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STUDY OF TECHNOLOGICAL PARAMETERS OF PYROLYSIS OF WASTE TIRES UNDER STATIC LOAD

Introduction. *Disposal of waste tires is a pressing problem in our country, since their amount has been constantly increasing. Inadequacy of the existing methods for thermal waste tire utilization has given rise to the necessity of developing an advance technology for their pyrolysis combined with static load.*

Problem Statement. *Since no data on specific features of work process are available, this complicates the adjustment works and implementation of waste tire utilization by thermal decomposition under static load in industrial conditions. The determination of specific features of waste tire destruction in the reactor under static load is a relevant problem to be solved.*

Purpose. *To determine the physical parameters of waste tire destruction in the pyrolysis reactor, under static load.*

Materials and Methods. *To assess the effectiveness of the proposed method a series of experiments have been carried out. It includes the conventional pyrolysis of grinded waste tires in the reactor and tire pyrolysis under static load. Using* COMSOL Multiphysics *program, the physical parameters of vertical pyrolysis reactor filled with tires under temperature effect and static compression have been studied.*

Results. *Diagrams that show thermal conductivity and distribution of temperature field inside the pyrolysis reactor in the case of compaction of processed products have been built using the method of end elements and solution of differential thermal conductivity equation. The time of tire stay in the reactor has been estimated as 7.8 hours. Optimal pressure on tire, which is required for maximum compaction has been determined.*

Conclusions. *Raising performance of the plant for waste tire utilization by introducing static load into the process technology for multi-contour circulation pyrolysis has been substantiated. The use of static load has been shown to be an effective method, as it leads to an increase in the thermal conductivity coefficient of waste tire mass in the reactor and, consequently, a more even temperature distribution in the compacted tire mass.*

Keywords: multi-contour circulation pyrolysis, waste tires, static load, compaction, thermal conductivity, and modelling.

The intensively developing transport links and increasing economic value of world transportations result in the fact that in the next few years the problem of rubber waste (RW) utilization and disposal will be very important and require effective solutions.

To solve this problem and to study the possibility of waste tire utilization, there has been carried out a research using a plant for multi-contour circulation pyrolysis (MCP) developed at the Admiral Makarov National Shipbuilding University.

To intensify thermal destruction, to raise the equipment efficiency, to ensure continuous operation and the possibility of full utilization of waste tires, a technique based on combination of MCP and stationary load [1] has been proposed.

The innovative technology for RW utilization by thermal decomposition under the action of static load is based on the principle of increasing the thermal conductivity of the whole mass of tires in the reactor due to achieving the maximum consolidation of tires during their pyrolysis, which enables to pressurize excessive air or other gas with low thermal conductivity from the mass of tires to be utilized [2].

Now, the research is at the stage of theoretical substantiation and development of design documentation, but there is no practical knowledge of the equipment working process, which complicates the commissioning and implementation of rubber waste utilization by thermal decomposition under the action of static load, in industrial conditions.

Main efforts towards raising the efficiency of pyrolysis are focused on optimizing efficiency of plants, intensifying the formation of vapor-gas mix and increasing the yield of target products that can be used as alternative fuel.

Thus, the most important research task is to obtain experimental data on the possibility of optimizing the thermal physical regime of the reactor at the established operating parameters of the pyrolysis process and to compare the thermal and operational parameters of the process with the traditional pyrolysis of rubber waste on the MCP technology and those of rubber waste utilization with the help of thermal decomposition under the action of static load.

The analysis of recent studies and publications on the combination of thermal destruction processes and static load for rubber waste utilization has not yielded any results. However, there are technologies for rubber waste utilization based on traditional pyrolysis combined with mechanical methods. In research [3], a mechanothermal way of rubber waste utilization has been proposed, calculations of the capacity required for treating waste tires and other rubber products have been given, and advantages of the method proposed by the authors as compared with the usual methods of pyrolysis have been proved. The obtained capacity is 2—3 times less than that required for conventional rubber pyrolysis.

To evaluate the efficiency of rubber crumb utilization, vulcanization by thermal and thermomechanical methods in M-100 fuel oil has been studied in [4]. As a result, it has been established that the thermomechanical vulcanization is the most promising and efficient method, since it enables to reduce the process time down to 2—3 hours and to decrease energy consumption.

An overview of researches directly related to the static load and deformation of rubber products in different configurations and areas of their application has showed that a special approach to calculating the elastically deformed state of rubber vibro-isolators, which regards the contact interaction with the design details was proposed [5, 6]. In [7], a stand for static and dynamic tests of pneumatic tires has been developed to determine the coefficients of normal stiffness and inelastic resistance of the tire.

The temperature effect on the strain-strength properties of high-filled composites based on polyethylene and rubber particles has been studied in [8]. It has been established that stretching does not lead to any practical change in the strength of rubber sheets containing from 36 to 66% of elastomeric as filling rate increases. At the same time, the strength decreases as temperature goes up.

There are also researches on mathematical modeling of hydrocarbon waste pyrolysis. Research [9] deals with the practical application of *FlowVision* software system when developing equipment for the pyrolysis plant for waste utilization. The temperature distribution during utilization and the distribution of velocity vectors of hot gas flows have been calculated using the finite element method, which enables to evaluate the effectiveness of the design of pyrolysis equipment.

The surface mechanism of methanol synthesis on a low temperature Zn-Cu-Al-catalyst has been studied in [10], and the efficiency of the upgrade of plant technological scheme has been assessed using the developed mathematical model for methanol synthesis.

For utilizing whole waste tires, modern technologies use recycled pyrolysis reactors that operate in cyclic mode. Such methods lead to energy losses in each heating-cooling process and to the emissions of harmful substances into the environment as a result of pressurization failures of equipment [11, 12].

The analysis of pyrolysis technologies for the recycling of rubber waste has shown that the existing plants use techniques based on grinding of raw materials. The process requires additional equipment and energy costs, which is inexpedient [13].

The difference between the above-mentioned technology and the others is the presence of a multi-contour circulation system that returns heavy condensed pyrolysis products to the reactor using the cooling loops [14]. As a result of this recycling process, high-energy pyrolysis gas and low molecular weight liquid fuel are produced [14]. Combined with static load, this technology does not have any analogs, which gives reason for studying the mentioned method and for justifying the expediency and efficiency of the proposed technology.

The purpose of research is to determine the physical parameters of the process that takes place in a pyrolysis reactor filled with tires under static load, using modern achievements of fundamental science and computer software tools for modeling and calculating the technological process.

The main tasks of research are to optimize the waste utilization using static load in order to reach maximum yield of vapor-gas mixes (VGM) and to determine optimal regime parameters for pyrolysis reactor (compaction, heat conductivity, and distribution of temperature filed inside the reactor). Among the tasks there are the calculation of reactor efficiency in the course of continuous load of tires and their compaction during pyrolysis and the determination of optimal pressure on tires in the reactor.

The thermal destructive utilization of rubber waste is realized by heating them in closed MCP reactor and is a complex physico-chemical process consisting of simultaneous heating, chemical decomposition of waste mass, and secondary reactions of vapor and gaseous products of destruction.

The amount and type of rubber in the rubber waste to be treated defines the parameters of utilization and the main products of destruction. Therefore, in order to improve and to optimize the MCP technology, the composition of waste tire and rubber waste has been analyzed. Based on the analysis results, the parameters of physico-chemical processes related to the thermal destruction of wastes in the reactor of MCP plant can be determined.

The chemical and component composition of gaseous mixes and waste rubber products are given in Table 1.

The analysis of rubber waste element composition has shown that they contain many various components, but the total share of these components does not exceed 4—6%. This means that the basic components of waste are natural rubber and various types of synthetic rubbers consisting mainly of carbon and hydrogen, as a result of which the rubber waste has a high calorific capacity that enables to utilize them without the use of additional energy resources.

The patented technology for RW utilization by thermal decomposition under the action of static load [15] is based on mechano-thermal destruction and depends on pressure, force acting on the tire mass in the reactor, and on temperature. The rubber destruction starts with rupture of the weakest chemical bonds. As temperature increases, under the static load, the strength of vulcanization grid goes down due to the destruction of active chains in rubber waste.

Mechanical forces that stretch but not break the chain molecules can change the reaction ability of chemical bonds and to influence the rate of chemical reactions. As a result, the activation energy decreases, and thermal destruction gets faster. This process is accompanied with the loss of a part of waste as a result of depolymerization reactions, and the rubber waste utilization gets intensified.

Above the flow temperature, there occurs thermal decomposition of the elastomer's molecular chains, which is accompanied by releasing low-molecular-weight volatile substances and forming the initial (VGM) of heavy macromolecular compounds. Table 2 shows the generalized process of RW thermal destruction.

Table 3 shows the key characteristics of destruction of basic types of rubbers in the case of

Table 1

Chemical Composition of Various Rubber Wastes

Rubber products	Chemical composition		Morphological composition	
	Component	Content, %	Component	Content, %
Standard rubber	SKN-26 rubber (butadiene trical)	48.11	Natural rubber	15—18
	SKI-3 rubber (isoprene)	47.16	Synthetic rubber	25—28
	Oil residues	0.381	Metal	9—12
	Technical sulfur	0.152	Textile	5—6
	Thiuram	0.762	Technical carbon	20—23
	Zinc white	3.049	Other components	10—13
	Stearin	0.381		
Waste tires	SKI-3 rubber (isoprene)	42.81	Rubber	86.5
	SKD rubber (butadiene)	43.95	Metal cord	8.33
	Technical sulfur	0.16	White carbon	0.27
	Carbon	8.89	Other components	4.90
	Other components	4.80		
Waste pneumatic tires	SKS-30 rubber (butadiene styrene)	86.86	Rubber	96
	Carbon	0.30	Steel	4
	Manganese	9.20		
	Silicon dioxide	0.05		
	Iron	3.40		
	Technical sulfur	0.18		
Waste tires with textile cord	BK butyl rubber	84.4	Rubber	95
	Iron	3.2	Steel	4
	Silicon dioxide	0.5	Capron	1
	Manganese	0.6		
	Carbon	10.8		
	Technical sulfur	0.17		
Waste tires with metal cord	STS rubber (chloroprene)	43.8	Rubber	76
	BK butyl rubber	44.1	Steel	17
	Iron	3.1	Textile	7
	Technical sulfur	0.149		
	Carbon	8.51		

their utilization and initial temperature of their decomposition (T_{dec}, °C).

VGM continuously ascends and goes from the reactor to the multi-contour circulation system for further separation. This results in decreasing the weight and volume of RW that are loaded to the reactor and constantly undergo thermal decomposition.

Materials of which modern tires are made are very diversified, but contain natural or synthetic rubbers characterized by low conductivity. Their pyrolysis is characterized by thermal destruction indices that can essentially differ from each other, but all of them definitely react on maximum temperature of heating, with the rubber destruction depth during pyrolysis depending only by the duration of thermal impact on the rubber. Taking into consideration the fact that the fractional volume of whole tires in the pyrolysis reactor is low, and the amount of rubber makes up several per cent of the empty space inside the reactor, the main task of pyrolysis is to ensure maximum heat transfer and, respectively, maximum temperature inside the pyrolysis reactor.

As the static load acts on the tires in the reactor, the entire thermoplastic rubber flows and fills all void spaces thereby forming a solid mass of compacted rubber with base rings in it. Due to the compaction, the tires are deformed and their volume in the reactor changes, which leads to an increase in the fractional volume of whole tires in the reactor's bottom section up to 0.97—0.99 % [15].

The physical properties of the mass in the reactor, in particular, its density and thermal conductivity, change depending on the aggregate state of rubber and mutual arrangement of the base rings. The transition of thermoplastic rubber into a gaseous gas-vapor mix of hydrocarbons is associated with consuming the phase transition heat both for the work of expansion and for the work against the forces of intermolecular interaction. The phase transition is accompanied by a sharp change in the density of tire mass.

The presented mechanism of rubber waste thermal decomposition using static load gives a reason for simulating the intensity of VGM formation in the reaction zone, i.e. in the reactor.

Table 2

Chemical Destruction of Rubber Waste

Stage and temperature of destruction, °C	Radicals and chain mechanism	Chemical reactions	Reaction products
First stage, 250–380	The formation of free radicals; the growth of the reaction chain is accompanied by a rupture of bonds and a decrease in the molecular weight	Depolymerization with the formation of monomer and other low molecular weight substances	Evaporation of various rubber components, such as special additives, oils, and plasticizers
Second stage, 400–550	Interruption of the reaction chain occurs by recombination or disproportionation of free radicals. The appearance of double bonds at the ends of macromolecules, the change in the fractional composition, and the formation of branched and spatial structures	Change in the degree of unsaturation; cyclization and isomerization. Cross-linking and destruction of macromolecules	Destruction of natural rubber, butyl and butyl styrene rubbers

Table 3

The Composition of Cracked Rubbers of Various Types

Rubber type	T_{dec}, °C	Monomer yield	Basic rubber pyrolysis products	Content, % per rubber
Natural rubber	198	Isoprene Dipentene	Isoprene 2-methylpentene-2	24.0 1.45
Chloroprene (neoprene) rubber	227	Chloroprene	Benzene Toluene	2.70 1.62
Butyl rubber	248	Butylene Vinylcyclohexane	M-Xylol Tetrahydroethyl toluene	1.94 1.80
Butadiene styrene rubber	254	Butadiene Vinylcyclohexane Styrene	Dipentene Heptens Hexens	29.0 3.80 4.16
Butadiene nitrile rubber	287	Butadiene Vinylcyclohexane Nitrilacrylic acid	Hexadienes Pentens Butens Butadienes	1.25 2.41 1.60 3.91
Siloxane rubber	360	Organic silicon compounds	Methylmercaptan Hydrogen sulfide	0.13 0.34

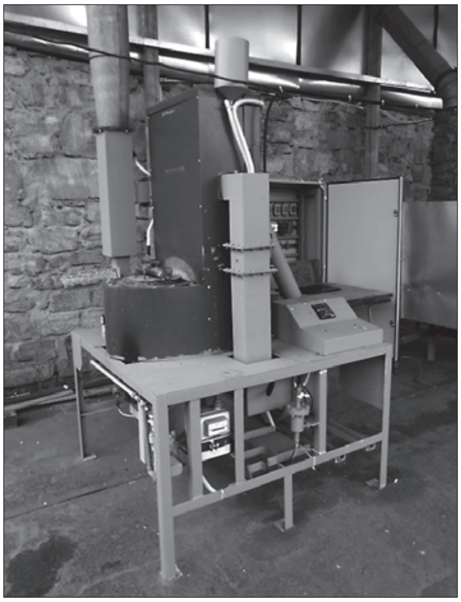


Fig. 1. Prototype plant БЦПШ-14

The objectives of static optimization of waste utilization based on pyrolysis aim at achieving the maximum yield of VGM and are related to determining the optimal set of regime parameters of the pyrolysis reactor, namely, compaction, heat conductivity, and distribution of the temperature field inside the pyrolysis reactor.

In order to solve the optimization problems, at the first stage, it is necessary to know the analytical relationships between the main parameters of a mathematical model of heat conductivity inside the reactor [16].

The total heat conductivity of tire mass can be written as follows:

$$c\,(u, r, t)\,\frac{du}{dt} = div\,[\lambda\,(u, r, t)\,gradu] + q(u, r, t), \quad (1)$$

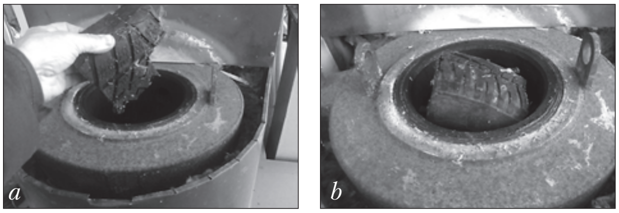


Fig. 2. Stages of preparation of grinded tires for utilization by the conventional pyrolysis method: *a* — download of tire pieces into the reactor; *b* — filling of reactor with grinded tires with a compaction under 60%

where u is temperature, c is specific volumetric heat capacity, λ — is heat conductivity coefficient, q is density of heat source for external heating of the reactor, and r, t are coordinates.

The heat conductivity equation for the heating zones in the spherical coordinate system is as follows:

$$c'(T)\frac{dt}{d\tau} = \frac{1}{r^2}\cdot\frac{d}{dr}\left(\lambda\,(T)\,r\,\frac{dT}{dr}\right) + \\ + \frac{1}{r^2\sin^2\theta}\cdot\frac{d}{d\theta}\left(\lambda\,(T)\frac{dT}{d\theta}\right). \quad (2)$$

The heat conductivity equation for compacted tire mass during destruction can be written in the cylindrical coordinate system as:

$$c'(T)\frac{dt}{d\tau} = \frac{1}{r}\cdot\frac{d}{dr}\left(\lambda\,(T)\,r\,\frac{dT}{dr}\right) + \\ + \frac{d}{dz}\left(\lambda\,(T)\,\frac{dT}{dz}\right), \quad (3)$$

where r, z are cylindrical coordinates; r, θ are spherical coordinates; T is temperature; τ is time, $c = \rho c$ is specific volumetric heat capacity; ρ — is density of tire component mix in the third reactor zone; and c is specific mass heat capacity.

To simplify the heat conductivity calculations, at a permissible error, any multicomponent system can be successively reduced to a bicomponent one under respective boundary conditions. The model is chosen based on the following assumptions and limitations: the rubber material is thermoelastic and has a uniform structure, wire cord is neglected, the base ring material is uniform metal located in the plane perpendicular to the heat flux.

To describe heat transfer in multicomponent model it is necessary to establish the dependence of effective coefficient of general heat capacity θ on the cell structure and on the coefficients of general heat conductivity of components θ_i and their concentrations m_i:

$$\theta = f\,(\theta_1, \theta_2, \dots\,\theta_i, m_1, m_2, \dots m_i). \quad (4)$$

Theoretical study of heat transfer has been made based on an idealized structure model that reflects basic geometric parameters of real tire cell

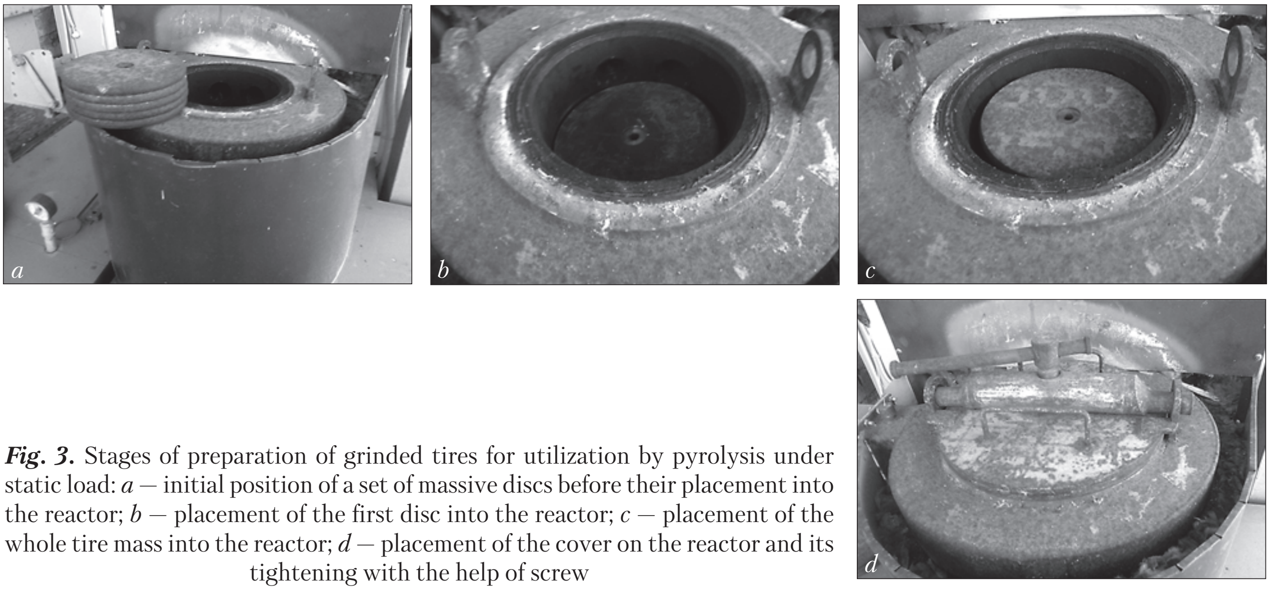


Fig. 3. Stages of preparation of grinded tires for utilization by pyrolysis under static load: *a* — initial position of a set of massive discs before their placement into the reactor; *b* — placement of the first disc into the reactor; *c* — placement of the whole tire mass into the reactor; *d* — placement of the cover on the reactor and its tightening with the help of screw

Table 4

Changes in the Temperature Field of Tire Mass in Pyrolysis Reactor at Various Static Loads

No.	Weight of tire pieces, kg	Static load, kg/cm^2	Temperature in the center of reactor, °C	Temperature at $^1/_4$ diameter distance from reactor, °C	Temperature of the inner surface of reactor body, °C	Temperature of the outer surface of reactor body, °C
1	3.68	—	310	450	550	582
2	3.75	—	312	462	551	582
3	3.62	—	311	457	551	583
4	3.70	0.08	365	480	550	581
5	3.78	0.08	370	475	550	582
6	3.68	0.08	368	460	552	583
7	3.65	0.1	380	485	551	580
8	3.77	0.1	385	490	550	582
9	3.81	0.1	385	492	551	582
10	3.69	0.2	428	507	551	583
11	3.68	0.2	420	512	550	581
12	3.78	0.2	425	510	550	582
13	3.72	0.3	430	510	552	583
14	3.82	0.3	429	511	551	582
15	3.65	0.3	425	515	562	583

with all important factors that define heat transfer process taken into account. This model can be considered adequate in the real system, which is shown by formula 5.

$$\frac{\lambda}{\lambda_1} = \frac{\nu - (\nu - 1)(1 - m_2^{\frac{2}{3}})\, m_2}{\nu - m_2^{\frac{1}{3}}(\nu - 1)}. \qquad (5)$$

The given formula for heat conductivity of anisotropic structure of elementary binary cell with components of metallic base ring and rubber enables to determine the heat conductivity of the mass which structure is the most realistic in the pyrolysis of whole tires under the action of static load.

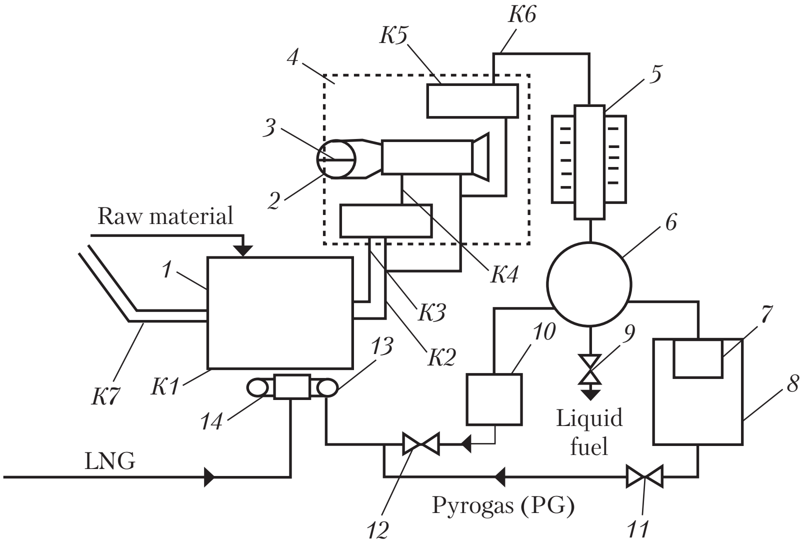


Fig. 4. Flow diagram of prototype plant BTsPSh-14: *1* — reactor; *2* — cair cooling system of the second loop; *3* — air shutter; *4* — loop circulation system unit; *5* — initial condenser with water cooling; *6* — distributing tank; *7* — interrupter; *8* — compensational tank; *9* — liquid fuel drain valve; *10* — pyrogas meter; *11*, *12* — pyrogas delivery cock; *13* — pyrogas complete combustion burner; *14* — LNG burner; *K1*, *K2*, *K3*, *K4*, *K5*, *K6*, *K7* — thermocouples

To estimate the efficiency of innovation technology and to elaborate the technological regimes, experiments were carried out using a BTsPSh-14 multi-contour circulation pyrolysis bench (Fig. 1) that operates in cyclic regime and can utilize only grinded tires. To maximally approach the results of temperature studies on the cyclic bench to the results that will be obtained on the industrial continuous-running plant, the pieces of grinded tires are selected in such a way as to keep a required ratio of the rubber volume and the total metal volume (wire cord and base ring wire), respectively, to the whole tire. The obtained results enable to use them for adjusting the mathematical model to the operation of industrial continuous-running plant for whole waste tire utilization.

Series of experiments for two options — option 1: conventional pyrolysis of grinded tires in the reactor (Fig. 2), when the density of tire mass in the reactor is less than 60%, and option 2: pyrolysis of grinded tires in the reactor with static load (Fig. 3) — have been carried out.

The tires with wire cord grinded to 100 × 100 mm pieces are loaded to the reactor having a volume of 14 dm^3. Various quantities of discs having a weight of 0.5 kg each (Table 4) are placed on them from above, which create static load on tire pieces in the reactor during their pyrolysis.

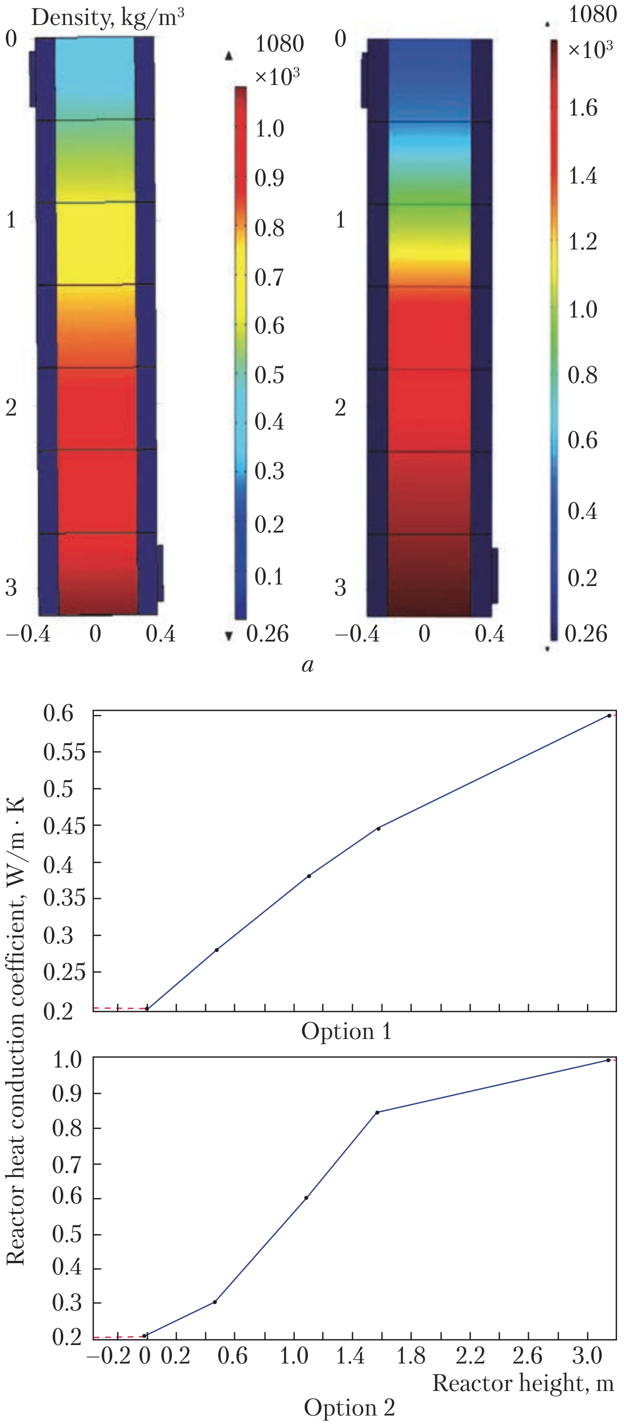
To measure the temperature field in the reactor thermocouples connected to device OVEN UKT38-Shch4.TP No.30108101104026097 were installed. The device records changes in temperature of tire mass during pyrolysis. The reactor is made of 08X18H9T steel with the following geometric parameters: diameter is 220 mm; wall thickness is 5 mm. The arrangement of thermocouples and the flow diagram of prototype plant EU BTsPSh—14 are given in Fig. 4.

COMSOL program theoretical studies of thermo-physical properties of vertical pyrolysis reactor filled with whole tires under temperature impact combined with static compression

Using *COMSOL* program calculations have been made to estimate the accuracy of mathematical model and to develop recommendations on raising efficiency of the plant for RW utilization.

COMSOL Multiphysics is powerful environment for modelling and solving R&D problems based on differential equations (*PDE*). Software makes finite-element analysis together with adaptive construction of grid using series of numerical solutions.

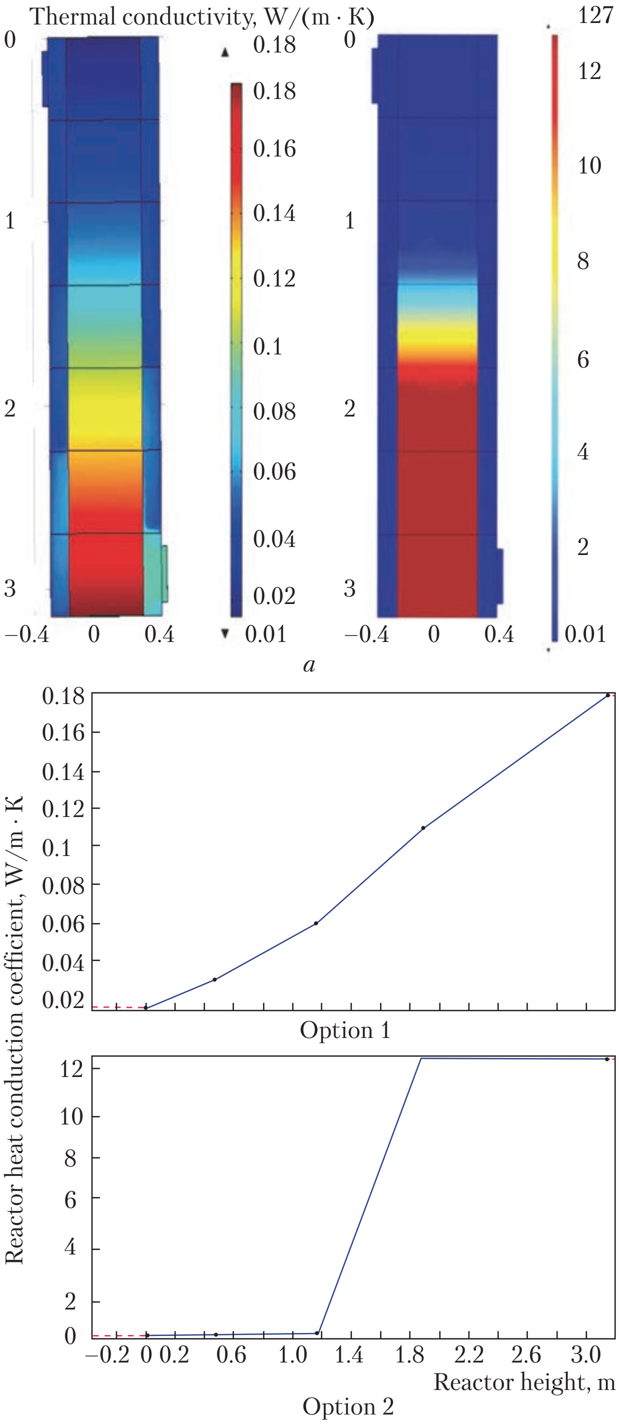
To calculate the temperature field in vertical pyrolysis reactor filled with tires under static load the finite element method is used. Based on



a

b

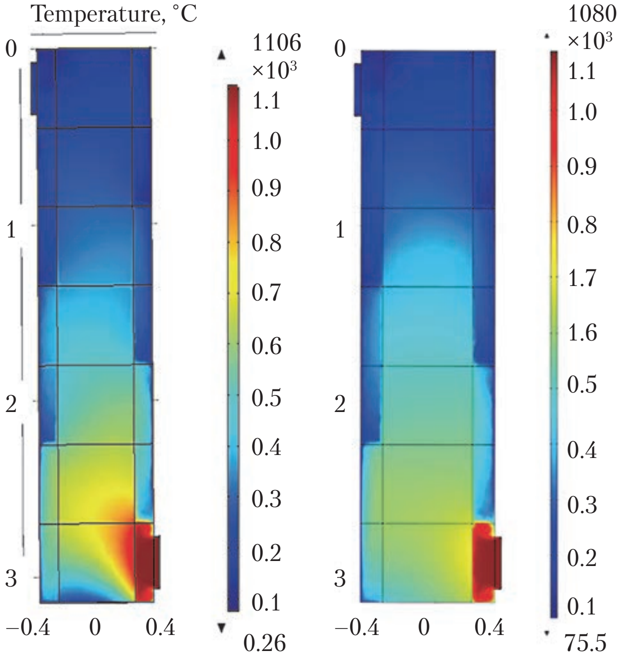
Fig. 5. Spectral analysis of tire mass density (*a*) and curves of changes in tire mass density (*b*) depending on the height of retort-type pyrolysis reactor without load (Option 1) and under static load (Option 2)



a

b

Fig. 6. Spectral analysis of heat conductivity (*a*) and curves of changes in heat conductivity coefficient (*b*) depending on the height of retort-type pyrolysis reactor without load (Option 1) and under static load (Option 2)



Option 1 Option 2

Fig. 7. Spectral analysis of temperature distribution inside grinded tire mass in retort-type pyrolysis reactor without load (Option 1) and under static load (Option 2)

the results of solution of heat conductivity differential equation diagrams showing compaction (Fig. 5), heat conductivity (Fig. 6), and temperature field distribution inside the pyrolysis reactor (Figs. 7—8) have been built.

The maximum density of tire pieces in the bottom section of the reactor in Option 1 is 1080 kg/m^3, while in Option 2 it is 1800 kg/m^3 (Fig. 5). The heat conductivity coefficient of tire mass in the reactor changes respectively.

Having compared the diagrams for the two options (Fig. 6, *a*, *b*), one can see that in for Option 2 the maximum heat conductivity in the bottom section of the reactor is 12.7 W/(m · K), while for Option 1 it amounts to 0.18 W/(m · K) that is almost 100 times less as compared with Option 2. Such a radical increase in heat conductivity is a result of both increase in the tire mass compaction rate and, mainly, asymmetrical arrangement and drawing to each other of metallic base rings heat the heat conductivity coefficient of which reaches 50 W/(m · K). Respectively, the given characteristics influence the intensity of reactor heating and decrease the total duration of waste utilization.

Having compared the temperature distribution for Options 1 and 2 (Figs. 7—8), one can see that as heat conductivity increases, the temperature within compacted tire mass is distributed more uniformly and, taking into consideration the fact that heat conductivity of the mass grows as well, at the same wattage of the reactor heater, the temperature in the center of the reactor for Option 2 decreases approximately by 100 °C. This is explained by the absence of a sharp peak of temperature distribution in the center of the reactor (Fig. 8, *b*).

The results of the study of technological parameters of waste tire pyrolysis under static load are summarized in Table 5. The conditions of theoretical calculations are as follows: Option 1 — model without static load, Option 2 — model with static load of 0.35 kg/cm^2. The practical studies: Option 1 — the reactor is filled with tire pieces without static load; Option 2 — the reactor is filled with tire pieces under static load of 0.32 kg/cm^2.

Hence, the obtained results have shown that the use of static load for RW utilization is effective, which is confirmed by an increase in heat conductivity of tire mass in the reactor both for

Table 5

Comparative Datasheet of Theoretical Calculations and Experiment Results

Parameters	Calculations		Experiment	
	Option 1	Option 2	Option 1	Option 2
Temperature of outer surface of the reactor body, °C	600	600	800	820
Heat conductivity, W/(m · K)	0.07	9.8	0.11	11.5
Temperature in the center of the reactor filled with grinded waste tire, °C	310	425	415	580

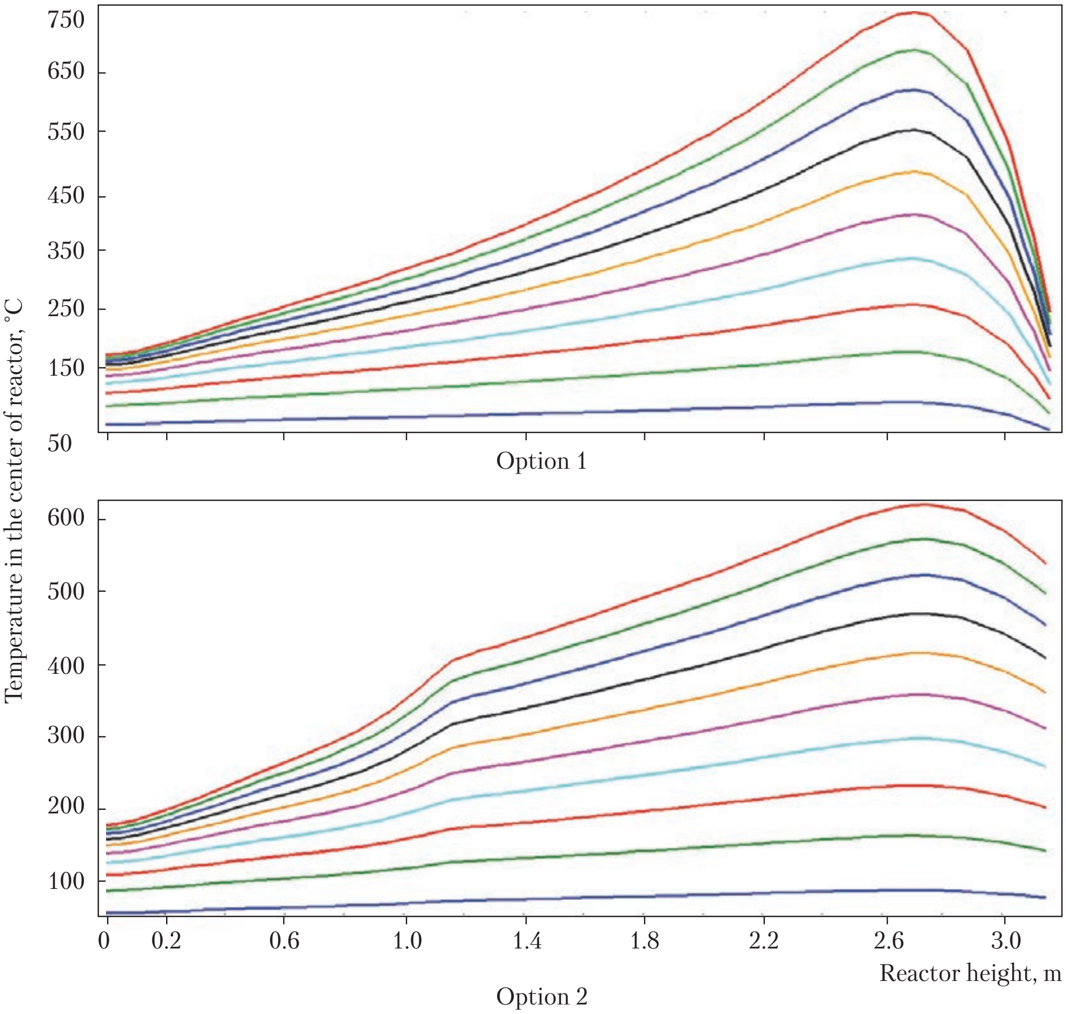


Fig. 8. Curves of temperature distribution in the center of grinded tire mass during its heating by flue gases of different temperature depending on the height of retort-type pyrolysis reactor without load (Option 1) and under static load (Option 2)

the theoretical and practical studies. Error of difference between the results of theoretical model calculations and those of practical study does not exceed 13%.

Estimated efficiency of reactor for continuous load of tires and their compaction during pyrolysis

For theoretical study of accuracy of estimated efficiency of designed reactor for compacted tire pyrolysis the following reference parameters of prototype reactor are used:

— rate of tire advance in the reactor: 0.35–0.525 m/hour;

— temperature of heat carrier for heating of the reactor: 900—1100 °C;

— static load on tires: 0.02—0.08 kg/cm^2;

— equivalent diameter of reactor: 0.6—1.2 m;

— frequency of tire supply to reactor: 10—15 pcs/hour;

— efficiency of treatment in reactor: 35—50 kg/hour.

Based on mathematical model of tire pyrolysis with compression effect during the pyrolysis process and analysis of experimental data a kinetic equation for average time of tire stay in the reactor, which is sufficient for extraction of

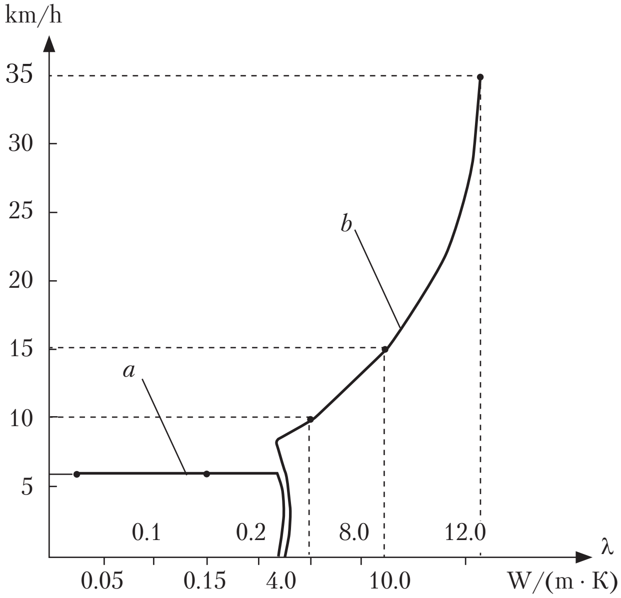


Fig. 9. Changes in continuous operation pyrolysis reactor efficiency at increasing heat conductivity of tire mass as a result of external load on it during pyrolysis in given temperature regimes: *a* — reactor efficiency curve without the action of external pressure; *b* — reactor efficiency curve for the case of pyrolysis under static load

80—95% light hydrocarbons from tires has been obtained. Taking into account the time of tire stay in the reactor and Fourier number, the following equation for relative efficiency of pyrolysis reactor has been written:

$$G = 1.6 \cdot 10^{-4} \cdot \mathrm{Re} \cdot \mathrm{Pr} \cdot \left(\frac{S_1}{S_2}\right) \cdot \left(\frac{Q - Q_0}{t_{\text{ст}} - Q}\right) \cdot$$

$$\cdot\, d^2 \cdot a \cdot G_3 \approx 32 - 42.4 \text{ km/h},$$

where Re_3 is Reynolds number ($\mathrm{Re}_3 = \frac{VD_1\rho_c}{\mu}$, V is rate of tire advance in the reactor (0.15—0.25 m/hour), D_1 is inner diameter of reactor (0.6 m), μ is viscosity of thermoplastic rubber (11.2 N · s/m^2), ρ_c is density of tire mass in the third zone of reactor (0.97); Pr is Prandtl number ($\mathrm{Pr} = \frac{\mu C_p}{\lambda} = 1.48$), C_p is heat capacity of compacted tire mass (1.68); λ is heat conductivity coefficient of compacted tire mass (12.7 W/m · K); S_1; S_2 are areas of inner and outer reactor cross sections with gas duct cross section taken into account, (0.28 and 0.43 m^2, respectively); Q is temperature of pyrocarbon at the reactor outlet (300 °C); Q_0 is temperature of tires at the reactor inlet (120 °C); $t_{\text{ст}}$ is temperature of reactor inner wall (400 °C); L is length of heated reactor working section (3.5 m); d is base ring diameter (0.38 m); a —is thermal conductivity coefficient of compacted tire mass (8 · 10^6 m^2/s); $G_з$ is weight of tires in the reactor (720 kg).

Dimensionless coefficients in the equation range: Re_3 (for highly viscous flux) = 7.76 · 10^{-5}.

Having analyzed the obtained efficiency equation by different parameters such as heat carrier temperature, reactor diameters, rate of tire advance in the reactor, and load, one can find an experiment value of reactor efficiency.

Proceeding from the above determined reactor efficiency and weight of tires in the reactor, time of tire stay in the reactor can be estimated as:

$$\tau = \frac{G_з}{G_{\text{пр}}} = \frac{720}{92} = 7.8 \text{ h},$$

which, according to the experimental data, ensures removal of 98% light hydrocarbons from tire mass.

To estimate the efficiency of heat transfer in the MLP reactor with static load during waste tire utilization, a dependence of reactor efficiency on tire mass heat conductivity in the given temperature regimes has been built (Fig. 9).

Analysis of graphical images has shown that at low heat conductivity, without external load and at a low compaction, at λ = 0.03—0.2 W/(m · K), the reactor efficiency is comparatively low and almost does not increase (Fig. 9, curve *a*). Under the action of external load, the heat conductivity of compacted tire mass grows up to λ = 4.0—12.0 W/(m · K), the amount of tires having optimal temperature for pyrolysis increases, with the reactor efficiency rising substantially (Fig. 9, curve *b*).

Determination of Optimal Pressure on Tires in the Reactor

To determine optimal pressure, i.e. external load on tire mass in cylindrical reactor, the physical condition of tires in each reactor zone has been analyzed.

The key parameter for calculating pressure (P) is thermal plasticity coefficient of rubber.

To estimate compressive force in the first approximation, the tires are assumed to be located horizontally, in smooth layers. The compressive force directed towards the axis of any pair of contacting layers with the cross section which is equal to that of the reactor in the case of general coefficient of rubber thermoelastic condition is estimated by the formula:

$$P = p'_{\text{пит}}\,\pi r^2, \tag{6}$$

where πr^2 is tire cross section in the sections 1 and 2, and reactor cross section in the section 3; $p'_{\text{пит}}$ is static pressure on tire mass (kg/cm^2), which depends on external load $p_{\text{пит}}$, in the case of vertical load of the reactor gravity force G of tire layers located at the top is taken into account.

Inasmuch as the tire mass consists of ideally smooth layers then:

$$p'_{\text{пит}} = p_{\text{пит}} + \frac{G}{\pi r^2};\; G = 9.81\rho_{\text{н}};$$

$$V = 10\,\rho_{\text{н}} h_{\text{сл}}\,\pi r^2, \tag{7}$$

where $\rho_{\text{н}}$ is bulk tire mass for each reactor section, $h_{\text{сл}}$ is half-height of the section (the compressive force is calculated for the midpoint of the section).

Based on obtained properties of thermoplastic rubber at a maximum temperature of 600 °C and a minimum rate of its expansion in free space inside of base rings, an estimated external load ranges within 0.01—0.07 kg/cm^2, at a viscosity of thermoplastic rubber of 112 cp.

Thus, a zero-waste technology for utilization of waste tire with the use of static load and production of alternative fuel has been developed. Production of alternative fuel by the mentioned method and dependence of its quality and yield on temperature parameters of the process in each loop of the multi-contour circulation system are to be studied at the next stages of research.

Based on the obtained results a series of trials in the reactor filled with tires in the case of the conditional pyrolysis (Option 1) and with static load (Option 2) has been carried out. Using *COMSOL Multiphysics* software the physical parameters of the process have been determined. For Option 1, the density in the bottom part of the reactor amounts to 1080 kg/m^3, while for the Option 2, it is equal to 1800 kg/m^3; the maximum heat conductivity in the bottom part of the reactor for Option 2 comes to 12.7 W/(m · K), whereas for Option 1, it is almost 100 times less, i.e. 0.18 W/(m · K).

Hence, the obtained results of this research have shown the effectiveness of static load for rubber waste utilization, which is confirmed by an increase in the heat conductivity of tire mass in the reactor. As a result, the temperature in the compacted tire mass is distributed more uniformly. Taking into consideration the fact that the heat conductivity of tire mass grows as well, at the same wattage of reactor heater, the temperature in the center of reactor for Option 2 is lower approximately by 100 °C as compared with Option 1.

Based on mathematical model of tire pyrolysis process with compression effect during their utilization and analysis of experimental data the reactor efficiency has been estimated for the case of continuous load of tires. The time of tire stay in the reactor has been determined (7.8 hours). According to the experimental data, it ensures removal of 98 % of light hydrocarbons from tire mass.

Optimal pressure on tires in the reactor at a maximum temperature of 600 °C has been determined. The estimated external load varies from 0.01 to 0.07 kg/cm^2, at a viscosity of thermoelastic rubber of 112 cp.

Further elaboration of technology for multi-loop circulation pyrolysis of waste tires under static load should be among the priority strategic directions of national science development and can allow Ukraine to address the problem of waste tire utilization and to produce alternative fuels. This will enable to essentially improve the environment situation in the country and, in future, to enter the world market of advanced technologies and equipment in this field.

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ДОСЛІДЖЕННЯ ТЕХНОЛОГІЧНИХ ПАРАМЕТРІВ ПІРОЛІЗУ ЗНОШЕНИХ АВТОМОБІЛЬНИХ ШИН ПРИ ЇХ СТАТИЧНОМУ НАВАНТАЖЕННІ

Вступ. Проблеми утилізації зношених автомобільних шин гостро постають на теренах нашої країни, оскільки обсяг останніх безперервно збільшується. Крім того, недосконалість наявних методів термічної утилізації зношених автошин спонукає до розробки новітньої технології піролізу в поєднанні зі статичним навантаженням.

Проблематика. Через відсутність даних щодо особливостей робочого процесу, що ускладнює проведення налагоджувальних робіт та реалізацію утилізації гумових відходів термічним розкладанням під дією статичного навантаження в промислових умовах, важливим є визначення особливостей деструкції гумових відходів в реакторі устаткування під час статичного стискання.

Мета. Визначення фізичних характеристик теплотехнічного процесу деструкції зношених автошин в піролізному реакторі в поєднанні із статичним навантаженням.

Матеріали й методи. Для оцінки ефективності запропонованого методу проведено серію експериментальних досліджень: традиційний піроліз подрібнених автошин в реакторі та піроліз автошин зі статичним навантаженням. За допомогою програми *COMSOL Multiphysics* досліджено тепло-фізичні характеристики вертикального піролізного реактора, заповненого автошинами, при взаємодії температури й статичного стискання.

Результати. Шляхом використання програмою методу кінцевих елементів та розв'язання диференціального рівняння теплопровідності, побудовано графіки, що демонструють теплопровідність і процес розподілу температурного поля всередині піролізного реактора за умов ущільнення переробльованих продуктів. Розраховано термін перебування автошин в реакторі, шо складає 7,8 год. Визначено оптимальний тиск на автошини, необхідний для досягнення максимального ущільнення.

Висновки. Обгрунтовано підвищення продуктивності установки утилізації гумотехнічних відходів шляхом впровадження в технологічну схему багатоконтурного циркуляційного піролізу статичного навантаження. Показано ефективність застосування статичного навантаження під час процесу, про що свідчить збільшення коефіцієнту теплопровідності масиву автошин в реакторі і, як наслідок, більш рівномірний розподіл температури в об'ємі ущільнених автошин.

Ключові слова: багатоконтурний циркуляційний піроліз, зношені автошини, статичне навантаження, ущільнення, теплопровідність, моделювання.

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ИССЛЕДОВАНИЕ ТЕХНОЛОГИЧЕСКИХ ПАРАМЕТРОВ ПИРОЛИЗА ИЗНОШЕННЫХ АВТОМОБИЛЬНЫХ ШИН ПРИ ИХ СТАТИЧЕСКОЙ НАГРУЗКЕ

Введение. Проблемы утилизации изношенных автомобильных шин остро стоят в нашей стране, поскольку их объем непрерывно увеличивается. Кроме того, несовершенство существующих методов термической утилизации изношенных автошин побуждает к разработке новой технологии пиролиза в сочетании со статической нагрузкой.

Проблематика. Из-за отсутствия практических знаний особенностей рабочего процесса затрудняется проведение наладочных работ и реализация утилизации резиновых отходов термическим разложением под действием статической нагрузки в промышленных условиях, важным является определение особенностей деструкции резиновых отходов в реакторе оборудования при статическом сжатии.

Цель. Определение физических характеристик теплотехнического процесса деструкции изношенных автошин в пиролизная реакторе в сочетании со статическим нагружением.

Материалы и методы. Для оценки эффективности предложенного метода проведена серия экспериментальных исследований: традиционный пиролиз измельченных автошин в реакторе и пиролиз автошин со статической нагрузкой. С помощью программы COMSOL Multiphysics исследовано тепло-физические характеристики вертикального пиролизного реактора, заполненного автошинами, при взаимодействии температуры и статического сжатия.

Результаты. Путем использования программой метода конечных элементов и решения дифференциального уравнения теплопроводности, построены графики, демонстрирующие теплопроводность и процесс распределения температурного поля внутри пиролизного реактора в условиях уплотнения перерабатываемых продуктов. Рассчитан срок пребывания автошин в реакторе, что составляет 7,8 ч. Определено оптимальное давление на автошины, необходимое для достижения максимального уплотнения.

Выводы. Обоснованно повышение производительности установки утилизации резинотехнических отходов путем внедрения в технологическую схему многоконтурного циркуляционного пиролиза статической нагрузки. Показана эффективность применения статической нагрузки во время процесса, о чем свидетельствует увеличение коэффициента теплопроводности массива автошин в реакторе и, как следствие, более равномерное распределение температуры в объеме уплотненных автошин.

Ключевые слова: многоконтурный циркуляционный пиролиз, изношенные автошины, статическая нагрузка, уплотнение, теплопроводность, моделирование.