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MODELING OF THE VAPOR THERMOLYSIS OF RUBBER WASTE

D. V. Aristarkhov[a] **and G. I. Zhuravskii**[b] UDC 536.246.2

Thermal destruction of rubber waste in a superheated water vapor at temperatures up to 500°C is considered. Relations to calculate the thermolysis time and the geometric dimensions of the reactor are obtained.

In the scientific aspect, the technology of vapor thermolysis of rubber waste has taken its first steps; certain kinetic regularities of thermal destruction of rubber in the medium of a superheated water vapor (steam) have been found and it has been established that the thermolysis of rubber and worn-out items made of it is a diffusion process (typical for solid organic materials) whose rate is limited by heat supply and diffusion of volatile destruction products.

Because of the low thermal conductivity of rubber and comparatively large dimensions of the pieces of rubber material and their inhomogeneity in shape and composition, the heat supply to rubber to carry out the destruction process is the main technological task, the successful implementation of which specifies the efficiency of the process, the apparatus employed, and the yield of the target products.

The development of highly efficient circuits of energy supply and optimization of the processes of vapor thermolysis of rubber waste can be accomplished only on the basis of physical and mathematical modeling of the thermal destruction of rubber in the medium of a superheated vapor.

In the present work, on the basis of experimental data obtained on experimental setups in the course of heat treatment of rubber waste with a superheated water vapor, a physical model of the process is formulated. This model has been applied to development of a calculational scheme for such parameters of the process as temperature, time of heating-up to a prescribed temperature, and geometric dimensions of a thermolysis reactor.

The essence of the physical concepts of the processes occurring in treatment of rubber waste with a superheated water vapor is as follows. At the initial instant, the superheated water vapor incident on the surface of rubber-waste pieces which are placed in a heat-treatment chamber becomes cooled and condensed. As a result, the waste is heated up to $T = 100^{\circ}$C and the condensation process ceases.

Next, the stage of evaporation of a precipitated condensate follows. Till the completion of this process the temperature in the zone is kept within $T = 100^{\circ}$C (in the heat-treatment chamber, the pressure is close to atmospheric).

Once the precipitated condensate has evaporated totally, the waste begins to undergo heating up to a temperature at which the thermal destruction of rubber begins. Here, the heat is absorbed (about 400–600 kJ/kg for rubber) and thermal stabilization (T = const) can be observed in the case where the quantity of heat supplied with a vapor flow is approximately equal to the quantity of heat consumed by heat loss and by the process of thermal destruction.

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[a] Scientific-Production Company "Ékologiya-Énergetika," Moscow, Russia; email: ee@esc.ru; [b] Academic Scientific Complex "A. V. Luikov Heat and Mass Transfer Institute," National Academy of Sciences of Belarus, Minsk, Belarus. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 74, No. 6, pp. 146–151, November–December, 2001. Original article submitted June 8, 2001.

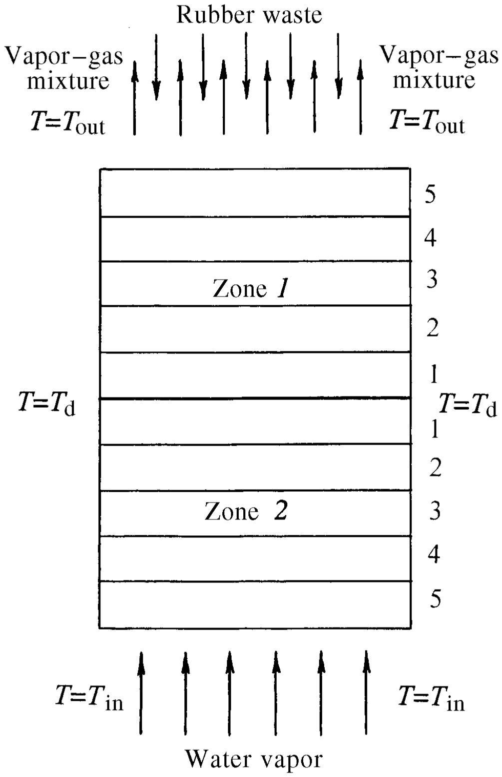

Fig. 1. Arbitrary zones and elements.

Experimentally, it has been established that the thermal destruction of rubber occurs to form first a liquid phase, which then evaporates. The rubber surface becomes coated with droplets of destruction products. With further heating, the liquid products of destruction are partly evaporated and partly undergo secondary destruction to form products which are in the gaseous state at this temperature.

Our observations and derivatographic studies have revealed that the temperature of the beginning of thermal destruction of rubber (depending on the kind of rubber) is 280–300°C. The temperature of the cessation of this process is within the limits 450–500°C.

To simplify the calculations of thermolysis, it is expedient to consider two zones: the zone of heating up to T = 280°C and the zone of thermal destruction of the rubber proper.

In the continuous process where the rubber is fed to the heat-treatment chamber from which the gaseous and solid products of thermal destruction are then removed, the temperature in the zones singled out arbitrarily changes from T_{in} to $T_{b.d}$ and from $T_{b.d}$ to T_{out}. The heat from the vapor flow to the rubber is transferred by convection. Here, the heat-transfer coefficient changes even within the limits of each of the zones. This is caused by many effects, among which are the change in the thermophysical characteristics of a heat-transfer agent with flow, the change in the characteristics of the rubber in the process of heating up, thermal destruction, and the formation of liquid and gaseous products diluting the heat-transfer agent.

The basic effects can be taken into account in the following mathematical model of rubber treatment with a superheated vapor.

We assume that the temperature of the vapor–gas mixture at the inlet of zone 2 is T_{in} (see Fig. 1), while at the outlet of zone 1 it is T_{out}. At this temperature the vapor–gas mixture is removed from the heat-treatment chamber.

Thus, the change in the temperature in zone 1 (the temperature of the heat-transfer agent) is $\Delta T = T_{in} - T_{out}$.

For calculations we arbitrarily subdivide zone 1 into n elements and assume that the change in the temperature in each element (see Fig. 1) is $\Delta T = (T_{\text{in}} - T_{\text{out}})/n$.

It should be noted that the heat-transfer agent arrives at zone 2 from zone 1. Such numbering of the zones is attributed to the fact that the waste (rubber) moves from zone 1 (the zone of heating up to the temperature of destruction) to zone 2 (the zone of thermal destruction).

On the basis of the balance relations we evaluate the amount of the heat-transfer agent (the superheated water vapor) required for accomplishing the process of thermolysis of the rubber waste:

$$M_{\text{v}} = 1.1 \frac{Q_{\Sigma}}{c_{\text{v}} \Delta T}, \tag{1}$$

where the coefficient 1.1 accounts for 10% of the heat loss and Q_{Σ} is the total quantity of energy consumed by the thermolysis process.

The quantity of energy consumed by the process consists of the energy consumed by the heating of the waste, thermal destruction, and evaporation of the liquid products of destruction and also of the heat loss.

Thus, on the basis of (1) we obtain

$$M_{\text{v}} = 1.1 \frac{c_{\text{mat}} M_{\text{mat}} \Delta T_{\text{mat}} + q_{\text{h.d}} M_{\text{mat}} + r_{\text{ev}} M_{\text{liq}} + c_{\text{s.r}} M_{\text{s.r}} (T_{\text{out}} - T_{\text{d}})}{c_{\text{v}} \Delta T}. \tag{2}$$

The calculation for c_{v} = 2 kJ/(kg·°C), M_{mat} = 1 kg, $q_{\text{h.d}}$ = 600 kJ/kg, T_{d} = 280°C, T_{out} = 500°C, c_{mat} = 1.7 kJ/(kg·°C), ΔT_{mat}= 260°C, ΔT = 350°C, $c_{\text{s.r}}$ = 1.21 kJ/(kg·°C), M_{liq} = 0.40 kg, $M_{\text{s.r}}$ = 0.6 kg, and r_{ev} = 256 kJ/kg gives M_{v} = 2.05 kg.

To carry out the calculations, we determine the following initial data: the number of elements of zone 1 is n = 5, the rubber density is 1140 kg/m^3, the thermal conductivity of the rubber is 0.26 W/(m·°C), the temperature of the vapor–gas mixture at the outlet of zone 1 is 200°C, the velocity of the mixture flow at the inlet of zone 1 is 1.48 m/sec, the mixture viscosity is $162 \cdot 10^{-7}$ Pa·sec at an outlet temperature of 200°C and at a temperature of the inlet to the zone of 350°C, and the thermal conductivity of the mixture is $33.1 \cdot 10^{-3}$ W/(m·°C) at an outlet temperature of 200°C and $49.0 \cdot 10^{-3}$ W/(m·°C) at a temperature of the inlet to the zone of 350°C.

The density of the vapor–gas mixture is calculated from the relation

$$\rho_{\text{v-g.m}} = \mu P / R\,(T + 273.15)\,. \tag{3}$$

The changes in the temperature in zone 1 are as follows (with respect to elements n):

$$1)\ T_{\text{in}} = 350^{\circ}\text{C}\,,\ \ T_{\text{out}} = 320^{\circ}\text{C}\,;\ \ 2)\ T_{\text{in}} = 320^{\circ}\text{C}\,,\ \ T_{\text{out}} = 290^{\circ}\text{C}\,;\ \ 3)\ T_{\text{in}} = 290^{\circ}\text{C}\,,\ \ T_{\text{out}} = 260^{\circ}\text{C}\,;$$

$$4)\ T_{\text{in}} = 260^{\circ}\text{C}\,,\ \ T_{\text{out}} = 230^{\circ}\text{C}\,;\ \ 5)\ T_{\text{in}} = 230^{\circ}\text{C}\,,\ \ T_{\text{out}} = 200^{\circ}\text{C}\,.$$

Let us calculate the mean values of $\rho_{\text{v-g.m}}$, c, λ, and $\mu_{\text{v-g.m}}$ in each of the elements. Here, we assume that the calculated temperature is the mean temperature in each of the elements, i.e., $T = (T_{\text{in}} + T_{\text{out}})/2$. The mean molecular mass of the vapor–gas mixture is determined from the following reasoning: (1) the amount of water vapor in the mixture is no less than 84%, while the amount of gaseous products of destruction is 16%; (2) the molecular mass of the liquid products of destruction of the rubber waste is calculated on the basis of the experimental data on the boiling temperatures from the following relation [1]:

$$\mu = -\,12272.6 + 9486.4\rho_0 + (8.3741 - 5.991\rho_0)\,(T_0 + 273.15) + (0.55556 - 0.42824\rho_0 - 0.011433\rho_0^3) \times$$

TABLE 1. Heat Capacity, Thermal Conductivity, Viscosity, and Density of the Mixture in Elements 1–5

Parameters	1	2	3	4	5
Mean:					
heat capacity, kJ/(kg·°C)	2.42	2.014	1.986	1.958	1.930
thermal conductivity, W/(m·°C)	$45.8\cdot 10^{-3}$	$42.6\cdot 10^{-3}$	$39.4\cdot 10^{-3}$	$36.2\cdot 10^{-3}$	$33\cdot 10^{-3}$
viscosity, Pa·sec	$211\cdot 10^{-7}$	$198.6\cdot 10^{-7}$	$186.4\cdot 10^{-7}$	$174.2\cdot 10^{-7}$	$162\cdot 10^{-7}$
density, kg/m^3	1.00	1.05	1.11	1.17	1.25

$$\times (1.3437 - 400.43/(T_0 + 273.15))\cdot 10^7/(T_0 + 273.115) + (0.1715 - 0.1387\rho_0 +$$

$$+ 0.003317\rho_0^2)\,(1.8828 - 101.1/(T_0 + 273.15))\cdot 10^{12}/(T_0 + 273.115)^3\,, \tag{4}$$

where T_0 is the normal point of boiling (it is taken as the mean point of the temperature range of boiling) and ρ_0 is the relative density (the ratio of the medium density to the water density).

From the experimental data the temperature range of boiling of the liquid products of destruction of the rubber waste is 105–400°C; therefore, $T_0 = (105 + 400)/2 = 252.5^\circ\mathrm{C}$, while the relative density is $\rho_0 = 0.920$ kg/m^3.

The calculation of the molecular mass μ on the basis of (4) and experimental data gives 184.24 kg/kmole.

Thus, the mean molecular mass of the vapor–gas mixture is $\mu_{\mathrm{v-g.m}}$ = (5.18 kg/kmole + 1.184 kg·mole)/6 ≈ 46 kg/kmole.

The values of the heat capacity $c_{\mathrm{v-g.m}}$, the thermal conductivity $\lambda_{\mathrm{v-g.m}}$, the viscosity $\nu_{\mathrm{v-g.m}}$, and the density $\rho_{\mathrm{v-g.m}}$ are adopted as the mean values and presented in Table 1.

We determine the velocity of the vapor–gas mixture at the inlet of zone 1 from the following reasoning. The vapor–gas mixture arrives here from zone 2. This mixture contains M_{v} and M_{liq} of the destruction products. With the output M_{mat}, the amount of the vapor–gas mixture (flow rate) is $(M_{\mathrm{v}} + M_{\mathrm{liq}})/\tau$. On condition that the cross-sectional area of zone 1 is S_1 and the density of the vapor–gas mixture is $\rho_{\mathrm{v-g.m}} = \mu P/R(T_{\mathrm{in}} + 273.15)$, we obtain the relation for calculation of the mixture velocity at the inlet of zone 1:

$$v_{1\mathrm{m}} = \frac{(M_{\mathrm{v}} + M_{\mathrm{liq}})\, R\, (T_{1\mathrm{in}} + 273.15)}{\mu P \tau S_1}\,. \tag{5}$$

For the conditions $M_{\mathrm{v}} = 2.05\cdot 1500$ kg = 3075 kg, $\tau = 3600$ sec, $M_{\mathrm{liq}} = 0.4\cdot 1500$ kg = 600 kg, $R = 8.31\cdot 10^3$ kJ/(kmole·°C), $T_{1\mathrm{in}} = 350^\circ\mathrm{C}$, $\mu = 46$ kg/kmole, $P = 1.1\cdot 10^5$ Pa, and $S_1 = 1.766$ m^2, we obtain from (5) $v_{1\mathrm{m}} = 0.591$ m/sec.

The vapor velocity at the inlet of zone 2 is determined based on the relation

$$v_{2\mathrm{m}} = \frac{M_{\mathrm{v}}\, R\, (T_{2\mathrm{in}} + 273.15)}{\mu P \tau S_1}\,. \tag{6}$$

For the conditions $T_{2\mathrm{in}} = 550^\circ\mathrm{C}$, $M_{\mathrm{v}} = 3075$ kg, and $\mu = 18$ kg/kmole, we obtain from (6) $v_{2\mathrm{m}} = 1.76$ m/sec.

Taking into account the porosity $\varepsilon = 0.4$, we obtain $v_{1\mathrm{m}} = 1.48$ m/sec and $v_{2\mathrm{m}} = 4.4$ m/sec.

For calculation of the heat-transfer coefficient in each of the elements of zone 1 we use the following reasoning and relations.

The rubber waste pieces represent plates whose length is much larger than the thickness. The vapor-gas mixture flows around them. Since the streamlined surface of the plates is not smooth and they themselves

TABLE 2. Change in the Temperature of the Waste in Elements 1–5 of Zone 1

Parameters	1	2	3	4	5
Bi number	0.294	0.292	0.291	0.288	0.287
Temperature at the center of the plate	280.7	244.5	204.1	156.8	98

are irregular, the flow around them can be considered to be turbulent even for small Re numbers. The process of heat transfer from the flow of the vapor–gas mixture can approximately be described by the expression [2]

$$\mathrm{Nu} = 0.037\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.43}\,(\mathrm{Pr}/\mathrm{Pr}_{\mathrm{w}})^{0.25}\,. \tag{7}$$

From (7) it follows that the heat-transfer coefficient can be calculated from the relation

$$\alpha = \frac{\lambda}{l}\cdot 0.037\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.43}\,(\mathrm{Pr}/\mathrm{Pr}_{\mathrm{w}})^{0.25}\,. \tag{8}$$

To calculate (mean) Re numbers in elements 1–5, we use the mean values of the velocity in each of the elements and the mean values of the viscosity ν. In the same way, the values of ν and a are chosen for calculation of the Pr and Pr_{w} numbers.

Using the data of Table 1 and the above relation (8), we determine the heat-transfer coefficient (W/(m$^2\cdot{}^{\mathrm{o}}$C)) with respect to the elements of zone 1: 1) $\alpha = 15.31$, 2) $\alpha = 15.18$, 3) $\alpha = 15.17$, 4) $\alpha = 14.95$, and 5) $\alpha = 14.90$.

For calculation of the process of heating of the rubber waste we introduce the following assumptions: (1) the pieces of rubber waste represent plates with a length of 300 mm and a thickness of 10 mm and 50 mm; (2) as a calculational relation, we adopt the following one:

$$\Theta_{x=0} = \frac{T_{x=0} - T_{\mathrm{v}}}{T_0 - T_{\mathrm{v}}} = N\,(\mathrm{Bi})\,\exp\,(-\,\mu_1^2\,\mathrm{Fo})\,. \tag{9}$$

Relations for calculation of Bi and Fo are as follows:

$$\mathrm{Bi} = \frac{\alpha d}{2\lambda}\,; \quad \mathrm{Fo} = \frac{4a\tau}{d^2}\,. \tag{10}$$

Let us determine the dimensionless temperature at the center of the plate ($x = 0$):

$$\Theta_{x=0} = \frac{T_{x=0} - T_{\mathrm{v}}}{T_{\mathrm{i}} - T_{\mathrm{v}}}\,. \tag{11}$$

Using the tabulated values [3] for the function $\Theta_{x=0} + f(\mathrm{Bi},\,\mathrm{Fo})$, we determine the Fo numbers for the prescribed values of $\Theta_{x=0}$ and prescribed Bi (with respect to the elements of zone 1), from which we find the time of heating-up of the plates in each of the elements (1–5) of zone 1 up to a temperature at the center ($x = 0$) close to the mean temperature of the vapor-gas mixture.

We consider the version where the waste moves uniformly with time via each element. This version is of greatest interest for practice.

We assume that the waste stays in each element for 360 sec. The calculated temperature of the waste at the outlet of zone 1 is presented in Table 2, from which it follows that the waste is heated from $T_{\mathrm{i}} = 20^{\mathrm{o}}$C to $T = 280^{\mathrm{o}}$C in 1800 sec (30 min).

The calculations show that for Bi = 1.5 (the thickness of the plates is 50 mm) the time of heating of the waste from $T_\mathrm{i} = 20^\mathrm{o}\mathrm{C}$ to $T = 280^\mathrm{o}\mathrm{C}$ is 190 min (38 min in each element).

For the prescribed output G_waste, we determine the geometric dimensions of zone 1 on condition that the time of heating-up of the waste to $T = T_\mathrm{d}$ is τ_h, the (bulk) density is $\rho^0_\mathrm{b.d}$, and the apparatus cross section is S_0. In this case, the output is calculated from the relation

$$G_\mathrm{waste} = \frac{\rho^0_\mathrm{b.d} S_0 L}{\tau_\mathrm{h}}\,, \tag{12}$$

and the dimension of zone 1 is

$$L = \frac{G_\mathrm{waste}\tau_\mathrm{h}}{\rho^0_\mathrm{b.d} S_0}\,. \tag{13}$$

Let us consider the processes that occur in zone 2, i.e., the zone of thermal destruction of the rubber waste. We determine the following initial data (for an hour): the mass of the waste arriving at the zone is 1500 kg, the mass of the residue leaving the zone is 900 kg, the mass of the volatile products formed in the zone is 600 kg, the mass of metal cord is (5% of the weight) is 75 kg, the temperature of the vapor-gas mixture at the zone inlet is $550^\mathrm{o}\mathrm{C}$, the temperature of the vapor–gas mixture at the zone outlet is $350^\mathrm{o}\mathrm{C}$, the heat of evaporation of hydrocarbons is 256 kJ/kg, the (mean) heat capacity of the vapor–gas mixture is 2.13 $\mathrm{kJ/(kg{\cdot}^oC)}$, the density of the vapor–gas mixture at the zone outlet is 0.997 $\mathrm{kg/m^3}$, the vapor density at the zone inlet is 0.308 $\mathrm{kg/m^3}$, the thermal conductivity of the vapor at the zone inlet is $67.3{\cdot}10^{-3}$ $\mathrm{W/(m{\cdot}^oC)}$, the heat capacity of the vapor at the zone inlet is 2.132 $\mathrm{kJ/(kg{\cdot}^oC)}$, and the vapor viscosity at the zone inlet is $284{\cdot}10^{-7}$ Pa·sec.

In zone 2, heating of the waste from $T = 280^\mathrm{o}\mathrm{C}$ to $T = 500^\mathrm{o}\mathrm{C}$ and the escape of volatile products of destruction occur. We subdivide zone 2 into five elements and assume that the yield of volatile products is the same in each element.

As the vapor–gas mixture moves through the layer of waste undergoing thermal destruction, the density of the vapor–gas mixture changes as a result of arrival of the destruction products at the mixture. The velocity of the latter changes in each element due to the change in the mixture density and the arrival of the destruction products at the flow.

An expression for calculation of the velocity of the vapor–gas mixture in each element has the form

$$v_\mathrm{2m} = \frac{\left(M_\mathrm{v} + M_\mathrm{liq}\dfrac{1+N-n}{N}\right) R\,(T + 273.15)}{\mu_\mathrm{v-g.m} P \tau S_1 \varepsilon}\,. \tag{14}$$

The molecular mass of the mixture in each element is calculated from the relation

$$\mu_\mathrm{v-g.m} = \frac{\left(M_\mathrm{v}{\cdot}18\,\dfrac{\mathrm{kg}}{\mathrm{kmole}} + M_\mathrm{liq}\dfrac{1+N-n}{N}\cdot 184\,\dfrac{\mathrm{kg}}{\mathrm{kmole}}\right)}{M_\mathrm{v} + M_\mathrm{liq}\dfrac{1+N-n}{N}}\,. \tag{15}$$

For calculation of the heat-transfer coefficient $\mathrm{(W/(m^{2}{\cdot}^oC)}$ we use (8) and obtain: 1) $\alpha = 16.27$, 2) $\alpha = 16.30$, 3) $\alpha = 16.35$, 4) $\alpha = 16.38$, and 5) $\alpha = 16.40$.

As the rubber waste moves in the zone in the direction from the inlet to the outlet, the characteristics of the waste itself, i.e., the density, thermal conductivity, and thermal diffusivity, change. In the zone, absorption of the latent heat of evaporation of the liquid fraction and of the heat of thermal destruction of the material (rubber) occur.

Proceeding from the assumption that the yield of volatile products with respect to the zone height is uniform (a linear approximation), we calculate the change in the density for each element of the zone and obtain (kg/m^3): 1) $\rho = 1049$, 2) $\rho = 958$, 3) $\rho = 867$, 4) $\rho = 776$, and 5) $\rho = 685$.

To determine the time necessary for vapor treatment of the waste in the zone, we make the following assumptions:

(1) energy consumptions by thermal destruction and evaporation of destruction products are determined as $\omega / c\rho$;

(2) the thermophysical characteristics of the solid residue weakly depend on the yield of volatile (liquid) destruction products and can be assumed to be equal to the thermophysical characteristics of the initial rubber;

(3) the outflow of liquid products and their evaporation are uniform with respect to the volume of the waste and with time;

(4) the geometric dimensions of the pieces of rubber waste in the course of outflow of liquid products change weakly, and these changes can be neglected.

In this case, the problem of heating of the waste in zone 2 is formulated as follows:

$$\frac{\partial T}{\partial \tau} = a \frac{\partial^2 T(x, \tau)}{\partial x^2} - \frac{\omega}{c\rho}, \tag{16}$$

$$T(x, 0) = T_i ; \quad \frac{\partial T(0, \tau)}{\partial x} = 0, \tag{17}$$

$$-\frac{\partial T(d/2, \tau)}{\partial x} + \frac{\alpha}{\lambda_{mat}} (T_v - T(d/2, \tau)) = 0 . \tag{18}$$

Having solved this problem, we can determine the mean temperature of the waste [4]:

$$\frac{T(\tau) - T_i}{T_v - T_i} = 1 - \frac{\omega d^2}{12\lambda_{mat}(T_v - T_i)} \left(1 + \frac{3}{Bi}\right) - \left(1 - \frac{\omega d^2}{4\lambda_{mat}(T_v - T_i)\mu_1^2}\right) B_1 \exp(-\mu_1^2 \, Fo) . \tag{19}$$

In our case, Bi = 0.315–0.321, $\mu_1 = 0.5325$–0.5368, and $B_1 = 0.9982$.

We assume that the waste stays for 900 sec (15 min) in each element of zone 2. The quantity ω is determined as follows:

$$\omega = \frac{\rho_i^0 q_{h.d}}{N\tau} = \frac{684 \text{ kg/m}^3 \cdot 600\,000 \text{ J/kg}}{5 \cdot 900 \text{ sec}} = 91\,200 \text{ J/(m}^3 \cdot \text{sec)} . \tag{20}$$

The calculations from relation (19) for the prescribed conditions show that the mean temperature (^{o}C) is: 1) $T = 320$, 2) $T = 360$, 3) $T = 400$, 4) $T = 440$, and 5) $T = 480$.

Let us determine the size of zone 2 proceeding from a time of stay of the waste in the zone of τ_h = 4500 sec and an (initial) output of G_{waste} = 1000 kg/h:

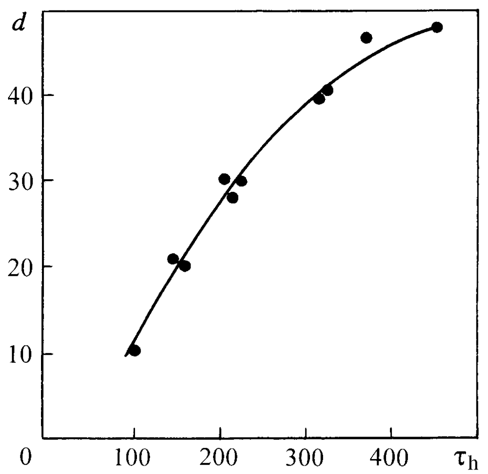

Fig. 2. Comparison of the calculated (solid line) and experimental data on the thermolysis time versus the thickness of rubber plates. *d*, mm; τ_h, min.

$$L = \frac{G_{\mathrm{waste}}\tau_{\mathrm{h}}}{\rho_{\mathrm{i}}^{0} S_0} = \frac{(0.278\ \mathrm{kg/sec})\cdot 4500\ \mathrm{sec}}{\left(684\ \mathrm{kg/m^3}\right)\cdot 1.766\ \mathrm{m^2}} = 1.04\ \mathrm{m}\,, \tag{21}$$

$$V_2 = S_0 L = 1.04\cdot 1.766 = 1.83\ \mathrm{m^3}\,. \tag{22}$$

Thus, the total volume of the apparatus for thermolysis of the rubber waste is 1.83 $\mathrm{m^3}$ + 0.73 $\mathrm{m^3}$ = 2.56 $\mathrm{m^3}$, where 0.73 $\mathrm{m^3}$ (V_1) is the volume of the zone of heating from T = 20°C to T = 280°C for the waste with d = 0.01 m. The total time of thermolysis of the waste is 1800 sec + 4500 sec = 6300 sec.

The calculational scheme described above and the assumptions made were tested by comparing the experimental and calculated data on the time of thermolysis of the rubber waste. The results are presented in Fig. 2, from which one sees the fair consistency of the calculated and experimental values, which is indicative of the admissibility of the adopted calculational model.

NOTATION

M_{liq}, M_{mat}, M_{v}, and $M_{\mathrm{s.r}}$, mass of the liquid, the initial material, the vapor, and the solid residue, respectively; c_{v}, c_{mat}, and $c_{\mathrm{s.r}}$, specific heat of the vapor, the material, and the solid residue; T_{in} and T_{out}, vapor temperature at the inlet and the outlet; T_{d}, destruction temperature; ΔT_{mat}, temperature difference of the material at the inlet and the outlet of zone 1; $q_{\mathrm{t.d}}$, specific heat of thermal destruction; r_{ev}, evaporation heat of the liquid; ΔT, difference of the vapor temperatures at the inlet and the outlet; $\rho_{\mathrm{v-g.m}}$, density of the vapor–gas mixture; μ, molecular weight; P, pressure; R, universal gas constant; ρ_0, relative density of the liquid; $\mu_{\mathrm{v-g.m}}$, molecular mass of the vapor–gas mixture; $\lambda_{\mathrm{v-g.m}}$, $c_{\mathrm{v-g.m}}$, and $\nu_{\mathrm{v-g.m}}$, thermal conductivity, specific heat, and viscosity of the vapor–gas mixture; v_{1m} and v_{2m}, velocity of the mixture at the inlet of zones 1 and 2; T_{1in} and T_{2in}, temperature of the mixture at the inlet of zone 1 and of the vapor at the inlet of zone 2; Nu, Re, Pr, and Bi, Nusselt, Reynolds, Prandtl, and Biot numbers; $\mathrm{Pr_w}$, Prandtl number at the apparatus-wall temperature; α, heat-transfer coefficient; λ, thermal conductivity of the material; l, plate length; Θ, dimensionless temperature; T_{i}, initial temperature of the material; $T_{x=0}$, temperature at the center of the plate; T_{v}, vapor temperature; τ, time; τ_{h}, time of heating-up of the material; $\rho_{\mathrm{b.d}}$, bulk density; S_0, cross-sectional area of the apparatus; G_{waste}, output of the waste; L, apparatus height; N, number of elements; n, number of the element in the zone; a, thermal diffusivity; d, plate thickness; λ_{mat}, thermal conductivity of the material; μ_1^2, first root of the characteristic equation; ε, porosity; V_1 and V_2, volume of zones 1 and 2, respectively. Subscripts: v, vapor; v–g.m, vapor–gas mixture; s.r, solid residue; m, mixture; d, destruction; h, heating-up; in, inlet; out, outlet; b.d, beginning of destruction; liq, liquid; mat, material; ev, evaporation; h.d, heat of destruction; b, bulk; waste, waste; w, wall.

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