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STEAM THERMOLYSIS OF TIRE SHREDS: MODERNIZATION IN AFTERBURNING OF ACCOMPANYING GAS WITH WASTE STEAM

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On the basis of experience in the commercial operation of tire-shred steam thermolysis in EnresTec Inc. (Taiwan) producing high-grade commercial carbon, liquid pyrolysis fuel, and accompanying fuel gas by this method, we have proposed a number of engineering solutions and calculated-analytical substantiations for modernization and intensification of the process by afterburning the accompanying gas with waste steam condensable in the scrubber of water gas cleaning of afterburning products. The condensate is completely freed of the organic pyrolysis impurities and the necessity of separating it from the liquid fuel, as is the case with the active process, is excluded.

Keywords: *shreds, tire processing, pyrolysis, fuel, carbon, gas, steam, modernization.*

Introduction. Thermolysis (pyrolysis) of used automobile tires is the most efficient method of their utilization to produce commercial carbon, liquid pyrolysis fuel, and accompanying fuel gas whose calorific value is higher than that of natural gas. The topicality and interest in this problem have been expressed in different methods and technologies of pyrolysis tire processing which, nonetheless, have not found wide use. The problem is in the thermal instability of the pyrolysis gas, which condenses (when the temperature regime is broken) not only in the liquid phase but also in the amorphous phase as soot, covering and clogging gas ducts and other equipment with this soot on slowdown and cooling of the process. The problem is aggravated by the low quality of pyrolysis fuel and carbon, which are in poor conformity with the existing standards, including the issues of environmental purity and safety of such pyrolysis industries [1].

Certain advantages in this field are offered by the use of steam, namely, superheated steam first used at the beginning of the last century in the USA [2] and later in the USSR where artificial liquid fuel was produced in the 1950s by coal pyrolysis with steam as a thermally stable heat-transfer agent [3]. At the same time, steam diffusion into the formed pores of a material obviously unclogs and displaces volatiles from them, improving the quality of the pyrolysis. The presence of the steam reduces the tire-thermolysis temperature to 315°C, which was first noted even in [2], and this is 100 to 150°C lower than the temperature of today's processes of steam-free pyrolysis of tires where we have thermal diffusion of only the volatiles themselves. Moreover, diluting the pyrolysis gas in the reactor and so reducing its partial pressure, the steam additionally produces a concentration-diffusion flow of volatiles from the material; apparently, without steam, this reduction in the temperature to 400°C is obtained just by the vacuum-pyrolysis method [4] where such diffusion acts due to the total reduction in the reactor's pressure.

In the works of the A. V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus, the potentialities of steam thermolysis have been realized in both the chamber technology for solid or solid-cut tires [5–7] and the screw technology for shredded tires in the form of the so-called scrap [8, 9]. The advantages of the latter as to pyrolysis with mixing and a comparatively high specific heating surface of a material are obvious and have been proved by the active production process at the tire-processing factory of EnresTec Inc. (Taiwan), which has been developed and put into operation in 2007–2008 with direct participation of the author. The factory has two thermal-equipment lines with an output of 1 ton/h each; the lines incorporate a furnace, a pyrolysis reactor, a steam recovery boiler, and successive fuel and steam condensers. The efficiency of such technology lies not only in the compactness of the screw-type reactor, which is heated mainly by afterburning the accompanying gas in the furnace, but

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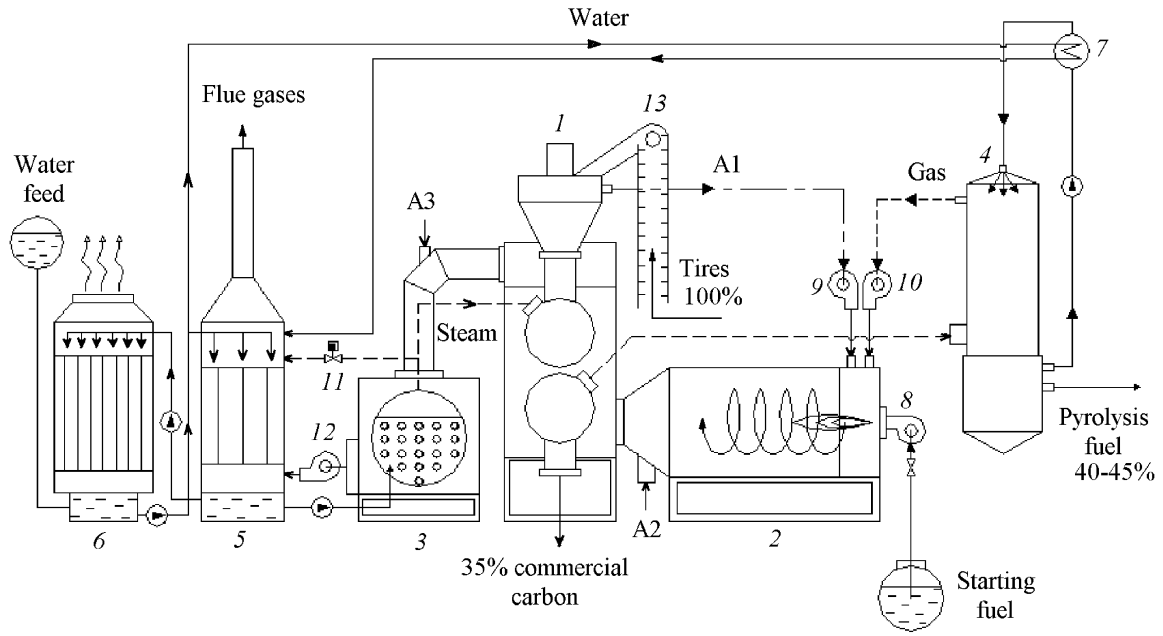

Fig. 1. Process flow diagram of a modernized process 1) screw-type thermolysis reactor; 2) furnace for afterburning the accompanying gas; 3) steam recovery boiler; 4) fuel condenser; 5) water gas-cleaning scrubber; 6) water-cooling tower; 7) cooling heat exchanger for the fuel in the condenser; 8) fuel-starting burner; 9) fan for feeding air to the furnace; 10) gas-feeding fan; 11) valve of controlled steam discharge; 12) induced-draught fan for flue gases; 13) elevator for top loading of the reactor (the bottom-unloading conveyer is not shown); A1, air feed to the furnace; A2, air inflow and suction into the reactor's heating chamber; A3, air inflow and suction in the boiler.

also in the environmental closeness of the process in which the steam condensate, on separation from the liquid fuel, is returned to the steam boiler. The quality of the carbon product is characterized as 1–1.5% of the residual content of hydrocarbons, which compares favorably with 3–4% in steam-free tire thermolysis.

It has been elucidated during the operation that water-cooled tubular condensers do not ensure separate condensation of the steam and the fuel; a combination of both partially condenses in them at each stage; the condensers themselves are contaminated by soot. For this reason, in the active process in Taiwan [9], the fuel together with the steam condensate are accumulated in a specially equipped tank where the fuel is allowed to settle and is separated from water by the method of simple overflow. The resulting pyrolysis fuel representing a mixture of light and heavy (mazut) fractions is unsuitable for the standard light (diesel)-fuel burner; therefore, it is separated into light and heavy fractions in a Laval centrifugal separator directly at the factory. Thereafter there remains up to 2–3% of mazut-carbon sludge, whose repeat pyrolysis together with the tire scrap has been considered in [9] but is not realized, since the sludge is used to produce asphalt.

The steam condensate is also not pure and contains all water-soluble benzenes, benzynes, and other light (aromatic) rubber fractions condensing with the steam at 45–50°C at exit, including minor hydrosuspensions of insoluble fractions that are separated by the coagulation method before recycling the condensate to the boiler. In the boiler, the dissolved organic matter evaporates again and enters, together with the steam, again the pyrolysis reactor and next the condensers where it is dissolved again, etc., increasing the yield and saturated state of the accompanying gas to 9–10% of the processed-tire mass [9]; the calorific value of the accompanying gas under normal conditions without steam is 39 MJ/m^3 (9350 kcal/m^3) from the data of [10, 11]. In our case, after condensation at the above temperature, the residual content of the steam in the gas is 20–25% of the volume; taking this fact into account, we can evaluate the working heat of combustion approximately at 29 MJ/m^3 (7000 kcal/m^3).

The operation of a steam boiler on a condensate with such organic impurities is not provided for by industrial standards as is the settling separation of a fuel from this condensate, which has complications of its own. In particular, there can be a situation where feeding of the pyrolysis reactor is temporarily not performed but the furnace must be in the so-called hot-downtime regime, continuing steam generation and so maintaining the operating thermal regime of the entire equipment. Without feeding, the pyrolysis gas ceases to escape from the reactor and only a steam condensate is formed in the condensers, which disturbs the normal level of settling and overflow of the fuel in the separation tank. All is simplified if one condenses the steam in pure form from the fuel, thus eliminating both the necessity of separating them and the problem of organic impurities in the condensate. In this connection, it is expedient to modernize the process as proposed below.

Steam Condensation on Afterburning with an Accompanying Gas. In steam-free tire-pyrolysis technologies, condensation of the fuel is usually performed in scrubber columns [10, 11] operating on the principle of recirculation refluxing by the condensate (by analogy with rectification columns) and in which pyrolysis soot is removed together with the fuel, including the last benzyne fraction of the fuel at 55–60^{o}C. In steam thermolysis with water-tube condensers, the benzyne fraction condenses, too, but is dissolved and lost with the steam condensate, presenting the above problems with this condensate. If the steam condenser is excluded and only the scrubber condenser of a fuel with a yield temperature of no less than 100^{o}C is used, this will prevent the condensation and mixing of the steam with the fuel, as is shown on the process flow diagram in Fig. 1. In so doing, the entire waste steam of the reactor, together with the accompanying gas, enters the afterburner furnace; thereafter the flue gases with the steam enter the reactor's heating chamber and next the recovery boiler, where steam generation thus increases and becomes a function of the additional rate of flow of the steam itself (self-production). According to this diagram, the steam condenses very late in the process in the water gas-cleaning scrubber where it, as part of the flue gases, enters from the recovery boiler. From the scrubber, the steam condensate, being completely freed of all fractions and impurities of the fuel after the afterburner furnace, is recycled back to the boiler; the benzene and benzyne fractions condensable and soluble earlier efficiently burn up in the furnace with the accompanying gas rather than being lost with the steam condensate. Just as in the active process [9], flue gases contain sulfoxides, which are formed when hydrogen sulfide H_2S burns up as part of the gas and are absorbed in the scrubber water. As a result, the steam condensate becomes a weakly acid solution with pH = 6.5, which requires the corresponding alkaline water treatment, drainage to 5% of the scrubber water for salt balance, and a corrosion-resistant steam boiler.

The scrubber cools down from the steam-condensation heat in a water-cooling tower whose system also includes a cooling heat exchanger for fuel recycling in the condenser, as is shown in Fig. 1 where the condensations of the fuel and steam are seen to be conceptually split and there is no need to separate them. The steam condensation outside the water scrubber is excluded, since even on start-up, steam is generated and appears as part of flue gases no earlier than the lined equipment of the furnace, the reactor, and the ducts between them is heated much above 100^{o}C. The boiler surfaces, being under an excess pressure of the steam superheater of to 0.5 MPa, also operate above 100^{o}C, even if only slightly. When the process is stopped, the residual steam from the boiler condenses in the scrubber before the lining of the equipment cools down to 100^{o}C or lower.

In the modernized process, we should note a new positive function of steam not only for diffusion intensification of the pyrolysis in the reactor but also as an additional heat-transfer agent as part of flue gases for heating of the reactor and then for generation of the same steam in the boiler. In this connection, it is required that the total balance and heat balances be reanalyzed at each step of a new steam-gas cycle by analogy with the active process [9]. Clearly, the volume, composition, and calorific value of afterburning of the accompanying gas mixed with the steam substantially change, which is to be analyzed first.

Steam Generation and Afterburning of a Steam-Gas Mixture. It has been shown earlier [8] that the minimum specific heat of combustion of a diluted fuel mixture, for which its ignition under normal conditions is hindered and the mixture is quite explosion-proof, is approximately $Q_{\text{gas,min}} \cong 4$ MJ/m^3 (950 kcal/m^3). Since afterburning of the accompanying gas with the steam is envisaged in our case in the furnace at a temperature of no less than 1000^{o}C, we can assume that this limit of ignition and combustion of the gas becomes lower under these conditions. Considering the reduction in the heat of combustion of such a mixture as a result of the steam dilution of the gas with the intrinsic heat of combustion of the gas Q_{gas} = 39 MJ/m^3, we can formulate this in the following form:

TABLE 1. Temperature Fractions in Distillation of a Pyrolysis Fuel from [4]

Distillation temperature, °F (°C)	Fractional yield, %	Degree of distillation, %	Distillation temperature, °F (°C)	Fractional yield, %	Degree of distillation, %
137 (58)	9.99	9.99	630 (332)	5.55	53.14
233 (112)	5.03	15.02	688 (364)	5.09	58.23
277 (136)	5.09	20.11	710 (376)	5.35	63.58
324 (162)	5.03	25.14	744 (396)	5.09	68.67
412 (211)	5.09	30.23	795 (424)	5.09	73.76
468 (242)	5.09	35.32	821 (438)	5.09	78.85
520 (271)	5.09	40.41	853 (456)	5.3	83.88
585 (307)	7.18	47.59	885 (474)	5.35	89.23

Note. The distillation residue is 10.77%; the degree of distillation with a residue is in the aggregate 100%.

$$Q_{\text{mix}} = \frac{G_{\text{gas}} Q_{\text{gas}}}{\dfrac{G_{\text{gas}}}{\rho_{\text{gas}}} + \dfrac{G_{\text{s}}}{\rho_{\text{s}}}} = \frac{Q_{\text{gas}}}{1 + \dfrac{G_{\text{s}}}{G_{\text{gas}}} \dfrac{\rho_{\text{gas}}}{\rho_{\text{s}}}} = \frac{Q_{\text{gas}}}{1 + \dfrac{\text{STEAM}}{\text{GAS}} \dfrac{\rho_{\text{gas}}}{\rho_{\text{s}}}} \geq Q_{\text{gas,min}} \,. \tag{1}$$

To determine the yield of the accompanying gas under our conditions, we use the data on fractional distillation of a pyrolysis fuel from tires [4], where up to 15% of the benzyne fractions have been separated in the range 58–112°C (Table 1); these fractions do not condense in our case and become part of the accompanying gas. From these data and many others, for the total production of the fuel to the extent of to 50% of the processed-tire mass, the gas yield increases by 7–8% on this scale and, together with an available value of 8–9%, will be GAS = 16–18% of the processed mass.

It has been shown earlier [9] that the minimum yield of the accompanying fuel gas for which the heat balance of the process is held due to the afterburning of the gas without fuel consumption, must amount to no less than 10% of the processed mass. Clearly, in our case burning of the fuel is excluded and is required only for start-up; moreover, by analogy with [9], it takes a certain excess of the air feed to the furnace to keep the flue-gas temperature from exceeding that required for heating the reactor. Allowing up to 3% of the heat loss through the lining, i.e., with thermal efficiency of the furnace $E_{\text{f}} \cong 0.97$, we include the sought air feed into the heat balance of the furnace where the entire heat of afterburning of the gas is expended for heating this air and the steam to the required temperature T_{g1}:

$$(G_{\text{a}} c_{p\text{a}} + G_{\text{s}} c_{p\text{s}})\,(T_{\text{g1}} - T_{\text{a}}) = G_{\text{gas}} Q_{\text{gas}} E_{\text{f}} \,, \tag{2}$$

$$G_{\text{gas}} = G_{\text{t}} \frac{\text{GAS}}{100} \,. \tag{3}$$

The flow rate of air includes its primary feed to the furnace (A1 on the diagram), with the furnace temperature no less than 1000°C for complete afterburning of individual toxic components of rubber as part of the accompanying gas, and its secondary feed (A2) to the reactor's heating chamber where the temperature must be no more than T_{g1} = 900°C. In the computational analysis of the active process [9], these quantities were determined separately as functions of the excess-air coefficients for burning of a liquid fuel and a gas respectively, but in this case no fuel is required and the air feed is formulated in general form as G_{a}.

Steam generation in the recovery boiler for flue gases is determined by the enthalpy of these gases on heating the reactor, in which the steam flow rate is involved as the sought quantity determined by the equation of heat balance of the boiler

$$(G_{\text{g}} c_{p\text{g}} + G_{\text{s}} c_{p\text{s}})\,(T_{\text{g2}} - 200) = G_{\text{s}}\,[c_{p\text{w}}\,(T_{\text{s}} - T_{\text{a}}) + h_{\text{s}}] \,, \tag{4}$$

where the flow rate and heat capacity of the flue gases can be assumed to be approximately equal to the total feed and heat capacity of air: $G_g \cong G_a$ and $c_{pg} \cong c_{pa}$; it is assumed that the boiler operates at an exit temperature of the flue gases of to 200°C, which is the existing standard for the induced-draught fan of any boiler.

Substitution of (2)–(4) gives computational formulas for the sought parameters of air feed and steam output for the relative mass of processed tires as a function of the temperature regime of the process:

$$\frac{G_s}{G_t} = \frac{\text{STEAM}}{100} = \frac{Q_{gas} E_f}{(A c_{pa} + c_{ps})\,(T_{g1} - T_a)} \frac{\text{GAS}}{100}\,, \tag{5}$$

$$\frac{G_a}{G_t} = \frac{\text{AIR}}{100} = \frac{A Q_{gas} E_f}{(A c_{pa} + c_{ps})\,(T_{g1} - T_a)} \frac{\text{GAS}}{100}\,, \tag{6}$$

$$A = \frac{G_a}{G_s} = \frac{c_{pw}\,(T_s - T_a) - c_{ps}\,(T_{g2} - 200) + h_s}{c_{pa}\,(T_{g2} - 200)}\,. \tag{7}$$

The temperature regime of the reactor is determined by the heat balance that lies in heating and the thermal decomposition of the tire material due to the enthalpy of flue gases, including the attendant superheating of the steam to a pyrolysis temperature in the coil pipe around the reactor, as is shown in [9]. In our case the generated steam (5) is involved in this balance as part of the flue gases; as previously, we have $G_g \cong G_a$ and $c_{pg} \cong c_{pa}$:

$$(G_g c_{pg} + G_s c_{ps})\,(T_{g1} - T_{g2})\,E_r = G_t\,[c_{pt}\,(T_p - T_a) + h_t] + G_s c_{ps}\,(T_p - T_s)\,, \tag{8}$$

whence, with account for (5) and (6), we formulate the difference in temperature of the flue gases at the inlet and outlet of the reactor's heating chamber in the following form (by analogy with the furnace, the efficiency of the reactor's lining is taken to be E_r = 0.97, too):

$$T_{g1} - T_{g2} = \frac{c_{pt}\,(T_p - T_a) + h_t + c_{ps}\,(T_p - T_s)}{E_f E_r \left(c_{pa} \frac{\text{AIR}}{100} + c_{ps} \frac{\text{STEAM}}{100} \right)} \frac{\text{STEAM}}{100}\,. \tag{9}$$

Table 2 gives, for the sake of comparison, the technological indices of the existing (active) [4] and proposed processes, where computational modeling of the latter ((5)–(7)) has been performed in the EXCEL program accurate to 1% by the method of successive approximations of the initial and calculated flue-gas temperatures (9) for the following parameters:

Temperature of the flue gases at the reactor inlet T_{g1}, °C	800
Temperature of the flue gases at the reactor outlet T_{g2}, °C	590
Temperature of the process inside the pyrolysis reactor T_p, °C	350
Steam temperature in the boiler (pressure to 0.3 MPa) T_s, °C	140
Outside-air temperature T_a, °C	20
Steam density (100°C), kg/m^3	0.58
Gas density (100°C), kg/m^3	0.785
Specific heat of destruction of the tire rubber h_t, kJ/kg	630
Specific heat of combustion of the accompanying gas Q_{gas}, MJ/m^3	39
Specific heat of vaporization (3 bar) h_s, kJ/kg	2170
Accompanying-gas yield (relative to the tire mass) GAS, %	18
Heat capacity of rubber c_{pt}, kJ/(kg·°C)	1.68
Heat capacity of air c_{pa}, kJ/(kg·°C)	1.050
Heat capacity of steam c_{ps}, kJ/(kg·°C)	2.09
Heat capacity of water c_{pw}, kJ/(kg·°C)	4.18

TABLE 2. Indices of Steam Thermolysis in the Active and Proposed Process at a Production Rate of 1000 kg/h and a Pyrolysis Temperature of 350°C

Indices and parameters of the process	Afterburning of the accompanying gas in the active process [9]	Afterburning of the gas together with the steam in the modernized process	
		with the total steam output from (5)	limitation of the steam output from (13)
Flow rate of the pyrolysis fuel, kg/h	20	—	—
Afterburning of the casing head gas, nm^3/h	100	200	200
Total air feed (A1 + A2), nm^3/h	2400	4600	4600
Thermal capacity of the furnace, MW	1.2	2.0	2.0
Afterburning temperature of the gas, °C	1100	1000	1000
Gas temperature, °C:			
at the reactor inlet	900	800	800
at the reactor outlet	480	590	590
at the boiler inlet	480	590	500
Flow rate of flue gases in the reactor, nm^3/h	2500	7000	6500
Air inflow and suction in the boiler A3, nm^3/h	—	—	1200
Flow rate of flue gases in the boiler, nm^3/h	2500	7000	7300
Steam output on the recovery boiler, kg/h	350	1300	1000
Quantity of steam in the casing head gas, m^3/h	25	2200	1700
Heat of combustion of the gas–steam mixture, MJ/nm^3	29	3.5	5.5

Thermal efficiency of the furnace E_f	0.97
Thermal efficiency of the reactor E_r	0.97
Relation of the air feed to the steam output from (7), kg/kg	4.513
Total specific air feed to the furnace per 1 kg of tires (6), kg/kg	5.932
Specific steam output per 1 kg of tire pyrolysis from (5), kg/kg	1.314
Temperature of flue gases at the reactor outlet T_{g2} from (9), °C	592

The modeling gives the difference in flue gas temperatures in heating of the reactor, which is approximately half as great as the difference in the active process [9]; the temperature required for heating diminishes from 900 to 800°C. The latter is a result of the more powerful flow of flue gases with a steam whose generation relative to the tire charge increases nearly fourfold compared to [9]: approximately to 130% instead of 30–35%. This increase is due to both the twofold increase in the volume of afterburning of the accompanying gas (to 18% instead of 9–10%) and the effect of self-production of the steam in the boiler where the waste steam after the reactor, as part of the flue gases, is reutilized as an additional heat-transfer agent for generation of new steam. With such self-production the steam output in the boiler from (5)–(7) grows and attains the indicated value for which the reactor's heat balance is ensured by half as great a temperature difference of flue gases (9), as has been given above.

The power (capacity) of the afterburner furnace per 1 ton/h of pyrolysis increases from 1.2 to 2.0 MW, which diminishes the thermal efficiency of the process with the same output. This does not minimize the practical result, since such modernization requires no fuel consumption at all, whereas in the active process, the flow rate of the fuel in the regime of automatic control of a 0.75 MW burner averages 20 kg/h (see Table 2). This power is sufficient to warm up the furnace in starting-up, but there is no reserve for keeping it hot in the case of a possible temporary slowdown of the process, when without charging the reactor, i.e., without the formation of a pyrolysis gas and the yield of an accompanying gas, it is only the steam that enters the furnace; it takes 0.7 MW to heat the steam to 1000°C in full volume according to (5). In this case automatically controlled discharge of the steam from the boiler to the scrubber (valve 11, Fig. 1) and a certain limitation of the steam output (as will be considered below) are provided for.

Limitation of the Steam Output for Afterburning of the Steam-Gas Mixture. For the total steam output (5), the calculated heat of combustion of a mixture of the gas and the steam (1) decreases to 3.55 MJ/m^3 (approximately 850 $kcal/m^3$), which is noticeably lower than the minimum permissible value and requires a certain limitation of the steam flow rate — in particular, by diminishing the temperature of flue gases in the boiler due to the corresponding air inflow and suction denoted as A3 in Fig. 1. By analogy with (1), this is formulated in the form of the following equation for diminishing the steam output by ΔSTEAM:

$$Q_{\mathrm{mix}} = \frac{Q_{\mathrm{gas}}}{1 + \dfrac{\mathrm{STEAM} - \Delta\mathrm{STEAM}}{\mathrm{GAS}} \dfrac{\rho_{\mathrm{gas}}}{\rho_{\mathrm{s}}}}, \tag{10}$$

solution of the equation in dimensionless form for the initial value gives

$$\left(\frac{\Delta G_{\mathrm{s}}}{G_{\mathrm{s}}}\right)_{\mathrm{min}} = 1 - \left(\frac{Q_{\mathrm{gas}}}{Q_{\mathrm{gas,min}}} - 1\right) \frac{\rho_{\mathrm{s}}}{\rho_{\mathrm{gas}}} \frac{\mathrm{GAS}}{\mathrm{STEAM}} \geq 15\% \,. \tag{11}$$

The required air inflow ΔG_{a} is determined by the fact that, instead of the excess part of the steam, the corresponding heat is expended for heating this air inflow:

$$\Delta G_{\mathrm{s}} \left[c_{p\mathrm{w}} (T_{\mathrm{s}} - T_{\mathrm{a}}) + h_{\mathrm{s}}\right] = \Delta G_{\mathrm{a}} c_{p\mathrm{a}} (T_{\mathrm{g3}} - T_{\mathrm{a}}) \,, \tag{12}$$

whence, with account for (7), for the total air feed we obtain

$$\left(\frac{\Delta G_{\mathrm{a}}}{G_{\mathrm{a}}}\right)_{\mathrm{min}} \geq \frac{T_{\mathrm{g2}} - 200}{T_{\mathrm{g3}} - T_{\mathrm{a}}} \frac{0.15}{1 - \dfrac{c_{p\mathrm{s}} (T_{\mathrm{g2}} - 200)}{c_{p\mathrm{w}} (T_{\mathrm{s}} - T_{\mathrm{a}}) + h_{\mathrm{s}}}} \,. \tag{13}$$

The temperature of diluted flue gases in (13) is determined from the fact that the required air inflow is mixed and heated to the same temperature T_{g3} due to the general decrease in the enthalpy of the gases with the steam, with the same assumption for the flow rate and heat capacity of the gases themselves in the form $G_{\mathrm{g}} \cong G_{\mathrm{a}}$ and $c_{p\mathrm{g}} \cong c_{p\mathrm{a}}$:

$$(G_{\mathrm{g}} c_{p\mathrm{g}} + G_{\mathrm{s}} c_{p\mathrm{s}}) (T_{\mathrm{g2}} - T_{\mathrm{g3}}) = \Delta G_{\mathrm{a}} c_{p\mathrm{a}} (T_{\mathrm{g3}} - T_{\mathrm{a}}) \,, \tag{14}$$

$$T_{\mathrm{g3}} = \frac{T_{\mathrm{g2}} + B T_{\mathrm{a}}}{1 + B} \,, \tag{15}$$

$$B = \frac{\Delta G_{\mathrm{a}}}{G_{\mathrm{a}}} \frac{1}{1 + \dfrac{1}{A} \dfrac{c_{p\mathrm{s}}}{c_{p\mathrm{a}}}} \,. \tag{16}$$

Below we give results of the same computational modeling in EXCEL on decreasing the steam output and increasing the heat of combustion of the steam-gas mixture with air inflow in the steam boiler from (10)–(13), including the temperature of diluted flue gases in it from (15) and (16):

Heat of combustion of the mixture with the total steam output (1), MJ/m^3	3.55
Temperature of diluted flue gases in the boiler T_{g3}, $^{\mathrm{o}}$C	500
Relative inflow and suction of air in the boiler from (13), %	27
Relative decrease in the steam output in the boiler from (11), %	24
Heat of combustion with a low steam output (10), MJ/m^3	5.47
Number B for calculation of the flue-gas temperature from (16)	0.1871
Calculated temperature of the flue gases in the boiler T_{g3} from (15), $^{\mathrm{o}}$C	501

These data are reflected in Table 2 where, with the corresponding suction of air in the boiler and decrease in the flue-gas temperature in it to 500^{o}C, the steam generation diminishes to approximately 100% relative to the processed-tire mass for which the specific heat of combustion of the gas mixed with the steam increases to approximately 5.5 MJ/m^3 (1300 kcal/m^3); afterburning of such a mixture is not a problem. In this connection, we should note special high-velocity (swirl) burners used since the 1980s for afterburning of low-calorie gas ejections in pyrolysis soot production in Russia [12] that are steam-diluted to 3.33–3.80 MJ/m^3 (800–900 kcal/m^3), which is lower than the critical specific heat of combustion (1). Gas and air flows in these burners mutually swirl and produce the effect of constant recirculation self-ignition of a flame on the source side of the furnace. In our case the ignition can be duplicated by a short flame of a fuel-starting burner (to 10% of power).

Conclusions. Balance methods of analysis are simple and reliable enough to draw a safe conclusion on the possibility of using the obtained calculated data for modernization of the process in which such a problem of steam tire thermolysis as separation of the steam condensate from the fuel and its impurities is solved. The solution lies in using a scrubber condenser of the fuel with a yield temperature of above 100^{o}C and afterburning the tail accompanying gas together with the reactor's waste steam, which further condenses in pure form in the scrubber of water gas cleaning of afterburning products and is returned to the steam boiler. The yield of the accompanying gas increases to 16–18%, which is sufficient to burn it up with the steam to the extent of 100% of the processed-tire mass using the above methods for limiting steam generation and stabilizing gas combustion.

NOTATION

AIR and ΔAIR, total air feed to the furnace and separate air inflow and suction in the boiler relative to the processed-tire mass, %; c_{pt}, c_{ps}, c_{pw}, c_{pg}, and c_{pa}, heat capacity (specific heat) of the tire rubber, steam, water, flue gases, and air respectively, J/(kg·^{o}C); E_f and E_r, thermal efficiency of the furnace and the reactor; G_t, G_{gas}, and G_g, tire-processing rate, yield of the afterburnt accompanying gas, and flow rate of flue gases respectively, kg/h; GAS, yield of the accompanying gas relative to the mass of processed tires, %; G_a and ΔG_a, total air feed to the furnace and air inflow and suction in the boiler, kg/h; G_s and ΔG_s, output and limitation of the steam output with the air inflow and suction in the boiler, kg/h; h_t = 640 KJ/kg, specific heat of thermal destruction (thermolysis) of rubber; h_s, specific heat of vaporization, J/kg; Q_{gas} and Q_{mix}, specific heat of combustion of the accompanying gas and its mixture with the steam, J/nm^3; $Q_{gas,min}$, minimum permissible specific heat of combustion of the steam-gas mixture, MJ/nm^3; STEAM and ΔSTEAM, output and limitation of the steam output relative to the processed-tire mass, %; T_{g1}, T_{g2}, and T_{g3}, temperature of flue gases at the inlet of the reactor's heating chamber, at exit from the chamber, and at the boiler inlet respectively, ^{o}C; T_p, T_s, and T_a, tire-pyrolysis, boiler-steam, and outside-air temperature respectively, ^{o}C; ρ_{gas}, ρ_s, density of the afterburnt accompanying gas and the steam, kg/m^3. Subscripts: a, air; f, furnace; g, flue gases; gas, accompanying fuel gas; max, maximum; min, minimum; mix, mixture; p, pyrolysis; r, reactor; s, steam; t, tires; w, water.

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