

Досліджено температурне поле в об'ємі ущільненої суміші компонентів цілих автошин в реакторі. Проаналізовано залежності між геометричними параметрами структури вихідної автошини і концентрацією компонентів елементарної ячійки з бортовими кільцями в об'ємі термопластичної гуми при змінній температурі та навантаженні. Досліджено вплив металевих бортових кілець зі збільшеною теплопровідністю на загальну теплопровідність масиву автошин в піролізному реакторі

Ключові слова: піролізний реактор, теплопровідність ущільненої маси гуми автошин разом з бортовими кільцями, цілі відпрацьовані автошини, тепловий опір

Исследовано температурное поле в объеме уплотненной смеси компонентов целых автошин в реакторе. Проанализированы зависимости между геометрическими параметрами структуры исходной автошины и концентрацией компонентов элементарной ячейки с бортовыми кольцами в объеме термопластичной резины при переменной температуре и нагрузке. Исследовано влияние металлических бортовых колец с увеличенной теплопроводностью на общую теплопроводность массива автошин в пиролизном реакторе

Ключевые слова: пиролизный реактор, теплопроводность сжатой массы резины автошин совместно с бортовыми кольцами, целые отработанные автошины, тепловое сопротивление

UDC 658.567.1

DOI: 10.15587/1729-4061.2016.73557

RESEARCH OF THERMAL CONDUCTIVITY OF THE CONDENSED MASS OF THE WHOLE WASTE TIRES AND DETERMINATION OF THEIR OPTIMUM ARRANGEMENT IN THE PYROLYSIS REACTOR

S. Ryzhkov

Doctor of Technical Sciences, Professor, Rector*

E-mail: rektor@nuos.edu.ua

N. Rudyuk

Senior Researcher*

E-mail: mykola.rudiuk@nuos.edu.ua

L. Markina

PhD, Associate Professor*

E-mail: markserg@ukr.net

*Department of Environmental and Technical Safety
Admiral Makarov National University of Shipbuilding
Heroev Stalingrada ave., 9, Mykolaiv, Ukraine, 54000

1. Introduction

The main feature of the universal automated technology of continuous whole waste tire pyrolysis (WTP) is that tires are condensed in the course of pyrolysis to improve thermal conductivity. According to previous studies of the pyrolysis reactor design features [1], the overall thermal conductivity of the mass of tires in the reactor increases by 70 times due to compression of whole tires in the reactor and high thermal conductivity of metal bead rings, providing high-rate heat transfer in the pyrolysis reactor and effective endothermic chemical transformations, which increases the process efficiency by 2–3 times.

The relevance of the present work lies in the theoretical study of the rational arrangement of the mass of tires in the reactor and the study of temperature fields with different combinations of the tire components in the reactor, as well as assessment of their impact on the overall thermal conductivity of the condensed mass of whole waste tires under load and temperature.

2. Literature review and the problem statement

Known tire rubber recycling technologies are labor-intensive and energy-consuming, because involve, first, cut-

ting of tires using expensive equipment [2], or shredding by specific complex methods [3], or the use of power-intensive processes [4]. Second, the use of interchangeable retorts leads to the need to work in a cyclic mode with large heat loss, heating – cooling [5], which involves the manual labor when unloading and loading of the reactor [6] or the use of expensive catalysts [7]. Thirdly, the coefficient of the reactor filling with tires does not exceed 60 % at a low thermal conductivity of the mass rubber in the retort, accompanied by low performance of technological equipment [8].

Heat transfer greatly depends on the proportion of rubber and air components that have low thermal conductivity per unit volume of the reactor, and the proportion of metal bead rings with a relatively high thermal conductivity [9]. Therefore, the overall thermal conductivity of tires in a radial plane at different stages of pyrolysis will be determined by the thermal conductivity of the proposed model of the composite cell with average parameters.

Known designs and pyrolysis technologies for tire recycling do not provide highly efficient feed material heating in the reactor [10, 11].

The low thermal conductivity of tire rubber causes high energy costs, which increases the cost of recycling and limits the introduction of pyrolysis technologies on an industrial scale [12].

3. Research goals and objectives

The goal of the research is theoretical calculations of the total thermal conductivity of anisotropic structures of binary cells that consist of rubber of whole tires and metal bead rings, depending on their volume concentration and of geometric arrangement for the maximum thermal conductivity of the mass of whole tires of different diameters with respect to each other.

To achieve this goal, the following tasks were identified:

- selection of rational anisotropic structures of binary cells that are the closest to realistic conditions of evaluating the thermal conductivity of the mass of whole tires in the pyrolysis reactor;
- development of the methods of theoretical calculations of thermal conductivity of different structures of binary cells and determination of their impact on the thermal conductivity of the environment;
- theoretical assessment of the impact of increased thermal conductivity of metal bead rings on the total thermal conductivity of the mass of whole tires in the pyrolysis reactor;
- determination of the optimum geometric arrangement of whole tires relative to the pyrolysis reactor.

4. Materials and methods of the study of thermal conductivity in the reactor

The total thermal conductivity of the mass of tires in the reactor zones can be expressed as:

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

where u – temperature, p – specific volumetric heat capacity, λ – thermal conductivity, q – density of the heat source of external heating of the reactor, r, t – coordinates.

As the internal heat source is absent in the reactor, the equation can be written as:

$$c'(T) \frac{dT}{d\tau} = \text{div}[\lambda(T) \text{grad}(T)]. \quad (2)$$

Given that the known reactor designs mostly represent the body of rotation, it is advisable to use a cylindrical coordinate system for theoretical studies.

Since tires with the reactor represent the body of rotation, it is advisable to use a cylindrical coordinate system. However, a spherical coordinate system shall be used in order to improve the solution accuracy for the first and second zones [13].

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

$$c'(T) \frac{dT}{d\tau} = \frac{1}{r^2} \cdot \frac{d}{dr} (\lambda(T) r^2 \frac{dT}{dr}) + \frac{1}{r^2 \sin^2 \theta} \cdot \frac{d}{d\theta} (\lambda(T) \frac{dT}{d\theta}). \quad (3)$$

The heat equation for condensed mass of the tire components in the III zone of destruction can be presented in the cylindrical coordinate system:

$$c'(T) \frac{dT}{d\tau} = \frac{1}{r} \cdot \frac{d}{dr} (\lambda(T) r \frac{dT}{dr}) + \frac{d}{dz} (\lambda(T) \frac{dT}{dz}), \quad (4)$$

where r, z – cylindrical coordinates; r, θ – spherical coordinates; T – temperature; τ – time, $c = \rho c$ – volumetric heat

capacity; ρ – density of the mixture of the tire components in the third zone; c – mass heat capacity [14].

Any multicomponent system can be gradually reduced to a two-component under appropriate boundary conditions to simplify the calculations of thermal conductivity at the margin of error. When choosing the model, the following assumptions and limitations are accepted: the rubber material is thermoplastic and has a homogeneous structure, a steel cord is neglected, the material of bead rings – a homogeneous metal, is in the plane perpendicular to the heat flow. The symmetrical model of the tire and its location in the pyrolysis reactor on the basis of the assumptions is a set of individual components that make up tires and their ratio per unit volume at each stage of pyrolysis (Fig. 1, 2).

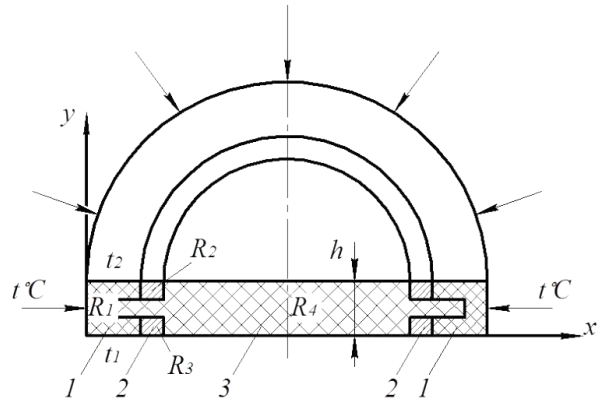


Fig. 1. The composite cell of the tire in the first and second reactor zones: 1 – rubber element; 2 – metal element (bead rings); 3 – air or flue gas element; R_1 – R_4 – thermal resistance of rubber and metal bead rings in the regions under study

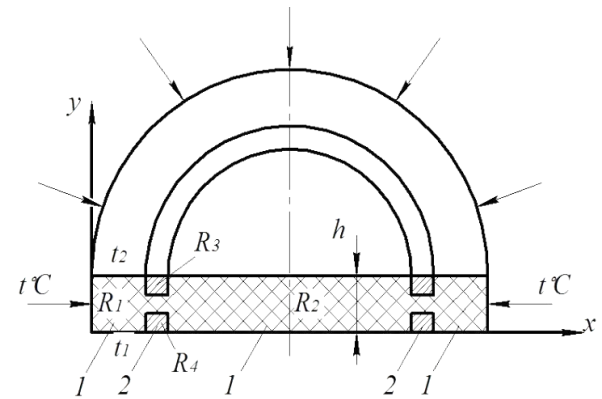


Fig. 2. The composite cell of the tire layer in the third reactor zone: 1 – rubber element; 2 – metal element (bead rings); 3 – air or flue gas element

The basis of the unit cell is isothermal compression characterized by the volume change at a constant temperature and thermoplastic rubber melting at a constant pressure.

The unit cell with heat resistance equal to 1/2 of the composite cell with heat transfer in the perpendicular plane is considered since the composite cell of the whole tire is symmetrical about the axis. Let us consider heat transfer in the unit cell of the tire layer based on thermal resistance on specific regions of the tire model (Fig. 3, 4).

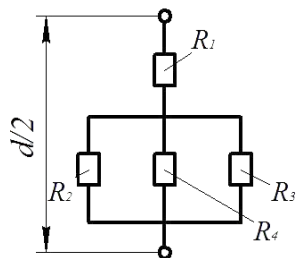


Fig. 3. The connection diagram of thermal resistance in the unit cell of each layer of the half the tire in the first and second reactor zones: R_1 – thermal resistance of rubber; R_2 and R_3 – thermal resistance of metal bead rings; R_4 – thermal resistance of air or flue gas

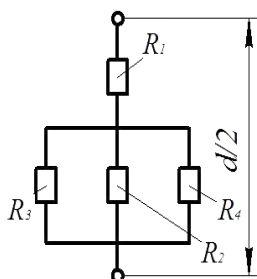


Fig. 4. The connection diagram of thermal resistance in the unit cell of each layer of the condensed half of the tire in the third reactor zone: R_1 – thermal resistance of thermoplastic rubber; R_2 – thermal resistance of thermoplastic rubber in the bead ring center; R_3 and R_4 – thermal resistance of metal bead rings

The total resistance of the unit cell according to Fig. 3 and 4 is determined as follows:

$$R = R_1 + \frac{1}{\frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}} \tag{5}$$

The formula R is the same for both diagrams, there is a flue gas component (R_4) in the diagram (Fig. 3), which is further expelled by thermoplastic rubber (R_2) in the diagram (Fig. 4).

In describing the heat transfer process in the multicomponent model, it is necessary to establish the dependency of the effective coefficient of generalized thermal conductivity q on the cell structure, the coefficients of generalized thermal conductivity of components q_i and their concentrations m_i , then:

$$\theta = f(\theta_1, \theta_2, \dots, \theta_i, m_1, m_2, \dots, m_i). \tag{6}$$

The theoretical study of the heat transfer process is performed on an idealized model of the structure, which reflects the basic geometric characteristics of the real tire cell regarding all significant factors that determine the heat transfer process. Such a model can be considered adequate to the real system [14].

5. The results of studies of thermal conductivity of the mass of the material of whole waste tires

The study of three options of the unit cell of the system of the tire components in the reactor and comparison

of the estimated thermal conductivity values with experimental data were performed. Each option differs in boundary conditions that characterize the composition and structure of the cell, provided full thermoplastic deformation of the tire under load and temperature and in the absence of air.

First, the option of the symmetrical cell structure, which is equivalent to the mass of shredded tires with removed bead rings is investigated. The heat flow is distributed only in the radial direction in the volume of a homogeneous material (rubber) in the coordinate system (x, y) (Fig. 5).

In the first option, symmetrical structure of the cell is homogeneous thermoplastic rubber; the influence of metal bead rings on the temperature field of the cell is neglected; the heat flow is distributed only in the radial direction.

The unit cell of the system of the tire, filled with a homogeneous material (rubber) along the reactor diameter in the coordinate system (x, y) is considered (Fig. 5).

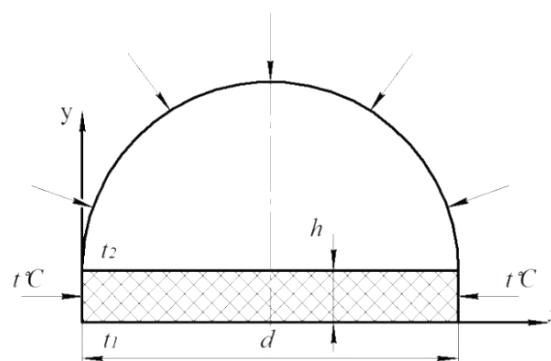


Fig. 5. The unit cell of the tire filled with homogeneous material

The lines of heat transfer on the surface $x=1/2d$ in the unit cell are isothermal, and in $y=h$ – adiabatic. The temperatures on surfaces are denoted by $x=0$ and $x=1/2d$ through $t(x,0)=t_1$, $t(x,h)=t_2$, and the heat flow that passes through an isothermal surface of the unit cell as Q . Since the surface $x=0$ is isothermal, its temperatures t_1 and t_2 are equal, then:

$$t_1|_{x=0} = t_2|_{x=0} = t'. \tag{7}$$

The thermal resistance R of the unit cell is defined as:

$$R = \frac{t' - t''}{Q} = \frac{|t_1|_{x=0} - |t_2|_{x=1/2d}}{Q}. \tag{8}$$

If we introduce the concept of effective thermal conductivity λ of the unit cell, its heat resistance is found provided that $x=0$ and $x=1/2d$ equal to $1 \cdot 1/2d$, and the cell height h :

$$R = \frac{\frac{1}{2}d}{\frac{1}{2}d\lambda} = \frac{1}{\lambda}. \tag{9}$$

When combining the two formulas, the following is derived for R :

$$\lambda = \frac{Q}{|t_1|_{x=0} - |t_2|_{x=1/2d}}. \tag{10}$$

The temperature field of the cell system shall be analyzed to determine the effective thermal conductivity.

1/2 of the cell is divided into three parts $0 \leq x \leq h$, $0 \leq y \leq h$ is denoted by t_2 , the temperature of the region $h \leq x \leq 1/2d$, $0 \leq y \leq h$ – by t_1' , the temperature of the region $0 \leq x \leq 1/2d$, $h \leq y \leq 1/2d$ – by t_1'' .

The temperature field of the above regions is described by differential equations:

$$\frac{\partial^2 t_2}{\partial x^2} + \frac{\partial^2 t_2}{\partial y^2} = 0, \quad 0 \leq x \leq h, \quad 0 \leq y \leq h; \quad (11)$$

$$\frac{\partial^2 t_1'}{\partial x^2} + \frac{\partial^2 t_1'}{\partial y^2} = 0, \quad h \leq x \leq \frac{1}{2}d, \quad 0 \leq y \leq h; \quad (12)$$

$$\frac{\partial^2 t_1''}{\partial x^2} + \frac{\partial^2 t_1''}{\partial y^2} = 0, \quad 0 \leq x \leq \frac{1}{2}d, \quad h \leq y \leq \frac{1}{2}d. \quad (13)$$

With the boundary conditions:

– adiabaticity of the surfaces $y=0$ and $y=1/2d$

$$\left(\frac{\partial t_2}{\partial y}\right)_{y=0} = \left(\frac{\partial t_1''}{\partial y}\right)_{y=0} = 0; \quad (14)$$

$$\left(\frac{\partial t_1'}{\partial y}\right)_{y=\frac{1}{2}d} = \left(\frac{\partial t_1''}{\partial y}\right)_{y=\frac{1}{2}d} = 0; \quad (15)$$

– isothermality of the surface $x=0$

$$t_2|_{x=0} = t_1'|_{x=0} = t_1''|_{x=0}. \quad (16)$$

The conditions of equality of temperatures and heat flows at the boundaries between the regions are as follows:

$$t_2|_{x=h} = t_1'|_{x=h}; \quad t_2|_{x=h} = t_1''|_{x=h},$$

$$(\lambda_2 \frac{\partial t_2}{\partial y})_{y=h} = (\lambda_2 \frac{\partial t_1'}{\partial y})_{y=h}, \quad (17)$$

$$(\lambda_2 \frac{\partial t_2}{\partial x})_{x=h} = (\lambda_1 \frac{\partial t_1''}{\partial x})_{x=h}, \quad (18)$$

$$t_1'|_{y=h} = t_1''|_{y=h},$$

$$\left(\frac{\partial t_1'}{\partial x}\right)_{x=h} = \left(\lambda_1 \frac{\partial t_1''}{\partial x}\right)_{x=h}. \quad (19)$$

When solving the system of equations with the conditions at the boundaries, the temperature field $t_1(x,y)$ and $t_2(x,y)$ and the heat flow were determined:

$$Q = -\lambda_1 \int_0^{\frac{1}{2}d} \frac{\partial t_1}{\partial y} \Big|_{y=\frac{1}{2}d} dx. \quad (20)$$

Knowing the expression $t_1(x,y)$ and Q , the analytical value for the total thermal conductivity of the unit cell can be found by the formula:

$$\lambda = \frac{Q}{|t_1|_{x=0} - |t_2|_{x=\frac{1}{2}d}}. \quad (21)$$

The formula of thermal conductivity of the unit cell allows an overall assessment of thermal conductivity of the mass of condensed rubber in the pyrolysis reactor without metallic elements present in the tire structure.

The estimated dependence of thermal conductivity of the unit cell filled with thermoplastic rubber under various temperature differences in the adopted cell for the first option is shown in Fig. 6.

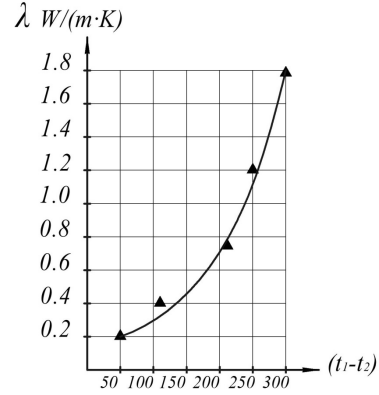


Fig. 6. The estimated dependence of thermal conductivity of the unit cell

Fig. 6 shows that the thermal conductivity of monocomponent thermoplastic rubber does not exceed 1.5 W/(m·K) and varies little under the temperature difference in the parallel plane of the heat flow. The resulting estimated characteristic of thermal conductivity with an error of no more than 50 % can be used for the analysis of binary systems with a wide range of initial thermal conductivity of components that are characteristic of condensed tires, which does not allow a real assessment of the temperature field in the reactor. Since the gas cavity is an intermediate element, the two-component structure of the tire is taken as the basis when analyzing the relationship between the geometric parameters of the structure and concentration of components (Fig. 5, 6).

The second option considers the symmetric binary structure of two-component cell (thermoplastic rubber with bead rings). It is conventionally assumed that the bead ring intersection is square. The composite cell is represented as a cube, the upper and lower cube faces are isothermal surfaces, and lateral faces – adiabatic (Fig. 7).

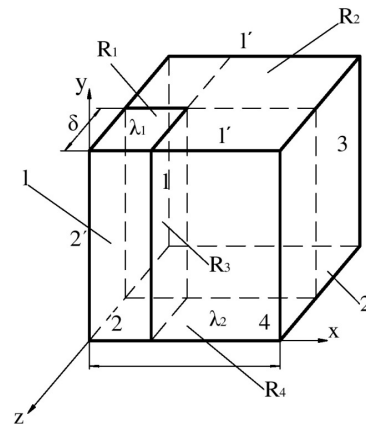


Fig. 7. The element of the composite binary cell: 1 – half of the metal bead ring; 2 – composite cell

For modeling, the following notations are introduced: δ – half of the width of the tire bead ring; V, V_1, V_2 – volumes of the unit cell and its components (bead ring and thermoplastic rubber); L – cube edge length; $C=\delta/L$ – relative size of the bead ring [16]. The relationship between the parameter C , which characterizes the geometric parameters of the bead ring and rubber volume is determined as follows:

$$m_1 = \frac{V_1}{V}; m_2 = \frac{V_2}{V} = \frac{V - V_1}{V} = 1 - m_1; V = V_1 + V_2, \quad (22)$$

$$V^3 - [\delta^3 + 3\delta^2(L - \delta)] = 2\delta^3 - \delta^2L + L^3, \quad (23)$$

$$m_2 = 2C^3 - 3C^2 + 1. \quad (24)$$

When introducing a new variable $y=C-1/2$, the equation m_2 has the form of:

$$y^2 + 3py = 2q = 0, \quad q = \frac{1 - 2m_2}{8}, \quad p = -\frac{1}{4}. \quad (25)$$

The number of real solutions of the equation depends on the sign of discriminant D of square trinomial ax^2+bx+c , equal to b^2-4ac .

$$D = q^2 + p^3 = \left(\frac{1 - 2m_2}{8}\right)^2 - \left(\frac{1}{4}\right)^3 = \frac{m_2(m_2 - 1)}{16} \leq 0. \quad (26)$$

For $D > 0$, the equation has three real roots:

$$y_1 = -\cos\frac{\phi}{3}; y_2 = \cos\left(60^\circ - \frac{\phi}{3}\right); y_3 = \cos\left(60^\circ + \frac{\phi}{3}\right), \quad (27)$$

where $0 \leq m_2 \leq 0.5$, $\phi = \arccos(1 - 2m_2)$, and $0.5 < m_2 \leq 1$, $\phi = \arccos(2m_2 - 1)$.

The relative size of the bead ring $C = \delta/L$ in the adopted model varies in the range of $0 \leq C \leq 1$, and y_1 are related by the relationship $y = C - 1/2$.

The analysis y_2 shows that the second root leads to the value of C_2 that is either greater than unity or negative. The first root y_1 provides physically justified results for C_1 throughout the range of changes $0 \leq m_2 \leq 1$, if the angle ϕ is taken from the last quarter $270^\circ \leq \phi \leq 360^\circ$. Similar results are obtained when using the third root y_3 , if the value ϕ is taken in the first quarter $0^\circ \leq \phi \leq 90^\circ$. Further calculation of the parameter C uses the first root of the equation (24), then:

$$C = 0.5 + A \cos\frac{\phi}{3}, \quad 270^\circ \leq \phi \leq 360^\circ, \quad (28)$$

where $0 \leq m_2 \leq 0.5$, $A = -1$, $\phi = \arccos(1 - 2m_2)$, and $0.5 < m_2 \leq 1$, $A = 1$, $\phi = \arccos(2m_2 - 1)$.

The analysis of the heat transfer process in the two-component composite cell element is based on the previously described relationship between the geometric parameters of the structure and concentration of the components in it. The planes 1'-1' and 2'-2' are adiabatic, which are parallel to the general direction of the heat flow and lateral faces of the cell, dividing the latter into individual sections 1-4 (Fig. 7).

Thermal resistance of individual sections of the unit cell R_1 is shown in the formulas for a flat wall (Fig. 8):

$$R_1 = \frac{L}{\lambda_1 \delta^2}, \quad R_2 = \frac{\delta}{\lambda_1 \delta(L - \delta)}, \quad (29)$$

$$R_3 = \frac{L - \delta}{\lambda_2 \delta(L - \delta)}, \quad R_4 = \frac{L}{\lambda_2(L - \delta)^2}. \quad (30)$$

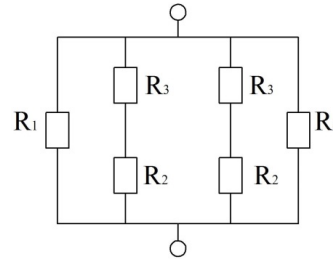


Fig. 8. The connection diagram of thermal resistance in the element of the part of the composite cell

The total equivalent thermal resistance of the composite cell (R) in this case can be represented as follows:

$$\frac{1}{R} = \frac{1}{R_1} + \frac{2}{R_2 + R_3} + \frac{1}{R_4}. \quad (31)$$

Thus, the total thermal resistance with the effective thermal conductivity λ is represented as:

$$R = \frac{1}{\lambda L^2} = \frac{1}{\lambda L}, \quad \text{where } \nu = \frac{\lambda_2}{\lambda_1}. \quad (32)$$

Equating (31) and (32) considering (30), the formula of effective thermal conductivity of the tire cell structure with a combination of the two components of thermoplastic rubber with thermal conductivity λ_1 and metal bead rings with thermal conductivity λ_2 can be derived:

$$\lambda = \lambda_1 [C^2 + \nu(1 - C)^2 + 2\nu C(1 - C)^2(\nu C + 1 - C)^{-1}]. \quad (33)$$

The dependence reflects the impact of thermal conductivity of each component on its concentration per unit volume on the total thermal conductivity of the unit cell (Fig. 9).

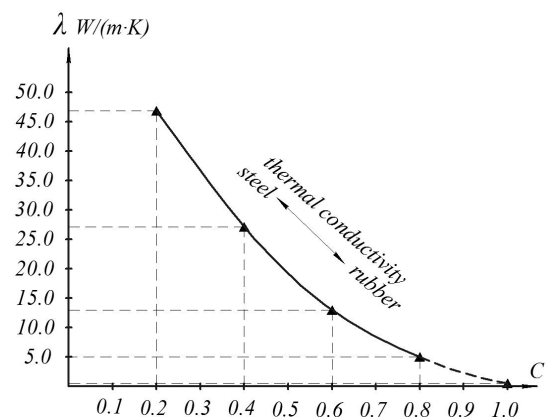


Fig. 9. The estimated dependence of the refined thermal conductivity of the binary unit cell (option 2)

Given that the initial thermal conductivity of rubber $\lambda_1 = 0.13$ W/(m·K) and metal $\lambda_2 = 58$ W/(m·K), the total ther-

mal conductivity of the mass of tires in the reactor does not exceed 0.18 W/(m·K).

The analysis of the results of theoretical calculations, options 1, 2, shows that the thermal conductivity in the reactor at a symmetric arrangement of tires and their components relative to the cylindrical reactor is low and does not exceed 0.18 W/(m·K), which is not the best option.

Let us consider *the third option*, when the reactor diameter is greater than the diameter of the tires that are loaded in it by at least 1.5 times, while the tires with bead rings are displaced relative to each other, leading to an asymmetric arrangement of metal bead rings in the form of volume metal lattice.

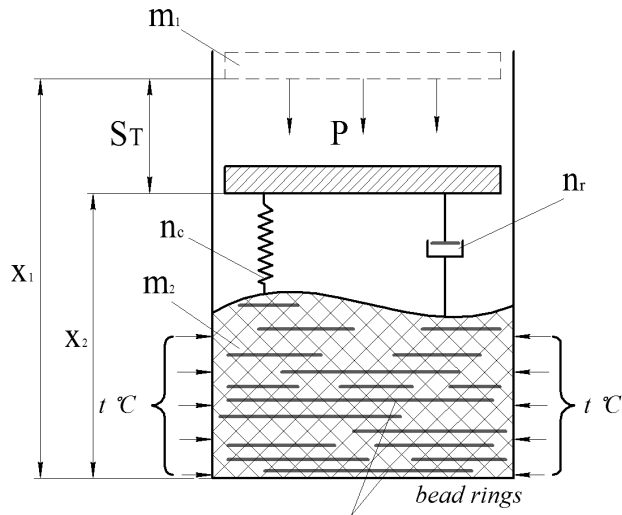


Fig. 10. The physical model of dynamic compression of tires in the pyrolysis reactor at asymmetric arrangement of tires relative to the cylindrical reactor axis

The asymmetric horizontal arrangement of bead rings with a high thermal conductivity and displacement in the reactor cross-section relative to each other provides bridging of relatively low thermal conductivity of rubber.

In *the third option*, theoretical research was conducted in more realistic conditions of the arrangement of the condensed mass of tires relative to the reactor and specification of estimation of the overall thermal conductivity of an isotropic asymmetrical structure of the unit cell with components of rubber and bead rings was performed (Fig. 11).



Fig. 11. The element of modeling of the pyrolysis reactor with a volume lattice formed by bead rings and steel cord of tires under static load

The volume of the element is characterized by the coefficient of filling of the pyrolysis reactor with metal inclusions of up to 98 % (bead rings and steel cord of tires) and rubber.

The asymmetrical structure of the binary cell consisting of thermoplastic rubber and two bead rings is considered.

The components of the overall structure are anisotropic and have different properties; in the asymmetric anisotropic structure of components – round-shaped bead rings.

The oriented arrangement system of the asymmetric unit cell components is singled out from the physical model (Fig. 10, 11) and 1/8 of it is presented (Fig. 12, 13). Further analysis is based on the unit cell division by infinitely thin adiabatic vertical (parallel to heat flow) planes a, b, c, d, e into the characteristic regions 1, 2, 3. In those regions, the thermal resistances are denoted by R₁, R₂, R₃. The values of these resistances are calculated by the formulas for flat walls:

$$R_1 = \frac{L_x}{\lambda_1(L_y L_z - l_y l_z)}, \quad R_2 = \frac{L_x - l_x}{\lambda_1 L_y L_z}, \quad R_3 = \frac{l_x}{\lambda_2 l_y l_z}, \quad (34)$$

where L_x, L_y, L_z, l_x, l_y, l_z – corresponding dimensions of the cell of thermoplastic rubber and bead ring respectively; λ₁ and λ₂ – coefficients of thermal conductivity of thermoplastic rubber and metal bead ring respectively.

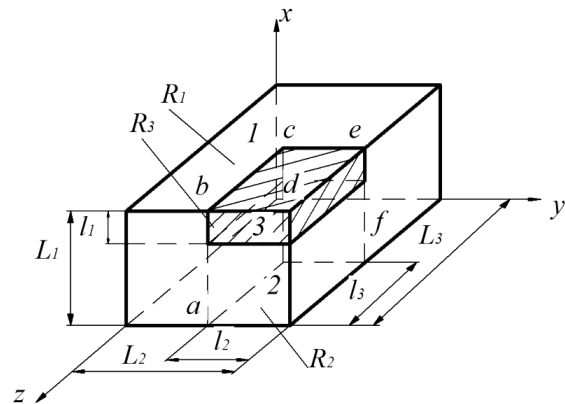


Fig. 12. Anisotropic structure of the binary unit cell with components of metal bead ring and rubber

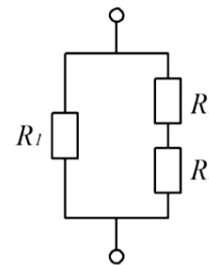


Fig. 13. The connection diagram of thermal resistance

According to Fig. 13, the total resistance (R) is calculated by the formula:

$$R_{23} = R_2 + R_3, \quad R = \frac{R_1 R_{23}}{R_1 + R_{23}}. \quad (35)$$

From the formulas (35) and (36), we find R₂₃:

$$R_{23} = \frac{l_x \lambda_1 + \lambda_2 (L_x - l_x)}{l_y l_z \lambda_1 \lambda_2} \quad (36)$$

and define the formula for the thermal resistance R for the entire cell

$$R = \frac{L_x}{\lambda L_y L_z} \tag{37}$$

Due to the change in the concentration of components in the tire unit volume, the concept of concentration factors k_x, k_y, k_z in the directions is introduced:

$$k_x = \frac{l_x}{L_x}, \quad k_y = \frac{l_y}{L_y}, \quad k_z = \frac{l_z}{L_z} \tag{38}$$

further, it is assumed that $k_y k_z = S$, then:

$$R_{23} = \frac{L_x [k_x + v(1-k_x)]}{\lambda_2 L_y L_z S}, \quad \text{where } v = \frac{\lambda_2}{\lambda_1} \tag{39}$$

Using (35), (36) and (39), we found:

$$m_2 = 1 - S + \frac{vS}{k_x + v(1-k_x)} \tag{40}$$

The relationship between the parameters S, k_x and volume concentration m_2 is determined as follows:

$$m_2 = \frac{v_2}{v} = k_x k_y k_z = k_x S, \quad \text{then } S = \frac{m_2}{k_x} \tag{41}$$

if $S \leq 1$, then $k_x \geq m_2$.

Given (41), the formula (40) is as follows:

$$\frac{\lambda_1}{\lambda_2} = 1 - \frac{m_2}{k_x} + \frac{vm_2}{k_x [k_x + v(1-k_x)]} \tag{42}$$

The equation (43) satisfies the following passages to the limit:

1. In the absence of bead rings $k_x=0$, then $\lambda=\lambda_1$ thermal conductivity of thermoplastic rubber (option 1).

2. In the case where the concentration factor of the component of bead rings $k_x=1, m_2=1$ and the total thermal conductivity will correspond to the component of bead rings $\lambda=\lambda_2$.

3. With the same thermal conductivity of the two components $v=1, \lambda=\lambda_1=\lambda_2$.

4. When $S=1$, bead rings can be seen as solid plates, parallel to the heat flow, if $k_x=1$, bead rings in the cross section form rectangles perpendicular to the heat flow. In this case, the formula (42) will show the largest or the smallest thermal conductivity effect of the two-component condensed mass of tires:

$$\lambda = 1 - \frac{\lambda_2}{vm_1 + (1-m_1)}; \quad \lambda = \lambda_2(1-m_1) + \lambda_1 m_1 \tag{43}$$

5. If $k_x=k_y=k_z=k$, then $k=m_2^{1/3}$, the components take the form of a cube, and the formula (42) takes the following form:

$$\frac{\lambda}{\lambda_1} = \frac{v - (v-1)(1-m_2^{\frac{2}{3}})m_2^{\frac{1}{3}}}{v - m_2^{\frac{1}{3}}(v-1)} \tag{44}$$

The presented formula of thermal conductivity of the anisotropic structure of the unit binary cell with components of the metal bead ring and rubber allows determining the thermal conductivity of the mass, the structure of which

is the most realistic, in the process of pyrolysis of whole tires, combined with the effect of static load on them.

6. Discussion of the results of research of thermal conductivity in the reactor

Calculations of the total thermal conductivity of the condensed two-component mass of tires in the reactor by the developed method found no restrictions on the length and thickness of the layer of binding thermoplastic rubber, surrounding the bead ring.

Fig. 14 shows the characteristics of the change in the total thermal conductivity of the binary cell depending on the concentration of thermoplastic rubber and steel of bead rings.

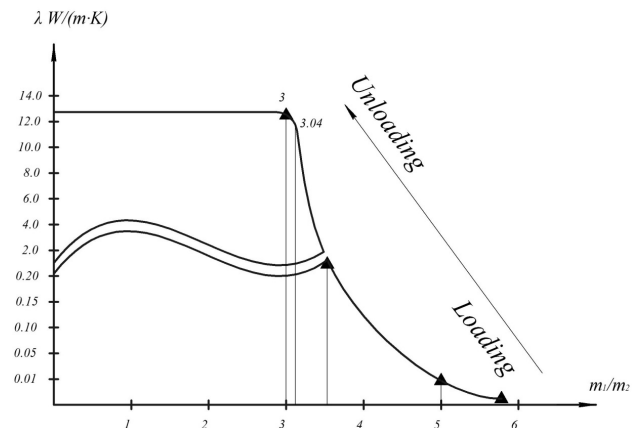


Fig. 14. The refined theoretical calculation of the total thermal conductivity of the anisotropic asymmetrical structure of the binary cell depending on the volume concentration of components (option 3)

According to the curve in Fig. 14, the total thermal conductivity of the mass of tires gradually increases under the influence of temperature and static load (right to left), respectively, from the time of loading, the gas (air) volume decreases due to compression of tires and the concentration of metal bead rings and rubber rises. The increase in the thermal conductivity of the mass of tires occurs exponentially until the bead rings touch each other and the thermal contact between them is formed. Then, until unloading, the region of the curve takes a horizontal position and thermal conductivity does not increase regardless of the temperature and rate of compression. The increase in the total thermal conductivity is due to the increase in the concentration of steel of bead rings. The calculation error does not exceed 3 %.

7. Conclusions

1. The theoretical study of the total thermal conductivity of three selected anisotropic structures of binary cells proved that the third option with the asymmetric arrangement of whole tires in the pyrolysis reactor is the closest to realistic conditions. Thus, the increased thermal conductivity of metal bead rings, which under compression are in thermal contact with each other, forming a three-dimensional structure in rubber provides the maximum thermal conductivity of the mass of whole tires in the reactor.

2. The developed method of calculating the thermal conductivity of different structures of binary cells of the mass of whole tires in the pyrolysis reactor under simultaneous static compression and heating to a rubber pyrolysis temperature provides optimization of the total thermal conductivity of the mass of tires in the reactor due to the introduction of the value of thermal conductivity of metal bead rings.

3. The theoretical study of the effect of increased thermal conductivity of metal bead rings on the total thermal conductivity of the mass of whole tires in the pyrolysis reactor confirmed the increase in the values from 1.8 W/(m·K) to 12.7 W/(m·K).

4. When modeling the volume lattice, formed by bead rings and steel cord of tires under static loads, the optimum geometric arrangement of whole tires relative to the pyrolysis reactor, where the reactor diameter is greater than the tire diameter by at least 1.5 times was determined. The tires with bead rings are displaced relative to each other in the horizontal plane.

5. The resulting values of thermal conductivity of the mass of whole tires in the pyrolysis reactor at the optimum arrangement of raw materials and coefficient of filling about 98 % allow optimizing the structural characteristics of the pyrolysis equipment.

References

1. Patent of Ukraine for the invention C. F23G5/24, F23G5/027, C08J11/04, C10G1/10, C10B53/07. Universal automated installation of continuous pyrolysis whole worn car tires [Text] / Markina L. M., Ryzhkov S. S., Rudiuk M. V., Kryva M. S. – No. 110678, declared: 06.10.2014; published: 25.01 2016, № 2.
2. Bekhiti, M. Properties of Waste Tire Rubber Powder [Text] / M. Bekhiti, H. Trouzine, A. Asroun // Engineering, Technology and Applied Science Research. – 2014. – Vol. 4, Issue 4. – P. 669–672.
3. Singh, B. Mechanistic Implications of Plastic Degradation [Text] / B. Singh, N. Sharma // Polymer Degradation and Stability. – 2008. – Vol. 93, Issue 3. – P. 561–584. doi: 10.1016/j.polymdegradstab.2007.11.008
4. Skoromnii, A. L. Snizenie energozatrat na utilizatsiyu iznoshennykh avtomobilnykh shin metodom termohimicheskoy destruktсии [Reduced energy consumption for recycling of used tires by thermochemical destruction] [Text] / A. L. Skoromnii // Ecology and industry. – 2008. – Vol. 4. – P. 68–71.
5. Kim, K. K. Noviy metod utilizatsii avtomobilnykh shin s metalokordom [A new method for recycling automobile tires with metal cord] [Text] / K. K. Kim, I. M. Karpova // Life safety. – 2007. – Vol. 7. – P. 24–27.
6. Vovk, O. O. Environmental Safety Technology of Scrap Tires Treatment [Text] / O. O. Vovk, J. S. Nikitchenko, // Proceedings of The National Aviation University. – 2009. – Vol. 41, Issue 4. – P. 94–99. doi: 10.18372/2306-1472.41.1805
7. Koc, A. Studying the Utilization of Plastic Waste by Chemical Recycling Method [Text] / A. Koc // Open Journal of Applied Sciences. – 2013. – Vol. 3, Issue 1. – P. 413–420. doi: 10.4236/ojapps.2013.37051
8. Hujuri, U. Modeling Pyrolysis Kinetics of Plastic Mixtures [Text] / U. Hujuri, A. K. Ghoshal, S. Gumma // Polymer Degradation and Stability. – 2008. – Vol. 93, Issue 10. – P. 1832–1837. doi: 10.1016/j.polymdegradstab.2008.07.006
9. Stalinsky, D. V. Modelirovanie temperaturnogo sostojaniya termohimicheskoy destruktсии iznoshennykh avtomobilnykh shin [Modelling of the temperature condition of the reactor thermochemical destruction for the worn out automobile tires] [Text] / D. V. Stalinsky, A. L. Skoromnyi, A. M. Sinozacky // Integrated technologies and energy efficiency. – 2011. – Vol. 1. – P. 58–66.
10. Development and model operation of installation for a heat treatment of combustible slates [Electronic resource]. – Available at: http://discollection.ru/article/27072009_kosova_ol_ga_jur_evna_93707/
11. Sposib pererobky polimernykh skladovykh znoshennykh avtomobil'nykh shyn [Electronic resource]. – Available at: <http://findpatent.com.ua/patent/240/2402591.html>
12. Ryzhkov, S. S. Otrabotka piroliznoy tekhnologii utilizatsii organicheskikh otkhodov dlya morekhozaystvennogo kompleksa – sistemy podachi otkhodov v piroliznyy reaktor [Working off of pyrolysis technology of utilization of an organic wastage for a morekhozaystvenny complex – system of giving of a wastage in the pyrolysis reactor] [Text] / S. S. Ryzhkov, L. N. Markina, N. V. Rudyuk, Yu. V. Zaboltnaya // Shipbuilding and marine infrastructure. – 2014. – Vol. 2, Issue 2. – P. 131–143.
13. Kirpichev, M. V. Modelirovanie teplovykh ustroystv [Simulation of thermal devices] [Text] / M. V. Kirpichev, M. A. Mikheev. – Moscow: USSR Academy of Sciences Publishing House, 1936. – 255 p.
14. Tyabin, N. V. Teploobmen. [Heat exchange] [Text] / N. V. Tyabin. – Soviet researches. Moscow: Science, 1974. – P. 195–198.
15. Dulnev, G. N. Teploprovodnost smesey i kompozitsionnykh materialov [Heat conductivity of mixes and composites. the reference book] [Text] / G. N. Dulnev, Yu. P. Zarichnyak. – Moscow: Energy, 1974. – 264 p.