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PYROLYSIS PROCESS OF WHOLE WASTE TIRES AS A BIOMASS ENERGY RECYCLING

PIROLIZA OPON SAMOCHODOWYCH JAKO ENERGETYCZNY RECYKLING BIOMASY

Abstract: The article is devoted to the description of material recycling of whole waste tires, including a new method of pyrolysis process, resulting in the final products: technically oil fractions (rubber plasticizer or rubber compounds) or diesel fuels (light, medium and heavy), activated carbon, gas fuel and steel scrap. Operational and performance tests of the first version of the pilot plant, consisting of three contributions cooperating with one pyrolytic reactor confirmed that this technology is applicable but has still some flaws and errors, both structural and technological. Usually such errors in the first test of technology development cannot be avoided. This paper describes: pyrolysis processes which occurs in the pilot plant, protected by a patent application design of continuously working prototype installation for recycling of tire and identifies future directions of research in this field.

Keywords: whole waste tires, material recycling, waste management, pyrolysis

Introduction

In this article biomass definition is mainly based on the definition from the Polish legislation acts, but it should be mentioned that in the relevant provisions the biomass term is defined in different ways. Biomass given by [1] means “products consisting of whole or in part of vegetable matter from agriculture or forestry which can be used as a fuel for the purpose of recovering its energy content”. Another definition, included in the Polish Journal of Laws from 2003 (No. 104 item. 971 § 2), treats as a biomass “substances of plants or animals origin, which are biodegradable, derived from products, wastes or residues from agriculture or forestry production, and related industries, as well as other parts of wastes that are biodegradable”, with the exception of wood wastes, which may contain harmful compounds, used *eg* for their preservation.

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Another commonly used in the European Union solution is the principle of extended producer responsibility (EPR). It introduced, arbitrarily imposed on the tire manufacturers, obligation of material and energy recycling of waste tires. The cost of the recycling is included in the price of the tires. Areas of different management systems functioning in the EU are shown in Figure 1.

Recycling and pyrolysis

There are many methods of waste tires disposal, including: material recycling (shredding, granulation, producing regenerated, re-use of tires in whole), energy recycling (combustion) and chemical recycling - raw materials (pyrolysis, gasification, carbonization, hydrocracking).

Whole waste tires, which have been cut, grinded and fragmentized, can be included in the material recycling. In the first case tires are used as raw material for creation of new products [3], such as flowerbeds, securities, bumpers, playground items, etc. The most important qualities of tires (the ability to reduce noise, shock and vibrations), and their material characteristics (elasticity and high strength due to the cord reinforced sides) are being used [4]. In the second case, created granules are used in rubber production and as an additive to asphalt.

Energetic recycling consists in waste tires combustion as alternative fuel. The high calorific value rate makes this method of disposal quite efficient. In Poland, especially in cement plants, it is now one of the most commonly used method of disposal of this kind of waste. Obtained in this technology, combustion heat of tires is used for clinker burning.

In chemical recycling the product consists in recovering and reusing substrates, which previously made the final product. In the case of plastics it's a monomer, for the broken glass it is glass, for scrap metal it is metal, etc. The recycling of raw materials for tires concerns only steel cord as the pyrolytic oil contains only trace amounts of isoprene and butadiene.

One of the interesting and dynamically developing methods of chemical - biomass and tires recycling, is the pyrolysis process. The process is based on the high-temperature degradation of organic compounds in anaerobic atmosphere, and though it is still often used mainly for wood biomass utilization, the shares of waste tires recycled this way continuously grow up.

The pyrolysis

Pyrolysis process takes place without air or in anaerobic atmosphere typically at a temperature of 400-700°C. During this process, in the case of tire pyrolysis, sulfide bonds occurring in the rubber become broken and next carbon chains are bursting and finally gaseous, liquid and solid products are formed, which then can be subjected to further processing. The main components are: methane gas (and other simple hydrocarbons), hydrogen, hydrogen sulfide and carbon monoxide (which constitute about 10%). Oil represents around 44%, and part of solids about 46% [5]. The liquid phase consists of a mixture of aliphatic and aromatic hydrocarbons, such as benzene, toluene and others. The separation of these components from the liquid fraction can be achieved by distillation and refining. The solid fraction consists of char, remnants of steel, silica, ZnO, ZnS, and any



residues of catalysts, which were used [6]. Char can be used as a filler for rubber compounds, or may be subject to activation.

The composition of the products formed, both qualitative and quantitative, is dependent on the pyrolysis process parameters such as temperature, the duration of the process, the conditions of pressure, inert gas and catalyst presence. There are technologies in which the process occurs in an inert atmosphere, mostly nitrogen, or in the presence of catalysts accelerating the process and facilitate the distribution of multi-particle compounds. It is also possible to carry out the process at the hydrogen flow through, so-called, hydrocracking.

Vacuum pyrolysis process was introduced in the late nineties, developed by Pyrovac International Inc. from Canada. The reactor is heated by the molten salts, pyrolysis occurs at a pressure of 20 kPa at a temperature of 480-520°C [5]. There are also waste tires disposal methods based on plasma pyrolysis and pyrolysis with water and CO₂ in supercritical conditions. Plasma pyrolysis of tires is used in Israel by Plasma Recycling Ltd, which produces synthesis gas [5].

Pyrolysis, as well as gasification, is a complex process consisting of several stages. Depending on temperature and oxygen content of the input biomass and its composition, as a result of oxidation, processes can be exothermic. The main reactions occurring during the pyrolysis of biomass and their enthalpy values for the temperature $T = 300$ and 1000 K are given in Table 1.

Table 1

Exothermic reactions of cellulose pyrolysis and values of their enthalpy [7]

Process	Reactions	Enthalpy [kJ/mol]	
		300 K	1000 K
Methanisation	$\text{CO} + 3\text{H}_2 = \text{CH}_4 + \text{H}_2\text{O}$	-205	-226
	$\text{CO} + 4\text{H}_2 = \text{CH}_4 + 2\text{H}_2\text{O}$	-167	-192
Methanolysis (Estrification)	$\text{CO} + 2\text{H}_2 = \text{CH}_3\text{OH}$	-92	-105
	$\text{CO}_2 + 3\text{H}_2 = \text{CH}_3\text{OH} + \text{H}_2\text{O}$	-50	-71
Carbonization	$0.17\text{C}_6\text{H}_{10}\text{O}_5 = \text{C} + 0.85\text{H}_2\text{O}$	-81	-80
Hydrogasification	$\text{CO} + \text{H}_2\text{O} = \text{CO}_2 + \text{H}_2$	-42	-33

Thermal pyrolytic degradation of biomass process carried out in oxygen-free atmosphere, leads to the formation of three products:

- Solid: biocarbon product - charcoal, in the case of decomposition of wood and ash.
- Liquid: oil and tar, which are mixtures of hydrocarbons, phenols, and about 200 different organic compounds (aliphatic and aromatic, saturated and unsaturated).
- Gas, being a mixture of CO, CO₂, H₂, hydrocarbon gas (CH₄, C₂H₆) and liquid vapour, eg C₃H₈, C₄H₁₀, and water vapour, with a calorific value of about 12 MJ/kg. Composition depends on the temperature of decomposition of biomass, and in eg temperature of 482°C/926°C percentage by volume is following: 5.56/32.48 H₂, 12.34/10.45 CH₄, 33.50/35.25 CO, 3.03/1.07 C₂H₆, 0.71/2.43 C₂H₂. A total of flammable gases in the mixture represent 54.97% for the temperature of 482°C or 81.68% for 926°C [8].

According to the researchers [9, 10] the largest liquid products fraction from biomass pyrolysis is the most economically reasonable way of conducting this process. In their opinion profits from the converting biomass into heat, electricity or liquid fuels are in proportions 1:3:9 (respectively; heat : electricity : liquid fuel). In the nearby future we can predict the growth of interest in thermal conversion of biomass in the direction of obtaining



the largest possible amount of liquid biofuels. Depending on the type of pyrolysis, there are two types of liquid fuels (Table 2):

- Biofuels which are formed directly in the flash pyrolysis with high efficiency, up to 85% by weight. They have a relatively low viscosity, and mix with water up to 35-50% moisture content. They are also easy to burn in boilers, furnaces and engines. Compared with petroleum fuels they are less stable, more vulnerable to temperature, and after some time may polymerize.
- Biofuels, obtained by a typical or slow pyrolysis with less efficiency, no more than 20% by weight [8].

Table 2

Properties comparison of liquid products from flash and slow pyrolysis [11]

Properties	Pyrolysis	
	Flash	Slow
Moisture content [%]	20.0	14.6
pH [-]	2.5	2.0
Specific gravity [kg/dm ³]	1.21	1.195
C [%]	56.4	61.9
H [%]	6.2	6.0
N [%]	0.2	1.07
S [%]	<0.01	0.03
Ash [%]	0.1	1.5
O [%]	37.1	29.5
C/H ratio [-]	9.1	10.3
Calorific value [MJ/kg]	23	26.3
Dynamic viscosity in 40°C [cP]	51	300
Kinematic viscosity in 25/40°C [cSt]	233/134	-
Pour point [°C]	-23	27

Energy required for biomass pyrolysis may be supplied from an external heat source or from combustion products of the biomass decomposition such as solid product, oil or gas.

The scheme of tube reactor with external heating jacket used for thermal decomposition of biomass is shown in Figure 2. Depending on the parameters of its work and the number of incoming steam and catalysts, it can adjust the composition of any product and make it: gasifier, pyrolyzer or biocarbonizer.

Decomposition process in pyrolyzer, shown in Figure 2, starts at the temperature of 200°C, and the upper temperature is unlimited, it may even be the temperature of the plasma. The final products of pyrolysis are gases, oils and biocarbon (charcoal) or ash [12].

The proportions of gas, oil and biocarbon in the decomposition products depend on the rate of temperature rise, time of decomposition, temperature and pressure. With rapid thermal decomposition more than 65% of the biomass becomes gas (gasification), at an average decomposition rate of over 70% the biomass is converted into oil (pyrolysis) and at slow decomposition, over 35% biocarbon (biocarbonization) is obtained [12].

The pyrolysis gas can be condensed at about 30% (by weight) into oil, which is at room temperature a mixture of approximately 200 liquid organic compounds, including hydrocarbons, alcohols, aromatics and other compounds.



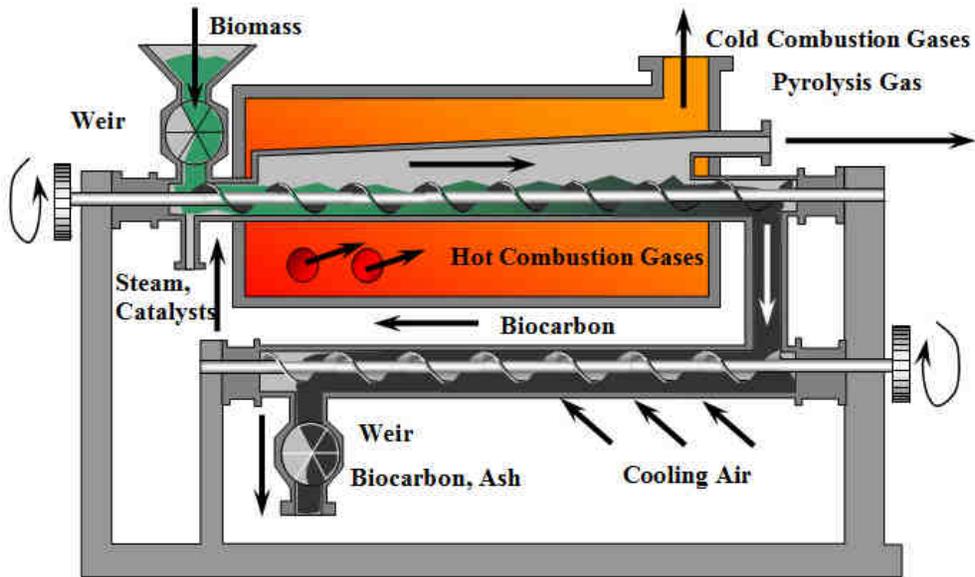


Fig. 2. Scheme of plate device for thermal decomposition of biomass working continuously [13]

Previous installations

The most famous biomass pyrolysis technologies are summarized in Table 3 [14].

Table 3

The best known and latest technologies of biomass pyrolysis [14]

Technology	Producer	Material	Efficiency	Temp.
			[kg/h]	[°C]
BTG Flash Pyrolyse	BTG Biomass Technology Group	Biomass	250, 5000 (Starting-up)	500
Pyrocycling Process	Pyrovac Group Inc. and Ecosun b.v.	Biomass	3500	475
ENTECH Pyrolytic Gasification System	ENTECH Renewable Energy Tech. PTY Ltd.	Biomass and biowaste	Series of Types 200 - 36000	500
Waste Gas Technology	Waste Gas Tech. Ltd.	Sludges	500	750-850
Ragailler Dry Distillation	RATech	Municipal wastes, biomass	NDA	450-560
HD-PAWA-THERM	UC Prozesstechnik GmbH	Sludges	NDA	600-700

NDA = No Data Available

The use of pyrolysis processes is now fairly well known and more often companies that specialize in this type of installation can be found. Here are some examples of the most popular and latest developments in this field.

Stored biomass is directed to the tray through a screw conveyor, which brings it to the air transport system ended in the cyclone. The material from the cyclone falls by gravity to a vibrating sieve separator. The fraction between 0.5 and 40 mm is sent to a vacuum-weir power system (consisting of two rotary cell dispensers, placed in series, between which vacuum pump suction is connected). In a similar way, by the same double vacuum locks, the char and ash from the vacuum pyrolyzer are discharged. In this way the leakage of gas from the pyrolysis reactor and the atmospheric oxygen influx are prevented. The process of thermal decomposition of biomass takes place at a pressure of about 20 kPa [14].

Biomass, as a result of pyrolysis thermal decomposition, is converted to pyrolytic oil, char (biocarbon), raw gas and water fraction. Char, which temperature on the reactor outlet is about 475°C, is cooled in the three-stage screw heat exchangers, initially with air and then with water. After passing through a vacuum-weir system, biocarbon is transported through conveyor belt and packed into bags of 1.5 m³ capacity, then stored and finally sold.

Gaseous products, including pyrolysis vapors, are conducted from reactor by a 600 mm head to a two-stage condensing system (packed column). In the first column heavy bio-oil is condensing and in the second - a mixture of light bio-oil and pyrolysis water. This mixture is separated by centrifugation. Both fractions of bio-oils are mixed together and stored in polyethylene containers of 1 m³ capacity or in 50 000 dm³ capacity tank. Water fraction before turning into municipal sewers, is neutralized with a caustic soda solution. The remaining flammable gas from the second column is compressed after cooling to a pressure of 170 kPa and burned together with natural gas in the molten salt heater. Molten salts provide the energy, necessary to carry out the pyrolysis reaction through the boards inside the reactor.

For better clarity in Figure 3 such details as installation of vacuum pumps, installation of pneumatic conveying, screw conveyors, valves and other components, less relevant to understanding the principles of operation the installation, are omitted.

ENTECH installation of biomass conversion

ENTECH Pyrolytic Gasification System (Australia) technology, with a single unit efficient varies from 0.25 to 125 Mg/24 h is designed to produce energy from biomass or organic waste treatment *eg* sewage sludge. The installation consists of two operating units working periodically: diaphragm heated pyrolysis chamber and the combustion chamber with a multi-stage air supply, allowing the burning of raw gas formed in the pyrolysis at 1400°C. With this temperature, disposal of hazardous wastes is also possible (waste from hospitals, used medicines, chemicals packages, etc.). Energy efficiency of the installation is up to 95 MW of thermal energy and up to 20.5 MW of electricity.

WGT Technology

The hybrid system from WGT (UK) is a hybrid process combining gasification and pyrolysis technology [19]. Dried sewage sludge, which is material in the process, is put into the tank, serving as a dispenser, and fed to gas inlet, protecting against oxygen access.

Then, deposits are directed to the horizontal, cylindrical, rotary reactor, heated to the temperature of 850-750°C. Application of such a high temperature causes pyrolysis of organic matter, leading to gas cracking into hydrogen and short chain hydrocarbons. The process conditions are strictly controlled to ensure optimal conditions for gas synthesis.



Formed in pyrolysis coke breeze is separated in a hot cyclone and the pyrolysis gas is cooled before the final treatment.

Ragailler's Technology

Ragailler's Technology was developed by Ragailler Anlagen Technik GmbH [20, 21]. Its main component is a distiller - pipe with a length of about $L = 21$ m and diameter $D = 3$ m propelled rotary. Its interior contains heated membrane, which provides the reductive atmosphere of the process and a small amount of exhaust gas. Uniform heating to the temperature of 450-560°C enables degassing of the material in about 1 hour.

In the distiller there is a slight overpressure, which eliminates the possibility of the air inwards, and thus prevents the danger of explosion. Added dry alkaline sorbents are associating when 90% of the acidic components and heavy metals are released. Recycling based on dry distillation gives four basic useable products:

- gas for proecological energy recovery (70-80% of the energy potential of waste),
- coke breeze, coal with mineral substances contained in waste (20-30% of the energy potential of waste),
- basalt-alike aggregates, of molten sorbent and mineral substances contained in waste (30-50% of the glass) or boiler slag, when coke breeze is burned as a supplement to coal dust,
- ferrous and non-ferrous metals.

RDF recycling installation

Technology of flash pyrolysis recycling has been developed from non-pressure conversion of combustible RDF wastes fraction [22, 23] into diesel or heating oil. Its diagram is shown in Figure 4.

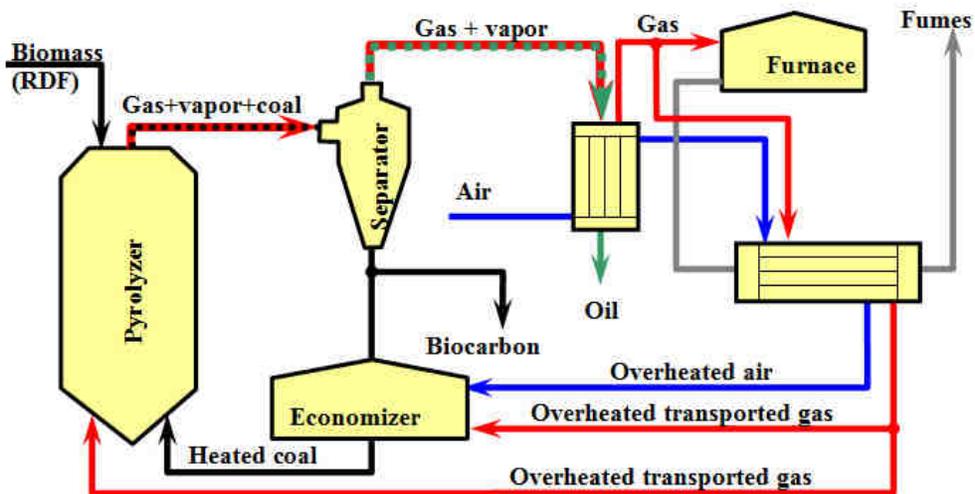


Fig. 4. Scheme of RDF pyrolysis into liquid fuels installation [7, 13]

In this technology from 1 kg of combustible fraction of municipal solid wastes approximately 0.23 kg of fine coal at the temperature of 760°C and a mixture of gas and liquid hydrocarbon vapours at the temperature of 510°C could be obtained. After their rapid cooling to about 80°C to prevent reaction with carbon, approximately 0.4 kg of liquid fraction is obtained. After separating the aqueous condensate, about 22.5% wt. of liquid fuel heating value 24.4 MJ/kg and ash content from 0.2 to 0.4% wt. is obtained. The remaining gas after multistep purification is designed to industrial use. Part of this gas is recycled to the process in order to maintain pyrolysis. Obtained char has a calorific value of 20.9 MJ/kg and contains about 30% ash, the amount of which, calculated on the dry weight of wastes, is about 7.5%. The installation (scheme shown in Figure 4) of sorted RDF stream processing, of daily efficiency at 181 Mg of raw mixed wastes, was built in the U.S. in 1977, but after a year and several thousand of fuel production it was dismantled. The cause was erroneous estimate of the reactor performance in relation to the RDF stream.

Polish experience in such technologies

One of more interesting pyrolytic recycling plants in Poland is the installation used by the “DS. Reecology” company. Most important components of the system are: main reactors, separator and storage tanks (Fig. 5).

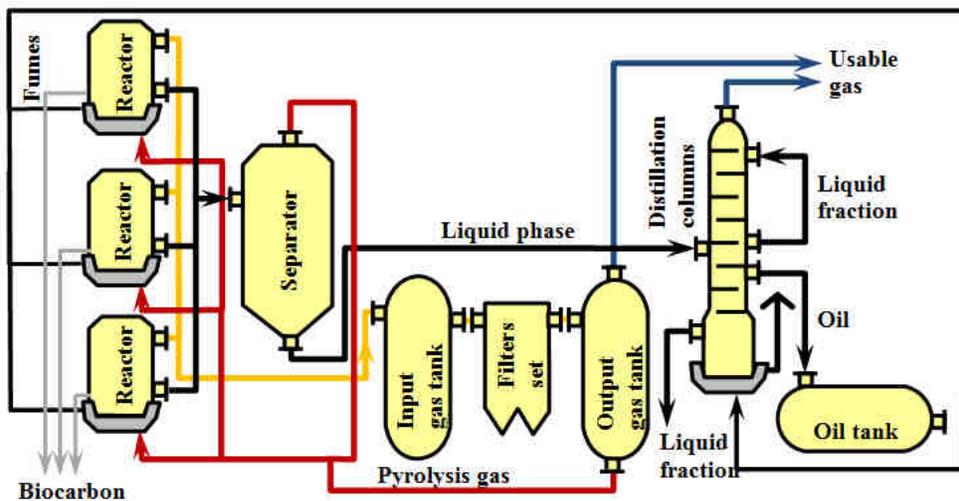


Fig. 5. Scheme of pyrolysis installation for waste tires recycling

In the reactors tire pyrolysis occurs without air or inert gas, and at atmospheric pressure. The process takes place in semi continuous reactors, which are running with a time delay in such a way, that obtained product streams are continuous. When the first reactor cools down, loading process of used tires begins in the next one etc. The installation is adapted to use both shredded and whole tires. The second variant is now a rarity, but it has one particular advantage - it allows conducting the utilization of tires without grinding step which reduces costs. Gas, formed during the process is used for heating the reactor, while

its excess is used to generate electricity and heat in the cogeneration. Liquid products are separated in a distillation column and the rest residue (carbon and steel cord) is removed by hands after process accomplishes. The installation has capacity of 5 Mg of feed per day, and pyrolysis efficiency is up to 1500 dm³ liquid fuel and 2.2 Mg of carbon residues. The reactor consumes annually 13.8 Gcal. of heat and 8.3 Mg of gas as fuel per year (gas recycled from the process). Contamination resulting from the combustion of pyrolysis products (gas) is about 0.096 g/s [24].

Technology of continuous pyrolysis of whole tires

Pyrolysis of whole tires is a difficult technological process, as it has to be done quickly and in high temperatures, which is difficult due to low thermal conductivity of tires. Their grinding before pyrolysis proved to be too much energy consuming and therefore economically viable. The problem of pyrolysis of whole tires could be technically solved only in a special reactor, which is shown in cross-section and the view in Figure 6.

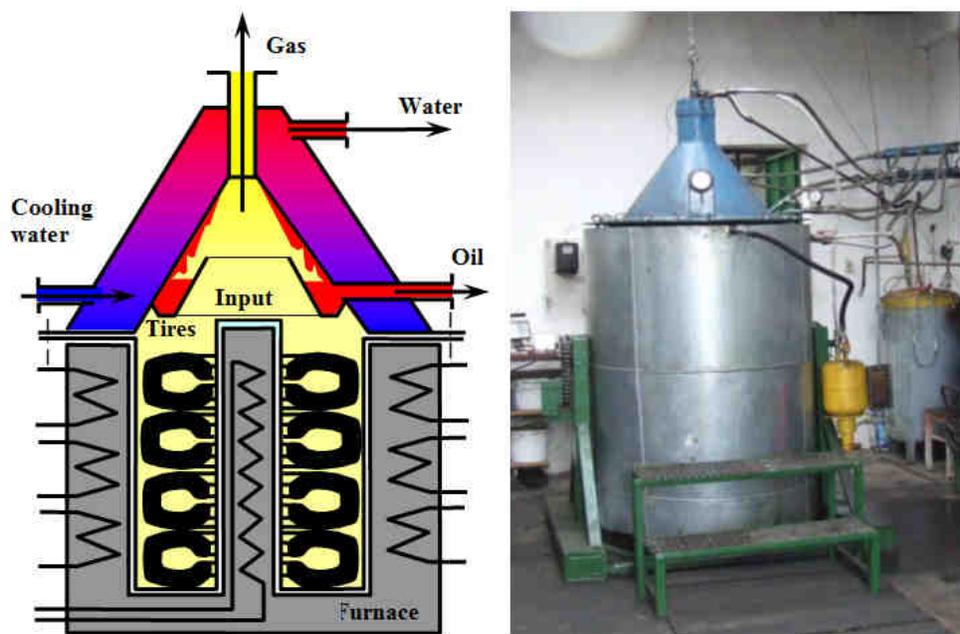


Fig. 6. Scheme and view of periodically working pyrolyzer for the whole tires recycling [13, 25]

Three reactors (hermetically sealed cartridges) in cooperation with one furnace, in which those cartridges are sequentially inserted, provide a quasi-continuous recycling process. When pyrolysis occurs in a cartridge containing 10 tires (about 60 kg), the second cartridge (previously removed from the furnace) cools down, and the third one is unloaded and refilled with the next portion of tires.

Thanks to tires external heating through the side walls of the cartridge and internal heating through the walls of the core, within good tire adhesion to the surface of the heating

plates, the effects of flash pyrolysis have been achieved, receiving up to 35% of oil (hydrocarbons), 35% of biocarbon, 20% of steel scrap and 10% of gas (mainly CO, H₂, CH₄, C₂H₆, C₃H₈).

From one 6 kg weight tire an of average 2.2 litres of oil fraction, 0.5 m³ of gas, 2.5 m³ of coal and 1 kg of scrap metal could be obtained. One two-hour cycle lasting about consumes about 35 kWh of electricity [24]. Based on these and other data, guidelines for the design of continuous installation, at a capacity of 5000 Mg of tires a year, has been specified and dimensions of its individual components have been determined.

Biocarbon received at the temperature of 500-550°C requires activation at about 800°C in a special activator in order to transform it into trade activated carbon, binder, carrier for catalysts or rubber filler.

However preliminary technological calculations revealed that the cost of heating biocarbon to its activation temperature (about 800°C), previously cooled to the temperature of 550°C (the end of the pyrolysis process) to a temperature below its flash point and its re-cooling after activation process will be higher than increase of its price after the activation. This situation forced the development of the new, third version of tires recycling technology.

Technology of continuous pyrolysis of whole tires

The concept of this technology implies that the pyrolysis of whole tires, section of received oil fractions (light, medium and heavy), and biocarbon activation are implemented in a single installation continuously, according to the model shown in Figure 7 [26].

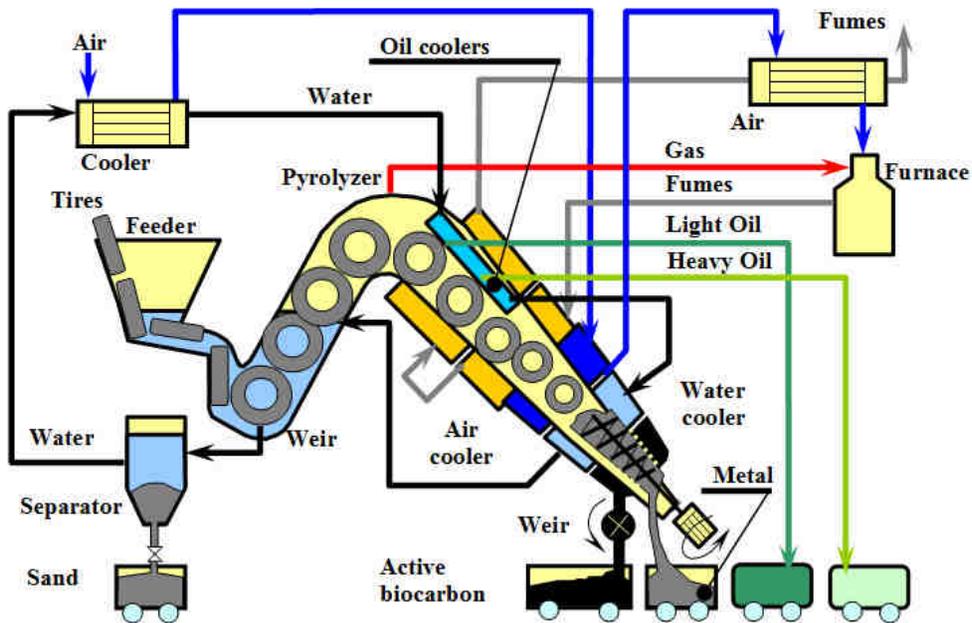


Fig. 7. Scheme of continuously working pyrolysis installation for waste tires recycling [13, 26]

The process begins with placing tires one after another into the tray, from which they are transported by the horizontal duct, through the hydraulic lock (weir), into the pyrolyzer. In the horizontal position, after the spin tires to vertical position, remaining air is removed, tires are filled with liquid and washed from the sand. Then the conveyor raises the next lowest tire and pushes others upwards.

The next operation is drying the tires with the pyrolysis gas flushed, and its heating through the side walls and bottom of the pyrolyzer to the temperature of 500-550°C. A large heat transfer surface (through sides membrane heated by exhaust fumes, which are in contact with the sides of the tire and the bottom, on which they are ongoing) together with high temperature make the heating and pyrolysis process very quick. These conditions are favourable to receive the maximum amount of oil and minimum emissions.

Three radiators, positioned in three areas of the facility, have been designed for continuous discharge of oil vapours. They consist of two concentric tubes: an outer (closed) tube, and inner (the open one). The cooling water is supplied with outer tube, on surface of which vertical wheel shape radiators are located. Oil condensed on the radiators drips into horizontal gutter. Heated water leaves the condenser within the inner tube and oil with a hydraulic closure connector. Cooler nozzles are located at different heights in the three sections of pyrolyzer for separation of different fractions of oil (light, medium, heavy).

Fraction, which has not been condensed, creates, along with hydrogen, trace amounts of carbon monoxide and dioxide and water vapour, a combustible gas which comes out through a hydraulic (water trap) nozzle lock, and within a compressor work, reaches the gas tank. This gas after treatment is provided to power the furnace or burners membranously heating a pyrolyzer. Excess gas can be burned in the engine, connected to the generator and used to produce electricity for technological purposes or for resale [26].

Summary

This paper presents an alternative possibility of material recycling using a pyrolysis process. Several identified biomass pyrolysis technologies, which have been applied in the world, can be adapted to Polish conditions. Scrap tires as a waste are a serious problem, and their number rises year by year, so the improvement of methods of their disposal is still a problem. Car tires belong to a group of bulky waste and their pyrolysis is now the problem, especially due to the fact that large tires occupy a large space as to its weight, which affects the cost of transport and pyrolysis reactor technology.

Analysis of existing technology solutions indicates that they could be successfully applied not only to the green biomass, but also to the dispose of car tires. The only requirement that its operator would have to meet, is the necessity of their early fragmentation.

Presented Polish technology of pyrolysis, is based on using the whole tires, which significantly reduces the disposal costs of expenses incurred for its grinding. It is worth mentioning that the pyrolysis process is still being improved, new technologies and new companies are continuously introducing innovative technologies, which allows an optimistic look in this field in the future.



References

- [1] The Ministry of Environment regulation act from 20 December 2005 - emission standards for installations - Polish Journal of Laws from 2005 (No. 260 item. 2181 § 5).
- [2] Taverne JP. End of life tyres - A valuable resource with growing potential. ETRma End-of-life Tyres Management Report of 2011.
- [3] Czupryński M. *Elastomery*. 2004;8(1):20-26.
- [4] Łuksa A, Olędzka E, Sobczak M, Dębek C. *Elastomery*. 2005;9(1):25-31.
- [5] Olędzka E, Pyskło L, Sobczak M, Łuksa A. Piroliza zużytych opon w aspekcie technicznym i ekonomicznym oraz uszlachetnianie otrzymanych produktów. *Polimery*. 2006;51(6):407-414.
- [6] Parasiewicz W, Pyskło L, Magryta J. Recykling zużytych opon samochodowych. Piastów: Instytut Przemysłu Gumowego „Stomil”; 2005.
- [7] Koukoulas N, Flueraru C, Katsiadakis A, Karlopoulos E. Fixed Bed Gasification of Biomass Fuels: Experimental Results. *Proc Energy for Sustainable Future Conf.*, Hungary: 2008.
- [8] Piławski M, Grzybek A, Rogulska M. *Ecol and Technol*. 2000; 8(2): 48-53.
- [9] Kowalik P. Development of bioenergy sector in European Union. *Proc. of Oil & Fuels for Sustainable Development AUZO Conf.* Gdańsk: 2008.
- [10] Popczyk J. Development of bioenergy sector in the light of European energy and climate policies. *Proc Oil & Fuels for Sustainable Development AUZO Conf.* Gdańsk: 2008.
- [11] Bridgwater A. Thermal biomass conversion and utilization biomass information system. European Commission, Directorate-General XII, Science, Research and Development B-1049, Brussels: 1996.
- [12] Pyrolysis, Arrow line DA Polska Sp. z o.o., <http://www.arrowline.cz/en/pyrolyza.html>.
- [13] Lewandowski WM, Ryms M. Biopaliwa - odnawialne proekologiczne źródła energii. Warszawa: WNT; 2012.
- [14] Lewandowski WM, Radziemska E, Ryms M, Ostrowski P. *Ecol Chem Eng S*. 2011;18(1):39-47.
- [15] Brammer EA, Brem G. A novel technology for fast pyrolysis of biomass: PyRos reactor. <http://www.brdisolutions.com/pdfs/bcota/abstracts/3/z244.pdf>.
- [16] Roy C, Morin D, Dubé F. The Biomass Pyrolysis Process. In: Kaltschmitt M, Bridgwater AV, editors. *Biomass Gasification & Pyrolysis: State of the Art and Future Prospects*. UK: CPL Press, 1997;307-315.
- [17] Roy C, Blanchette D, de Caumia B, Dubé F, Pinault J, Belanger E, Laprise P. Industrial Scale Demonstration of the Pyrolysis Process for the Conversion of Biomass to Biofuels and Chemicals. *Proc. of 1st World Conference on Biomass for Energy and Industry*. Spain: 2000. In: Kyritsis S, Beenackers AACM, Helm P, Grassi A, Chiaramonti D, editors. London, UK: James & James (Science Publishers) Ltd.; 2001; 2: 1032-1035.
- [18] Rabe RC. A Model for the Vacuum Pyrolysis of Biomass. Master of Science degree, supervisor: prof. JH Knoetze, Dep. of Process Engineering, The Univ of Stellenbosh, Dec. 2005, <http://scholar.sun.ac.za/bitstream/handle/10019.1/1675/Rabe.pdf>.
- [19] Waste Gas Technology Ltd. (UK), www.wgtuk.com.
- [20] RATEch (Poland), <http://www.ratech.com.pl>.
- [21] Ragailler T. Piec obrotowy. Patent Nr 192415 PL, Zgł. P-342160 (24.08.2000).
- [22] U.S. Environmental Protection Agency “San Diego County Demonstrates Pyrolysis of Solid Wastes,” Report SW-80d.2. Washington; 1975.
- [23] Preston GT. *Clean Fuels from Biomass, Sewage, Urban Refuse, and Agricultural Wastes* (Ed. F. Ekman). Institute of Gas Technology, Chicago: 1976; 89.
- [24] Technologia recyklingu całych opon samochodowych. www.phu-gmg.eu.
- [25] Szewczuk M, Przybyłowicz J, Kondlewski T. Budowa urządzenia do pirolizy opon samochodowych - Układ do utylizacji materiałów na bazie kauczuku syntetycznego zwłaszcza opon metodą krakingu. Zgł. Pat. P-368005 (14-05-2004).
- [26] Lewandowski WM, Kondlewski T, Klugmann-Radziemska E, Lewandowski L, Ryms M, Meler P. Technologia ciągłego, bezodpadowego i proekologicznego recyklingu chemicznego całych opon samochodowych, prowadząca do otrzymania zwiększonej ilości oleju opałowego lub napędowego, węgla aktywnego i złomu stalowego. Zgł. Pat. P-388394 (26.06.2009).



PIROLIZA OPON SAMOCHODOWYCH JAKO ENERGETYCZNY RECYKLING BIOMASY

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Abstrakt: Artykuł poświęcony jest opisowi recyklingu materiałowego całych opon samochodowych z uwzględnieniem nowej metody procesu pirolitycznego, w wyniku którego produktem końcowym są: frakcje oleju technicznego (plastyfikator mieszanek gumowych), opałowego lub napędowego (lekkiego, średniego i ciężkiego), węgiel aktywny, gaz opałowy i złom stalowy. Badania ruchowe i eksploatacyjne pilotażowej instalacji, składającej się z trzech wkładów współpracujących z jednym reaktorem pirolitycznym, wykazały, że technologia ta jest możliwa do zastosowania, ale posiada jeszcze pewne wady i błędy zarówno konstrukcyjne, jak i technologiczne, których zazwyczaj nie udaje się uniknąć w pierwszej próbie opracowywania technologii. W pracy opisano zachodzące w wysokich temperaturach procesy pirolityczne, chroniony zgłoszeniem patentowym projekt prototypowej instalacji do recyklingu opon w sposób ciągły oraz wskazano przyszłe kierunki badań w tym zakresie. W pracy opisano procesy pirolityczne zachodzące w pilotażowej instalacji oraz opracowany, na podstawie uzyskanych wyników i zebranych doświadczeń, projekt prototypowej instalacji do recyklingu opon w sposób ciągły, który jest chroniony zgłoszeniem patentowym. Na zakończenie wskazano przyszłe kierunki badań w tym zakresie.

Słowa kluczowe: całe zużyte opony, recykling materiałowy, utylizacja odpadów

