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LABORATORY AND PILOT RESEARCH OF PYROLYSIS PROCESS

LABORATORNÍ A POLOPROVOZNÍ VÝZKUM PYROLÝZNÍHO PROCESU

Abstract

Pyrolysis is a suitable recycling method that leads to a creation of 3 pyrolyzed phases (gas, liquid and solid) and every phase has its possible utilisation. Pyrolysis is a complicated process and its description in the light of system analysis by means co called transport system enables its reduction on a system of masses transport and a system of energy transport. A transport system consists of accumulative elements (a reservoir), transformation elements (a pyrolysis retort, a burner) and transport elements (pipes). In a system of pyrolysis, by means of transformation elements, the following actions are realised: a flow of mass and energy, transformation of input material to a pyrolyzed phase in a transformation element and storage of products in accumulative elements. Quantity and composition of pyrolyzed products are dependent on process conditions of a pyrolysis especially temperature. Pyrolysis of scrap tyres was tested in a laboratory thermic analyzer and in semi operational unit of Pyromatic. Presented article presents results obtained from both devices.

Abstrakt

Pyrolýza je vhodným recyklačním procesem, při kterém z organického materiálu vznikají produkty tří fází (plyn, kapalina polokoks). Každý z těchto produktů má své využití. Systémová analýza umožňuje pomocí transportního systému popsat pyrolýzu jako transport hmoty a energie. Transportní systém je složen ze 3 druhů prvků – akumulačních (nádoby různého typu), transformačních (pyrolýzní retorta, hořák) a transportních (potrubí). V takto definovaném systému dochází k přeměně hmoty a energie vstupního materiálu v transformačních prvcích na jednotlivé pyrolýzní fáze, které jsou následně ukládány v akumulačních prvcích. Kvantita a kvalita jednotlivých pyrolýzních fází závisí na procesních podmínkách pyrolýzy, především na teplotě. Pyrolýza odpadní pryže byla testována v laboratorním termickém analyzátoru a následně v poloprovozním zařízení Pyromatic. Tento článek se v souladu se systémovou analýzou zabývá výsledky experimentálních měření na obou těchto zařízeních.

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1 INTRODUCTION

Production, and consumption of polymers and consequently, waste created by them, increase very sharply every year because these materials have excellent properties (they are resistant, light, workable, etc.) and nowadays are irreplaceable from the point of view of human life. Annual consumption of plastic in west Europe is about 60 *million tons* [1]. OZO Ostrava s.r.o. (Ltd.) company that is engaged in cartage and disposal of waste from the city of Ostrava (the third biggest city in the Czech Republic) and its surrounding villages manipulated with 86.61 thousand tons of municipal solid waste (MSW) in 2009. From that quantity plastics formed 17 *wt. %* of the *MSW*. In this context, there are five main types of plastics contained in *MSW* - polyethylene of high and low density (18 *wt. %*), *PET*, polystyrene, polypropylene, rubber and other kinds of plastics in lower quantity [2].

Upgrading of polymers waste is a necessity for environmental protection and sustainable development. However, nowadays, waste disposal and incineration of polymers (connected with a number of environmental problems, e.g. formation of dioxins) are the most commonly used methods.

Pyrolysis of polymers waste can be a perspective way for their conversion into valuable products and for a reduction of their volume. Generally, pyrolysis is a thermal degradation (without oxygen agent) leading to char, oil and gas production, which have a big potential as useful end products.

Many articles were published about pyrolysis especially in laboratory scale but there are still unexplained areas which can contribute to better understanding of pyrolysis process and better utilisation of waste material processed by pyrolysis in semi operation scale. Simplification of pyrolysis process by system analysis and connection of knowledge from laboratory and semi operation scale pyrolysis affords better look at pyrolysis process, at better understanding of material and energy transportation, at transformation of waste material via thermo chemical reaction in a pyrolysis chamber and at accumulation of pyrolysis phases. The aim of this work is theoretical and practical understanding of pyrolysis of scrap tyres under various conditions and scales of pyrolysis unit. We try to find optimal conditions of pyrolysis of scrap tyres leading to maximum quality and quantity of solid and gas yields.

Many experimental studies (from laboratory to semi operation scale) on the disposal of scrap tyres have already been reported by various researchers but many problems are still far from solution. Due to high calorific value of pyrolysis products they can be used to support pyrolysis process. Liquid and solid phases can be also stored and consequence used for next valorization (e.g. ash-free combustion or rubber industry) [3]. Gas phase can be used in situ e.g. for gas turbines. Baggio et al. [4] designed pyrolysis as a system which consists of two pyrolysis lines connected with two gas turbines. The system described the energy and the environmental impact of the pyrolysis of municipal solid waste. Temperature affected only the distribution of the electric production between turbines while whole system did not effected by temperature. Pyrolysis can be also described by mathematical model of heat and mass processes [5]. This model enabled quantitative understanding of scrap tyres pyrolysis. Optimal pyrolysis conditions depends on types of pyrolysis unit and material and not only temperature but also heating rates influenced the product composition and kinetic. For example, Barboti et al. [6] studied pyrolysis of scrap tyres in a stainless steel tubular reactor and optimum conditions using computer program "Optimization Techniques". The maximum yields of pyrolysis solid and liquid phase were temperature 430 *°C*, particle size 10 *mm* and a flow rate of nitrogen 0.35 $m^3.h^{-1}$.answer.

1.1 Theoretical

A system is a hypothetical concept that people choose for easier view on a real object around themselves. A system is chosen for better understanding and operating of features of a real difficult object. A system is a simplified real object and we can process it, change its status or change its feature. System approach is concerned with solving of problems in complexity.

Generally, a system is an ordered set of elements. Elements interact among each other by mutual links. An element is a part of system which is further impartible and it has an undistinguishable structure. A subsystem is a subset of elements and links that are segregated from

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a system for some reason. Such subsystem is considered to be a new system. Fig. 1 provides documentary evidence for a scheme of a system and its surrounding.
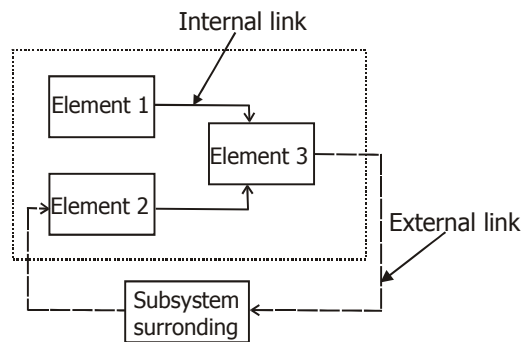

Fig. 1 Scheme of System.

First step of a system formation is to determine a kind of a system. There are many types of systems but according to Strakoš [7] every system looks like a "transportation system". However, there is a necessity to specify and to define what will be transported in this system whether it deals with material, energy, people, information, etc. or not. In this case we will choose elements that participate in transportation, in transformation (a change of features) or in accumulation (stocking) of a selected medium. From this point of view, systems are composed of three types of elements:

- Transportation elements (e.g. streets, pipelines, routes, etc.)
- Transformation elements (e.g. a cogenerative unit, an engine, a computer, etc.)
- Accumulative elements (e.g. a chamber, a reservoir, a memory in a computer, etc.).

For a system formation there are three concepts which are very important - (i) a structure of the system, (ii) static features of the system and (iii) dynamic features of the system. Every system exists in some surroundings and it is important to define only an essential surrounding which have a direct contact with the system. We are not interested in links in surroundings of the studied system.

System analysis describes system performance of a system with known structure. On the opposite side, system synthesis describes system performance of a system with an unknown structure. The analysis provides a unique solution, the synthesis does not. Systems with various structures can have the same performance. It is very important to find a structure that is most relevant to a given performance in the system theory [8]. The system analysis permits to analyse connections between a technological and an energetical subsystem, as well as internal connections in the subsystems.

2 EXPERIMENTAL

Pyrolysis experiments have been carried out using a simultaneous laboratory apparatus TG-DTA NETZSCH STA 409 EP. All the experiments have been conducted in the crucibles (aluminium oxide) in dynamic inert atmosphere of argon (with the flow rate of 100 $cm^3 min^{-1}$) with heating rate of 10 °C/min and maximum temperature 380, 450, 500 and 1200 °C. Material for pyrolysis used during the presented research was scrap tyres (denoted ST) from personal cars and its proximate and elemental analysis is documented in Table 1.

Tab. 1. Proximate and elemental analysis of ST, gross calorific value (GCV) of ST.

Moisture	Volatile	F. carbon	Ash	C	H	N	S	O	GCV
	[wt.%]					[%]			[J.g^{-1}]
0.7	62.3	32.7	4.3	85.3	0.3	0.3	2.3	0.01	38034

Pyrolysis was also tested in a semi operational range in a pyrolysis device of Pyromatic (Fig. 2). This unit processes organic raw materials at intake of 50 *kg* up to 150 *kg* per an hour. It deals especially with waste rubber, selected parts of municipal waste and unemployed parts of assorted waste. The unit is created by a few partial devices that enable to execute the whole technological process. That means a transport of input material to a retort, heating the material up under barred access of air, modifications of created pyrolyzed gas and transport of solid and liquid products.

Delivery of input material is realised by a belt conveyer that feeds it to a hopper from which it is advanced further by means of a snail conveyer to a reactor. The raw material is under parallel shifting pyrolyzed in a snail reactor. The shift is realised by snails - two primary ones and one secondary one which advances material back to the input part of the retort.

Pyrolysis proceeds under temperature from 500 °C to 800 °C and time of material stay in the retort ranges from 45 *min* to 1 *hour*. Created pyrolyzed gas is taken from the retort to a cyclone and consequently to aerial and hydraulic coolers. Heat for material heating up is supplied by indirect heating from five gas burning sections that are placed in sequence under the retort. Burners' arrangement under the whole retort's length enables to regulate required thermal intake to individual sections in dependence on already achieved temperature of pyrolyzed material. For the time being, natural gas has been used for heating. Maximal thermal input of the furnace is 200 *kW*.
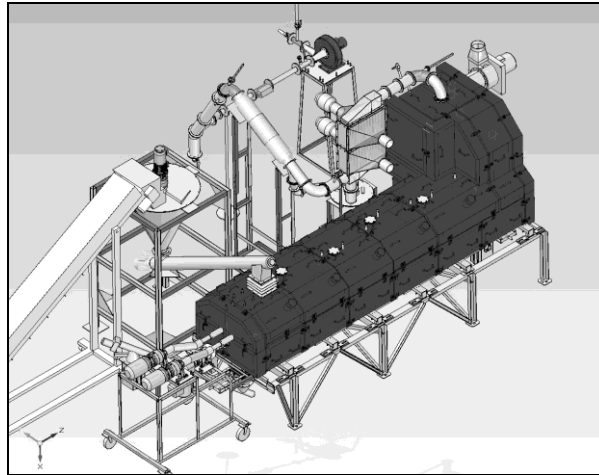

Fig. 2. Pyrolysis unit Pyromatic.

3 RESULTS AND DISSCUSION

Pyrolysis is a system defined as a set of installations and equipment with internal relationships between them and external relationships with the environment. This type of a system is divided into distinguished subsystems – in a technological subsystem (consisting of technological processes) and an energy subsystem (energy, heat). If pyrolysis is a transportation system, we can reduce it and simplify it to a flow of mass and a flow of energy. Then, this type of the transportation system consists of transportation of material (Fig. 3) or transportation of energy (Fig. 4).
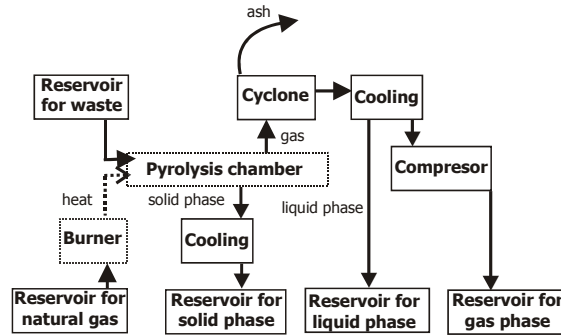
Fig. 3. Pyrolysis as a transportation system of material.

We can deduce that pyrolysis as a transportation system consists of three types of elements:

(i) a pyrolysis chamber and a burner are transformation elements (in Fig. 3 a dotted rectangle). Material (ST) and energy (heat) is delivered into a pyrolysis chamber. Inside the pyrolysis chamber, waste material warms up and thermo chemical reactions take place here. From the pyrolysis chamber two streams flow away: (i) a solid phase and (ii) gas (hot volatiles). The solid phase is after cooling collected in a reservoir. This phase is composed of carbon black and inorganic compounds and can be used in rubber or pigment industry. Volatiles are after cleaning them in a cyclone cooled and consequently separated into two phases – gas and liquid phases. Gas phase contains light hydrocarbons (less than C6). The gas phase has high gross calorific value and can be used for example for electricity production. High hydrocarbons (more than C6 or aromatic compounds) form a liquid phase. Liquid phase can be used in fuel industry. Natural gas is fed into burner where it is oxidized. Heat is formed for heating the pyrolysis chamber up

(ii) Reservoirs for waste, natural gas and output pyrolysis phases are accumulative elements (in Fig. 3 a line rectangle).

(iii) Pipelines with different section and length are transportation elements. A cooler is generally a transportation element too because warm gas flows around cooling medium and its heat is taken away. The heat is transported into a cooler by warm gas and taken away by cooling medium.
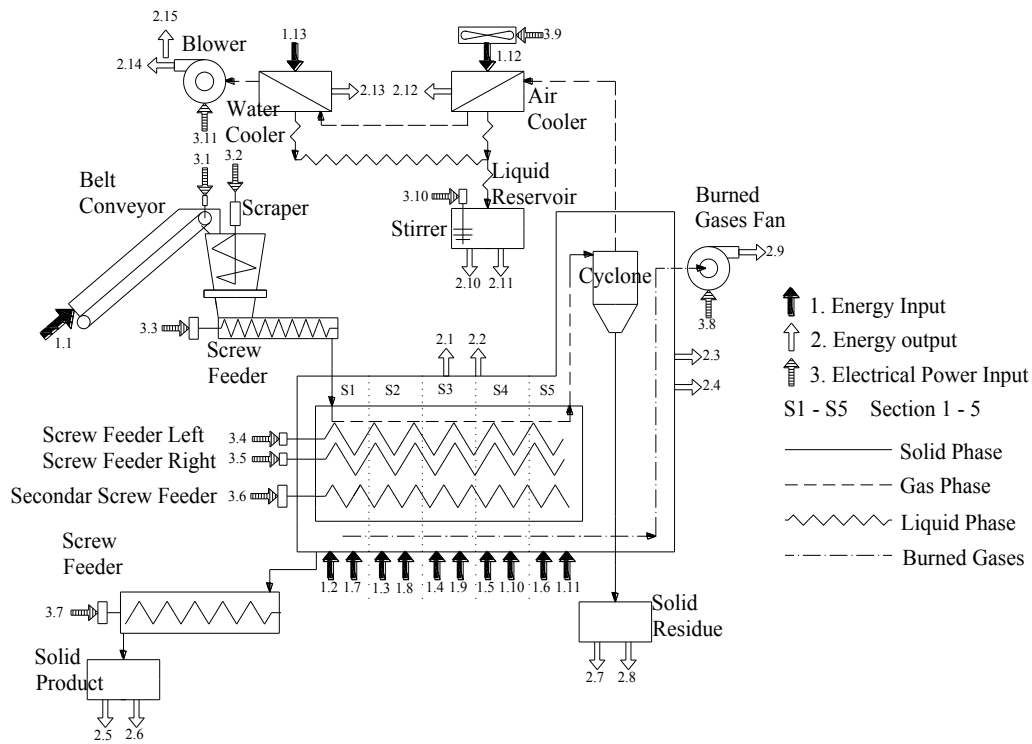
Fig. 4. Energy flows in Pyromatic pyrolysis system.

Key:

1.1 Energy input in material
1.2 - 1.6 Input of chemical and physical heat in heating has (natural gas)
1.7 - 1.11 Input of physical heat in burning air
1.12 Input of physical heat in cooling air
1.13 Input of physical heat in cooling water
2.1 Thermal losses through unit wall by free convection (around reactor)
2.2 Thermal losses through unit wall by radiation (around reactor)
2.3 Thermal losses through unit wall by free convection (around cyclone)
2.4 Thermal losses through unit wall by radiation (around cyclone)
2.5 Chemical energy in solid product
2.6 Loss by physical heat in solid product
2.7 Chemical energy in solid residue from cyclone
2.8 Loss by physical heat in solid residue from cyclone
2.9 Thermal loss in waste burned gases

2.10 Chemical energy in liquid product
2.11 Loss by physical heat in liquid product
2.12 Loss by physical heat in heated cooling air
2.13 Loss by physical heat in heated cooling water
2.14 Chemical energy in gas product
2.15 Physical heat in gas product
3.1 El. input power for belt conveyor
3.2 El. input power for scarper
3.3 El. input power for screw feeder
3.4 El. input power for left screw feeder
3.5 El. input power for right screw feeder
3.6 El. input power for secondary screw feeder
3.7 El. input power for screw feeder of solid product
3.8 El. input power for burned gases fan
3.9 El. input power for air cooler
3.10 El. input power for liquid stirrer
3.11 El. input power for blower

Fig. 3 and Fig. 4 are simplified due to absence of transportation of cooling medium, transformation of gas phase to electricity, transport of natural gas etc. because these elements belong to sub-systems around our defined system.

On a basis of these figures, pyrolysis can be divided to the following processes:
- preparation of input material (warming, expression of air and water vapours, entering the pyrolysis chamber),

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- pyrolysis (warming to required temperature, external and internal transport of heat and mass, chemical reaction, separation of gas and solid phase),
- cleaning (separation of a solid phase from gas in a cyclone),
- cooling (cooling of gas and solid phase and heat removal),
- storage (storage of input and output materials).

Tab. 2 Mass and energy flow in system Pyromatic (selected flow).

| | | Temperature [°C] | | | |
		500	550	600	650
Input Mass/volume	Mass flow-material [kg.s^{-1}]	0.0083	0.0083	0.0083	0.0083
	Flow rate-natural gas [m^3_N.s^{-1}]	0.0011	0.0016	0.0019	0.0022
Input energy	El. energy 3.1-3.11 [kWh.30min^{-1}]	1.37	1.72	1.82	1.93
	Power in NG 1.2-1.6 [kW]	40.20	58.27	69.75	79.69
Output Mass/volume	Flow rate-waste combustion [m^3_N.s^{-1}]	0.0284	0.0412	0.0495	0.0566
	Volume flow- gas phase [m^3_N.s^{-1}]	0.0018	0.0023	0.0021	0.0028
	Mass flow-solid phase [kg.s^{-1}]	0.0034	0.0031	0.0030	0.0026
	Mass flow-liquid phase [kg.s^{-1}]	0.0027	0.0029	0.0028	0.0027
Output energy	Power in waste combustion 2.9 [kW]	10.99	18.07	22.84	29.34
	Power in PG (chem., NCV) 2.14 [kW]	55.76	64.94	69.62	88.72
	Heat loss 2.1-2.4 [kW]	10.70	12.73	14.96	17.09

Production of energy amount depends on energy consumption of elements of the system. For this reason there is interdependence between production of energy and elements in the system and the system can be solved in more complex way. Energy flow in a concrete system of pyrolysis is described in Fig. 4. The figure is related to Pyromatic pyrolysis unit described above where various kinds of materials under various process conditions have been tested. The aim of tests and measurements in relation to the article subject is a determination of transformation degree of inputs to the system (chemical energy of heating gas and a charge) per individual outputs from the systems (chemical energy and material heat of individual products, thermal losses) and description of all energy flows in Pyromatic device as a system of pyrolysis.

Values of individual energy flows into system elements are stated in Table 2. These values were measured and analysed during a continual operation of the pyrolysis unit. Individual flows are numbered in accordance with Fig. 4. Calorific value of pyrolysis gas was determined on a base of chemical composition analysis.

From Fig. 4 and on base of concrete data from Table 2, a transformation process of heating gas chemical energy to physical energy of products of combustion is obvious. The energy is burned off on the one hand on the pyrolysis itself and on the other hand on reimbursement of thermal losses, (flue loss and heat transmission to surroundings). Chemical energy from mass of input material is changed by influence of physical energy of burned gases to chemical energy of gas, liquid and solid product then. Mechanism of this transformation is constant. However, with a change of process conditions (temperature, pressure), the amount of chemical energy in individual products (per a unit) is different. Further, it results from Table 2 that flow of gas pyrolyzed phase and its physical heat increase with increased temperature of the pyrolysis process. On the opposite, the flow of liquid and solid pyrolyzed phase decreases. At the same time, energetical quality (net calorific value) of gas product falls. Further, a flow of heating gas, volume flow of burned gases and thermal losses of the whole device increase with increasing temperature of the pyrolysis. Understandably, consumption of electrical energy per 30 *min* of operation under constant input power for all temperatures differs minimally.

3.1 Transportation Elements

A transportation element is a basic element in transportation systems. According to Fig. 3 a transportation element removes material (waste) or energy (heat) from one element to another element. Generally, a transportation element has one input and one output and transports whatever we need. An input of energy, sometimes also water and air, is a necessity for realization of a transport. During the transportation some energy is consumed. It means energy, water or air are released to other elements. A transportation element picks material or energy up for transport from a place where material or energy is stored (e.g. a reservoir, storage, a container or others). Technical support is a system which provides all needed for a transportation element.

3.2 Transformation Elements

Thermo gravimetry and kinetics

A transformation element changes properties or a form of input magnitude – material, raw material, energy or others. This element is generally the most important element in the system because this element transforms raw material into end products or energy. On the other hand, it is very important to point out that without transportation and accumulation elements this element will not work.
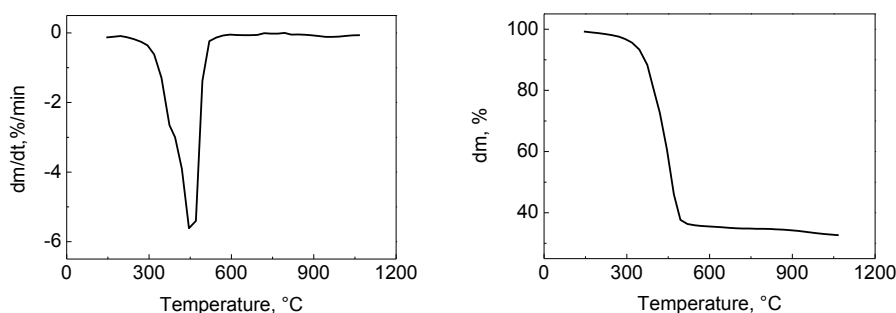

Fig. 5. TG and DTG curves of pyrolysis of ST, measurement conditions: 10°C/min, max. temperature 1200°C.

Pyrolysis of ST proceeds in two stages (Fig. 5). First peak at temperature about 359 *°C* corresponds to oils, plasticators and additives vaporization. Second peak at temperature 438 *°C* fits into rubber decomposition. ST are composed of three types of rubbers – nature rubber (NR), butadiene rubber (BR) and styrene-butadiene rubber (SBR). Maximum weight loss of NR is at 373 *°C*, of BR at 372 *°C* and of SBR at 372 *°C* and at 429-460 *°C*. According to DTG curves these three rubbers decompose together over temperature region 372-460 *°C* [9], that respond with our measurement.

Tab. 3. Weight loss and characteristic temperatures of pyrolysis of ST in a laboratory apparatus.

Temperature	Weight loss	T_I^1	T_{max}^2	T_F^3
[°C]	[wt.%]		[°C]	
1200	66	05	359. 438	70
500	64	15	359. 431	00
450	52	04	357.000	50
380	24	11	351.000	80

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The characteristic temperatures determined from DTG curves are documented in Table 3, including these parameters: temperature of (i) initial weight loss (T_I), (ii) the end of the reaction (T_F) and (iii) maximum pyrolysis rate (T_{max}). T_{max} is related to material structure and usually plastics with similar structure have almost the same value [10]. Accuracy of determination of T_I/T_F is quite difficult due to deciding when weight loss begins/ends, whereas T_{max} is easier to determine because it responds to the maximum of peak. DTG curves document that pyrolysis of ST start at about 305 $°C$ and end at about 570 $°C$. Above temperature 600 $°C$ is not weight loss on the upgrade and its value is 66 *wt. %*.

Heat and mass transport affect pyrolysis rate and there are three transport processes that influence a total rate: (i) intra particle transport that is affected by particle size, (ii) particle-to-fluid transport that depends on inert gas flow rate and particle size and (iii) inter particle transport that depends on a number of layers of particles in a sample basket. For a fixed particle size and for one basket, the third process can be studied by changing a weight of an initial sample [11]. For these reason characteristic temperatures of pyrolysis in a semi operational range pyrolysis unit are shifted to higher temperatures due to bigger particle size, weight of ST and larger scale of Pyromatic.

Product yields of pyrolysis

The gas, liquid and solid phases obtained in the ST pyrolysis in Pyromatic carried out at 500, 550, 600 and 650 $°C$ are presented in Table 4. These temperatures were chosen according to thermogravimetric measurements. It can be seen from this table that at every temperature pyrolysis was complete because gas and liquid yields are close to theoretical values expected from TG curves of ST analysis (66 *wt.%*). At the temperature 600 and 650 $°C$ amount of solid phase is higher than theoretical value derived from TG curves (34 *wt.%*). Literature explains that a certain amount of char or coke-like carbonaceous material is formed in the pyrolysis of many polymeric materials, due to secondary repolymerisation reactions among the polymer-derived products. With increasing temperature increases amount of gas phase and conversely decreases amount of liquid phase. This is probably caused by the strong thermal cracking at this temperature [12].

Tab. 4. Product yields from pyrolysis of scrap tyres in Pyromatic aparatus.

Temperature [°C]	Gas phase	Liquid phase [*wt.%*]	Solid phase
500	26.5	32.5	41.0
550	27.8	34.9	37.3
600	30.2	33.7	36.1
650	36.2	32.5	31.3

Table 5 lists the composition of gas phase. The gases were mostly hydrogen and light hydrocarbons. The presence of CO and CO_2 in the gas phase is derived from decarbonylation and decarboxylation reactions (from oxygenated organic compounds - stearic acid, extender oils or inorganic components – $CaCO_3$, metal oxides) or secondary oxidation reactions of carbon [13]. An increase of temperature led to increase in all gases except CO and CO_2. Gross calorific value (GCV) is for every temperature comparable and its value is about 34 $MJ.m^{-3}$. This value is comparable with other authors [13 - 15].

Tab. 5. Average abundance of important components in gas from pyrolysis of scrap tyres in Pyromatic

Temp. [°C]	H_2	CO	CO_2	CH_4	C_2H_4	C_2H_6 [%]	$\sum C_3H_Y$	$\sum C_4H_Y$	$\sum C_5H_Y$	$\sum C_6H_Y$	GCV [MJ.m^{-3}]
500	12.4	2.8	2.4	17.9	3.0	4.4	5.6	4.2	4.5	0.8	33.9
550	13.3	3.7	2.3	19.8	3.9	4.7	5.2	3.6	2.4	1.0	31.4
600	22.2	3.1	1.9	29.2	4.0	4.9	5.4	3.7	2.5	1.1	37.1
650	28.3	2.9	1.4	4.6	5.2	6.3	7.0	4.8	3.2	1.4	34.7

The elemental composition, GCV and moisture and ash content of the 500 to 650 °C pyrolysis solid phase are presented in Table 6. With increasing temperature increase amount of carbon and GCV. Compare to commercial carbon blacks, composition of solid phase pyrolysed at 650 °C has the most comparable composition. [12]

Tab. 6. Elemental analysis of pyrolysis carbon black.

Temperature [°C]	C	H	N	S [%]	O	Moisture	Ash	GCV [MJ.kg^{-1}]
500	85.13	0.53	0.18	2.44	0.00	1.71	10.67	29.72
550	85.84	0.54	0.24	2.49	0.00	1.38	10.21	30.42
600	86.31	0.58	0.27	2.63	0.00	1.22	10.54	30.32
650	87.88	0.57	0.21	2.19	0.03	0.97	9.09	30.91

Commercial carbon black contains less amount of ash. The ash containing in the pyrolytic residues come from the inorganic fillers (stell excluded) of the original ST. With increasing amount of inorganic compounds increased amount of ash that confirms Fig.
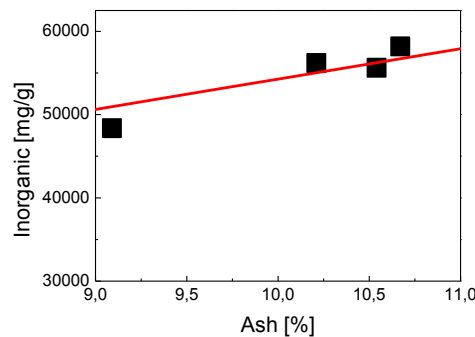

Fig. 6. Amount of ash in pyrolytic solid phase depending on inorganic compounds.

3.3 Accumulative Elements

Reservoir is one from accumulative elements where material or energy is stored and consequently delivered to a transportation element. An accumulative element is gradually in filled – we sum up what is filled in inside the element. For this reason this element is very often called an integration element. This element has real static and dynamic properties of an integration element.

Reservoirs are stores, containers, gas-holders and others. Inside each reservoir there is a space for storing and input and output is the same. An input of a reservoir is an output from a transportation element and an output of a reservoir is an input to another transportation element. Energy (air or water) is also important for transport of that what we need.

From the text mentioned above a question is rising – what type of the element is a real cooler? In general, a cooler has two inputs and two outputs and it is not a basic element of a system but element's composing from several basic elements. Fig. 7 documents one from two possible reductions of coolers in the system and it is called semi-parallel connection. On the left side, there is a cooler with main stream of pyrolyzed gas from the pyrolysis retort. Pyrolyzed gas is cooled in a cooler and it is separated into two parts – gas phase and liquid phase. On the right side, the main stream is heat from warm pyrolyzed gas. Cold water is warmed by pyrolyzed gas up and at the output warm water is used for other applications (e.g. vapour in other production process).

We choose one from these two reductions according to our needs. For this reason system analysis is so advantageous because we can choose substantial things useful for clear understanding of properties of analysed process.
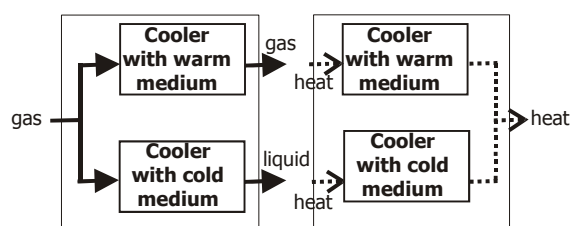
Fig. 7. Two Views on Cooler, left: Main Stream is Pyrolyzed Gas, right: Main Stream is Heat.

4 CONCLUSIONS

Pyrolysis is a very complicated process from chemical point of view as well as from energetical point of view. The article deals with pyrolysis process description in terms of system analysis what enables a new look at pyrolysis as a system and easier understanding of the pyrolysis as a whole and further with thermogravimetric measurements and its application in a semi operational range in a pyrolysis device of Pyromatic.

Pyrolysis was defined as a so-called transport system of mass and energy. A transport system consist of three elements - (i) a transformation element (a pyrolysis retort and a burner) in which energetical transformation of material proceeds, (ii) an accumulative element (reservoirs) in which input materials, output materials and products are stored and (iii) a transportation element (pipes) by which material or energy are transported. In the article, the individual mass and energy streams and their transformation are described in details as regards of a process in laboratory equipment as well as in semi operational equipment.

Authors of the article come to the conclusions on quality and quantity of process products and energy demands leading to their creation. It can be said that temperature is a basic process condition that influences a degree of transformations in the system. On the one hand ratio of individual final products created from a unit of charge mass on the other hand sole features of created products in the system are dependant on temperature. Temperature 650 °C is the most suitable temperature for pyrolysis of scrap tyres in a semi operational range in a pyrolysis device of Pyromatic. This temperature leads to (i) highest ratio of gas and (ii) comparable composition of solid phase to commercial carbon black.

Already many articles have been written and many papers have been given on pyrolysis and yet, under the authors, there are still new approaches that might bring a different focus on this process.

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