction was obtained at $440^\circ C$ and an inert flow of $0.05 \text{ L}\cdot\text{min}^{-1}$. The lowest yield was observed at $460^\circ C$ and $0.1 \text{ L}\cdot\text{min}^{-1}$. The difference between the lowest and the highest yield was significant and represented 15 wt%.

The yield of the jet fuel fraction was more stable than the gasoline yield, and the difference between the lowest and highest yield was around 9 wt%. The relative stability of the jet fuel fraction yield resulted, on the one hand, increasing the yield of jet fuel by decomposition of C_{17}^+ from the higher decomposition of C_{17}^+ hydrocarbons into molecules in the range of jet fuel and, on the other hand, by decreasing the yield of jet fuel by its decomposition into gasoline. As a result, the amount of jet fuel slightly gradually decreased with increasing maximal temperature in the reactor. The lowest jet fuel yield was observed at $460^\circ C$ and inert flow 0.2 and $0.05 \text{ L}\cdot\text{min}^{-1}$. The highest yield of jet fuel fraction, 33.8 wt%, was reached at $420^\circ C$ and an inert flow of $0.1 \text{ L}\cdot\text{min}^{-1}$.

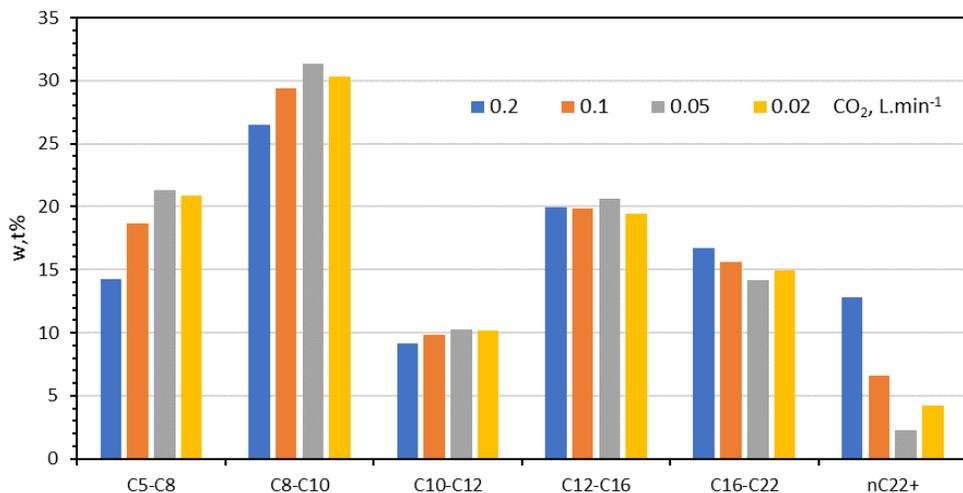


Fig.7. Mass distribution of hydrocarbons in pyrolysis liquids according to the number of carbon atoms in dependence on CO₂ flow rate, the maximum temperature in the reactor 440°C.

Table 4. Composition of pyrolysis liquids by GC at temperatures 420°C and 440°C with decreasing inert flow.

T, °C	420				440			
wt%/CO ₂ , L.min ⁻¹	0.2	0.1	0.05	0.02	0.2	0.1	0.05	0.02
<nC ₅	5.3	6.3	6.8	7.4	4.6	6.0	7.0	7.0
nC ₅ -nC ₆	6.0	6.2	6.7	6.5	4.9	6.1	7.1	6.7
nC ₆ -nC ₇	2.5	2.9	3.2	3.3	2.5	3.2	3.5	3.7
nC ₇ -nC ₈	3.1	3.4	3.6	3.5	2.2	3.3	3.6	3.5
nC ₈ -nC ₉	26.7	26.9	27.1	27.5	24.6	26.9	29.1	27.7
nC ₉ -nC ₁₀	2.0	2.3	2.4	2.4	1.9	2.5	2.2	2.7
nC ₁₀ -nC ₁₁	7.0	7.0	7.1	7.0	6.2	6.6	7.1	6.8
nC ₁₁ -nC ₁₂	3.2	3.3	3.5	3.5	2.9	3.2	3.2	3.4
nC ₁₂ -nC ₁₃	1.6	1.8	1.8	1.9	1.6	1.8	1.6	1.9
nC ₁₃ -nC ₁₄	13.0	12.6	12.1	12.2	11.9	11.3	12.5	11.1
nC ₁₄ -nC ₁₅	1.5	1.5	1.4	1.4	1.3	1.4	1.0	1.3
nC ₁₅ -nC ₁₆	5.8	5.8	5.6	5.6	5.2	5.4	5.6	5.1
nC ₁₆ -nC ₁₇	1.6	1.6	1.4	1.5	1.4	1.5	1.0	1.3
nC ₁₇ -nC ₁₈	5.8	6.0	5.4	5.5	5.6	4.9	5.2	4.8
nC ₁₈ -nC ₁₉	2.4	2.6	2.2	2.3	2.4	2.3	2.2	2.2
nC ₁₉ -nC ₂₀	2.6	3.0	2.6	2.9	2.8	2.6	2.4	2.6
nC ₂₀ -nC ₂₁	2.1	2.3	1.8	1.8	2.4	2.2	1.8	2.1
nC ₂₁ -nC ₂₂	1.8	2.0	1.9	1.8	2.2	2.1	1.7	2.0
nC ₂₂ ⁺	6.1	2.5	3.6	2.1	12.8	6.6	2.2	4.2

Table 5. Yields of gasoline, jet and residue fractions (Y, wt%) calculated from GC analyses.

T, °C	420				440				460*			
wt%/CO ₂ , L.min ⁻¹	0.2	0.1	0.05	0.02	0.2	0.1	0.05	0.02	0.2	0.1	0.05	0.02
C ₅ -C ₉	40.6	43.0	43.3	44.0	35.8	41.6	45.8	45.6	34.4	30.7	37.3	39.8
C ₉ -C ₁₇	33.1	33.8	32.4	32.5	29.9	30.7	30.8	29.1	24.5	28.0	24.5	28.1
C ₁₇ ⁺	19.3	17.3	15.9	14.9	26.1	19.0	13.5	16.7	31.7	31.6	29.1	22.6

* from Simdist analysis according to ASTM D2287

The yield of hydrocarbons C_{17}^+ decreased with decreasing carbon dioxide flow at every temperature studied. This was probably caused by the prolonged residence time of the cracking products inside the reactor, so deeper splitting of the hydrocarbon molecules was enabled. The most significant amount of residue was obtained at 460°C and the lesser amount at 440°C with an inert flow of 0.05 L.min⁻¹.

3.4. Gas composition

Propene was the compound with the highest content in the gas phase, up to 58.6 wt%. Ethane was the second most common compound, up to 14.5 wt%, followed by methane and isobutene. Propane, ethene, and hydrogen were in smaller amounts (Table 6). Due to the low yield of gases, the yield of the most represented propene was only about 5 wt%, and the yield of valuable isobutene was, on average, 0.6 wt%.

Table 6. Distribution of key components (wt%) in gas products for different temperatures and inert gas flows

T, °C	420				440				460			
wt%/CO ₂ , L.min ⁻¹	0.2	0.1	0.05	0.02	0.2	0.1	0.05	0.02	0.2	0.1	0.05	0.02
Hydrogen	0.6	0.5	0.8	0.8	0.6	0.5	0.8	0.5	0.6	0.6	0.8	0.8
Methane	7.6	8.0	8.8	9.3	7.2	7.4	8.6	7.7	7.9	7.6	8.4	8.8
Ethane	12.7	11.5	14.5	13.8	10.9	10.7	13.1	11.2	13.5	12.7	13.5	14.5
Ethene	2.2	0.8	2.8	1.7	1.0	1.0	1.4	1.0	2.1	2.2	2.7	2.8
Propane	4.1	3.9	4.1	4.1	3.4	3.4	3.7	3.3	3.8	4.1	4.0	4.1
Propene	57.8	58.6	57.6	58.6	57.3	58.5	58.5	61.6	54.3	57.8	49.6	57.6
Isobutene	8.8	7.7	6.9	7.1	7.7	7.5	6.7	7.6	7.9	8.8	10.0	6.9

The results of significant differences in the yields of individual liquid fractions achieved at different temperatures and different inert flow rates show an evident influence of these parameters on the course of cracking reactions during the decomposition of polypropylene in the conical reactor used. The reaction parameters can be modified in certain intervals depending on which fraction is desired to obtain a greater yield.

To evaluate the best conditions for pyrolysis, we have stated two conditions. The first was the highest amount of the C₉-C₁₇ fraction, and the second was the lowest yield of the C₁₇⁺ fraction, which means that the PP plastic is broken up as much as possible into liquid products. The best in the first condition were experiments at 420°C, where all the inert gas flows were studied, and one experiment at 440°C with an inert gas flow of 0.05 L.min⁻¹. If we only focus on jet fuel production, the best conditions are 420°C and 0.1 L.min⁻¹ inert gas flow. In the second condition, the experiment was carried out at 440°C, the highest amount of gas products and the lowest average boiling point of all experiments.

4. Conclusion

Our experiments prove that the reactor is capable of pyrolysing polypropylene plastic and producing large amounts of liquid product. However, at a temperature of 460°C, it shows its limits. At this temperature, the thermodynamics inside the reactor cause rapid pyrolysis at the reactor walls with high energy consumption, which causes a high-temperature gradient between the reactor wall and the centre of the reactor. It was manifested by the highest distillation end of liquids.

Typically, the thermal pyrolysis of polypropylene produces large quantities of monomers, dimers, trimers, tetramers, and pentamers, which we also observed in our experiments. Monomer propene was dominant in all gas products. The most prevalent liquids were trimer, pentamer, and tetramer.

The optimisation of the working conditions of the reactor resulted in the need to control the temperature not only in the centre of the reactor but also on the wall in order to prevent overheating of the reactor wall and to minimise a more significant difference between these

temperatures. Such a thermocouple was installed in the new reaction system. Further experiments with real PP waste were carried out under optimised conditions from this work with simultaneous measurement of the temperature on the reactor wall and in its centre.

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