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STEAM FEED AND EFFECT OF STEAM-THERMAL SEAL IN THERMOLYSIS OF TIRE SHREDS IN A SCREW-TYPE REACTOR

V. A. Kalitko

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On the basis of experience in commercial operation, the effect of steam seal in tire-shred pyrolysis in a screw-type reactor with superheated steam has been considered and analytically substantiated; there, local steam feed produces the above effect at the total reduced pressure and keeps air from entering the reactor without sluices or valves used for hermetization of its loading and unloading. It has been shown that the increase in the production rate of pyrolysis due to the heating by steam amounts to 10–15% and is limited by the diffusion transfer in the reactor's charge bed.

Keywords: *shreds, tires, processing, pyrolysis, steam, pressure, rarefaction.*

Introduction. The basic method of utilization of used tires in the USA at present is their shredding and use in civil engineering in the form of asphalt rubber as a binding component and filler in various tar and asphalt pavements [1]. Use is also made of the burning of used tires as tire-derived fuel, which is done in both cement kilns and industrial boiler rooms in similar and other production processes (in total, 115 applications in 2005), which requires special furnaces certified for burning this rubber fuel with supercharging in a moving or fluidized bed [2]. Thermolysis (pyrolysis) of tire shreds in screw-type, drum-type, and other mechanical reactors is also carried out with their preliminary shredding; however, this does not yield the required quality of liquid fuel and is used first of all for the production of carbon black whose market value, if its quality is maintained, is equal to that of oil [3]. Shredding tires in the form of the so-called scrap up to 2 inches in size ensures a high-quality pyrolysis in a duly mechanized and automated process. Otherwise, the carbon product contains residual rubber substances and requires a repeat pyrolysis processing.

In this connection, the method of steam thermolysis of tire scrap in a screw-type reactor [4, 5] developed at the A. V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus (HMTI) for the Taiwanese Company "EnresTec Inc," when compared with similar technologies without steam [6–8], ensures a higher quality of the carbon product and reduces the residual content of volatiles to 1–2%. The superheated steam diffusing inside the scrap-charge bed not only completes its total heating outside the reactor, but also penetrates into the pores formed inside each pyrolysis fragment, cleaning them of the residue of volatiles at the end of the process. The latter is a determining factor for the quality of pyrolysis, for which purpose the release of the steam with volatile pyrolysis gases is carried out on the source side of the loading of the reactor, and the feed of steam into it is carried out in the unloading zone where a 100% steam environment is thereby created for the said cleaning of the carbon product. The reactor is heated basically due to afterburning of the accompanying gas after condensation of liquid fuel and steam, which is produced in a recovery boiler on exit of flue gases after the reactor. The superheating of the steam is done in a coil pipe along with the heating of the reactor, and the steam condensate is returned to the boiler after settling separation and coagulation cleaning from the residues of fuel hydrosuspension [5].

One important technical problem in any pyrolysis is the airtighness of the reactor, since the removal of pyrolysis gases from it is carried out under rarefaction to prevent their leak outside. There is an inflow of air into the reactor, if no use is made of sluices, valves, or seals to hermitize the loading and unloading of the reactor, which may lead to ignition and even explosive inflammation of pyrolysis fragments and products in it. Based on experience in the adjustment and commercial operation of two HMTI steam screw-type reactors in Taiwan in 2007–2008, in the present work, we consider the problem of airtighness of such reactors, which are protected from air inflow even without the use of sluices, if there is sufficient feed of steam.

A. V. Luikov Heat and Mass Transfer Institute, National Academy of Sciences of Belarus, 15 P. Brovka Str., Minsk, 220072, Belarus; email: kalitko@tut.by. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 83, No. 2, pp. 304–309, March–April, 2010. Original article submitted May 12, 2009.

TABLE 1. Calculated Data of Diffusion Heat Exchange and Steam Heating of the Tire Scrap in the Charge Bed of the Screw-Type Reactor at a Steam Thermolysis of 1 ton/h

ΣF_t, m^2	α_{ss}, W/(m^2·°C)	ΔT, °C	ΔQ_{s1}, kW	ΔQ_{s2}, kW	Q_t, kW
40	8	162	52	52	350

Steam Feed and the Reactor's Output. First, we will show to what extent feed and superheating of steam complement heating and raise the production rate of such a pyrolysis in which the estimated steam output, according to [5], depending on the temperature regime in the reactor, does not exceed 35% of the mass of recycled tires and in reality is no more than 0.3 ton/h in a pyrolysis of up to 1 ton/h. The problem lies in evaluating the diffusion heating of the pyrolysis material by steam inside the charge bed of the reactor, where a convective steam flow just does not take place. This is dealt with quite easily if it is taken into account that the internal specific surface of 1 m^3 of the charge of tire scrap as chips with an average thickness of d_t = 10 mm is at least f_t = 20 m^2/m^3, the bulk density of this scrap is $\rho_{t(b)}$ = 0.5 ton/m^3, and the Nusselt diffusion number for heat exchange of a particle without convection is equal to Nu_d = 2:

$$\sum F_t = f_t \frac{G_t}{\rho_{t(b)}}, \tag{1}$$

$$\alpha_{ss} = \frac{Nu_d \lambda_{ss}}{d_t}, \tag{2}$$

$$\Delta T = \frac{T_p - T_a}{\ln \dfrac{T_s - T_a}{T_s - T_p}}, \tag{3}$$

$$\Delta Q_{s1} = \alpha_{ss} \sum F_t \Delta T, \tag{4}$$

where additional heating of tires (4) is provided by superheating of steam at $\Delta Q_{s1} = \Delta Q_{s2}$:

$$\Delta Q_{s2} = c_{p(s)} G_s (T_{ss} - T_s), \tag{5}$$

and the heat of tire heating and pyrolysis is determined, as earlier in [5], by the expression

$$Q_t = G_t (c_{p(t)} (T_p - T_a) + h_t. \tag{6}$$

Table 1 gives data on the diffusion heating of the charge bed by steam, which have been calculated from (1)–(6) for the initial parameters of the process in operation in Taiwan [5] T_a = 20°C, T_s = 100°C, T_p = 350°C, T_{ss} = 400°C, G_s = 300 kg/h, h_t = 630 kJ/kg, λ_{ss} = 0.04 W/(m·°C) $c_{p(s)}$ = 2.1 kJ/(kg·°C), and $c_{p(t)}$ = 1.9 kJ/(kg·°C). With these data, the sought increase in the production rate of steam pyrolysis as compared to similar processing of tires without steam under otherwise equal conditions is determined accurate to 2–3% by the following formula:

$$\frac{\Delta Q_{s1}}{Q_t + \Delta Q_{s2}} = \frac{52}{350 + 52} = 13\%. \tag{7}$$

With account taken of the indicated error, the obtained result should be limited to the range of 10–15%, which is the limit to increasing the production rate due to the use of steam, since its superheating is combined with heating the reactor, and for steam of above 400°C the required total temperature of heating will be at least 1000°C,

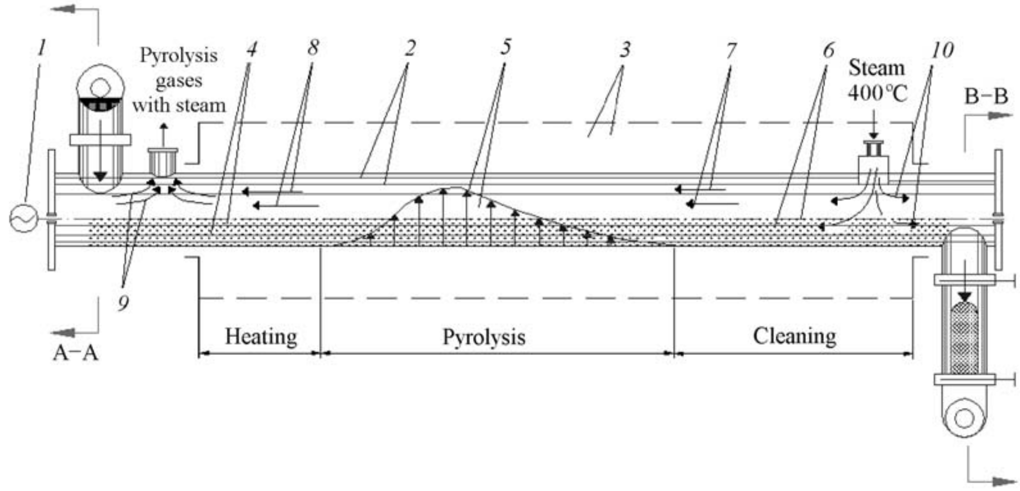

Fig. 1. Longitudinal view and the diagram of steam thermolysis of shredded tire scrap in the screw-type reactor (the helix of the screw conveyer inside is not shown): 1) geared motor of the screw conveyer; 2) tube casing of the reactor; 3) reactor's heating chamber; 4) pyrolysis material; 5) release of volatiles; 6) carbon pyrolysis product; 7) cleaning steam flow; 8) resulting steam flow with pyrolysis gases; 9) possible air inflow on the source side of loading; 10) pulse of steam counterflow toward the air inflow on the source side of unloading.

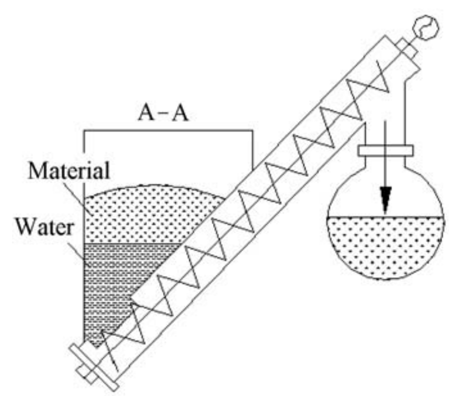

Fig. 2. Screw-conveyer loading of the reactor with a water-seal bin.

which is not practical for a number of reasons. First, compared to 900°C, as is the case in the active process, such an increase in temperature will be at least 15% more energy-consuming and will require the use of more heat-resistant and more expensive steels for the reactor. Second, with rise in the temperature, pyrolysis shifts toward gasification and the yield of condensed fuel decreases. Third, in such heating, the temperature of the reactor wall will be above 700°C, which will lead to carbonization of the rubber and to formation of a burn-on layer on the wall which reduces the performance (indices) of the process. If, to raise the output, the production and feed of steam to the reactor are simply increased at the same temperature, this will lead to carbon dust removal; therefore, this is not practical either.

Access for Air, Steam Feed, and Steam Seal of the Reactor. With all existing limitations, the steam output of up to 0.3 ton/h significantly improves the purity and quality of the pyrolysis carbon product and at the same time keeps air from entering the reactor, which was established in practice in the active process in Taiwan [5] and is theoretically treated below. Figures 1–3 show a longitudinal view and both lateral views of the reactor's loading and unloading in sections A–A and B–B, of which the longitudinal view is given as a diagram of a process which shows in successive order the zones of heating and pyrolysis of the material with a symbolic representation of a histogram of volatile yield over the length, and also the zone of cleaning the carbon product by steam where the latter is fed before the unloading of the reactor (see Fig. 1). For the sake of better visualization, the screw conveyer inside is not shown

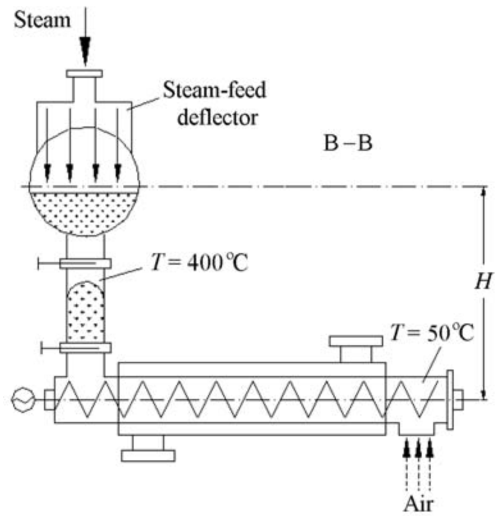

Fig. 3. Screw-conveyer unloading of the reactor with sluice gates and cooling.

and the reactor's heating chamber is symbolically represented by a dashed line. At the same time, the reactor itself is symbolically represented as one long screw, which in practice is done using two short screws placed compactly one over the other in the heating chamber.

For hermetic loading of the reactor, which was under slight rarefaction, we first used a water-seal bin (Fig. 2), which subsequently operated without water, since the water seal produced up to 15% of the charge humidity, thus impairing the indices of the process. Without a water seal, the access of air to the reactor was limited by the natural compaction of the material bed in the bin. Figure 1 shows that in this case air inflow cannot possibly enters the reactor in loading, since it is immediately removed, together with the steam and pyrolysis gases, to the condensers where there is no hazard and conditions for their ignition. As practice has shown, the air inflow with loading has no effect on the quality and quantity of condensable fuel; the only requirement in this case is that the air does not lower the pyrolysis-gas temperature to less than 300°C, at which condensation deposition of soot on pipeline walls occurs.

The thermal condition of unloading lies in cooling the pyrolysis carbon product to exclude the possibility of its ignition in air at a temperature above 400°C and in preparing it for further open transportation and processing. For this purpose unloading is carried out by a cooled screw conveyer via a sluice system of two gates (Fig. 3) which operate alternately, thus protecting the reactor from the air inflow through the screw conveyor. However, gates of this type are intended for operation in a liquid and rather pure medium; the practice of their use under the present conditions has shown that the working grooves of such gates are clogged with carbon, their flow area is not covered completely, and airtighness is broken.

Nonetheless, this virtually does not affect the indices and parameters of pyrolysis, since the steam feed forms a local counterpressure pulse (steam seal) which precisely keeps air from entering the reactor. For a uniform steam distribution in the reactor's cross section and prevention of the carbon dust removal by a sharp steam jet, steam is fed via a multijet deflector (see Fig. 3). In Fig. 1, this pulse is shown by dashed arrows as the steam counterflow toward a possible air inflow, which acts locally and does not propagate farther, since the steam with pyrolysis gases is removed in the opposite direction. The value of this pulse is determined in a regular manner from the dependence of the dynamic pressure of the steam flow on its velocity

$$\Delta p_1 = \frac{v_{ss}^2}{2}\rho_{ss}, \tag{8}$$

where the velocity is calculated from half the reactor's cross section whose second half is filled with material (see Fig. 3):

$$v_{ss} = \frac{2G_s}{S_r\rho_{ss}} = \frac{2g_s}{\rho_{ss}}, \tag{9}$$

TABLE 2. Specific Steam Feed per 1 m^2 of the Reactor Seal as a Function of the Cooling Temperature of Unloading of the Reactor at an Air Temperature of $20^{o}C$

Unloading temperature T, °C	400	300	200	100	50
Steam feed according to (12), tons/(m^2·h)	3.7	3.45	3.0	2.3	1.55

TABLE 3. Specific Steam Feed per 1 m^2 of the Reactor Seal as a Function of the Air Temperature in Natural Cooling of the Unloading to $50^{o}C$

Air temperature T_a, °C	20	10	0	–10	–20
Steam feed according to (12), tons/(m^2·h)	1.55	1.74	1.94	2.12	2.3

and where the specific steam feed is determined per unit of the entire cross section of the reactor:

$$g_s = \frac{G_s}{S_r} . \tag{10}$$

Next we consider static pressure (rarefaction) at the outlet of the unloading screw conveyer, which is produced by the difference between the temperature and density of the air inside and outside and under which possible air flow into the reactor may occur via the screw conveyer. Such an inflow is shown in Fig. 3 symbolically by dashed line arrows. The indicated pressure is formulated by analogy with the rarefaction (draft) of a smoke stack whose height corresponds to the height of the reactor above the screw conveyer:

$$\Delta p_2 = (\rho_a - \rho)\, gH , \tag{11}$$

$$\rho = \rho_a \frac{T_a}{T} . \tag{12}$$

The air inflow under the action of the rarefaction of the screw conveyer (11) is hindered by the counterpressure (dynamic head) of the steam fed to the reactor (8); the action of the counterpressure spreads in the screw-conveyer's steam-air medium as quite an incompressible one on condition that the counterpressure and rarefaction are minor compared to atmospheric pressure:

$$\Delta p_2 = \Delta p_1 , \tag{13}$$

Equations (8)–(13) yield the sought quantity

$$g_s = \sqrt{\frac{g\rho_a\rho_{ss}H}{2}\left(1 - \frac{T_a}{T}\right)} . \tag{14}$$

Formula (14) explicitly determines the effect of steam seal in the reactor as a function of the cooling temperature of its unloading, because of which this seal has been defined, in the title of the work, as a steam-thermal one. Indeed, if the unloading screw conveyer is cooled down to such an extent that the outlet temperature in it is the same as the temperature outside ($T = T_a$), no draft and air inflow occurs and, theoretically, the need for steam feed for the seal disappears ($g_s = 0$). However, there is little sense in such cooling because of the condensation of the steam and moistening of the carbon product in the screw conveyer and since the medium's temperature in it should not be lower than the dew point — in particular, no less than $50^{o}C$, as practice has shown. And conversely, if it is granted that unloading is carried out directly from the reactor's workspace at a temperature of $400^{o}C$, the amount of steam required for creation of such a seal multiply grows. In this connection, Table 2 gives, accurate to ± 0.05 ton/(m^2·h), the calculated data on the steam feed (14) as a function of the cooling temperature of unloading of the reactor (within 50–$400^{o}C$)

at an outside-air temperature of 20^{o}C. The latter is also a substantial factor if we take into account a possible difference of summer and winter temperatures when the reactor is located at an open site, e.g., in Russia. For this evaluation, Table 3 gives, accurate to ±0.01 ton/(m^2·h), the calculated data on the steam feed (14) as a function the outside-air temperature (+20 to −20^{o}C) in normal cooling of the reactor's unloading to 50^{o}C.

Conclusions. The obtained calculated data are consistent with the practice of operation of the above reactors in Taiwan where the thermal equipment is located in a workshop at a temperature of no less than 30^{o}C at which, according to (14), q_s = 1.2 ton/(m^2·h) of steam per 1 m^2 of the reactor cross section is needed. The steam velocity in the free cross-sectional area of the reactor is v_{ss} = 4 m/sec according to (9); at a steam temperature of 350–400^{o}C, the dynamic pressure of such a flow does not exceed 3 Pa (0.3 mm of water column), which allows the initial assumption of the incompressibility of a steam-gas pyrolysis medium under these conditions. For a reactor diameter of 0.6 m, such counterpressure requires feed G_s = 0.34 ton/h and the available steam output (to 0.3 ton/h) is virtually sufficient for normal operation of the reactor even with the broken airtighness of the gates. In both this case and the general case a certain shortage of steam within 10–20% of the value calculated from (14) is allowed; the possible air inflow in it is estimated at no more than 5% of the stoichiometric volume required for ignition and burning of rubber in the reactor, which is not hazardous and is quite acceptable. And conversely, even a small escape of the steam from the reactor saturates the volume of the unloading screw conveyer with time and, on condition of its constant cooling, leads to a partial condensation of the steam and to an extremely undesirable moistening of the carbon product in unloading.

NOTATION

$c_{p(s)}$ and $c_{p(t)}$, specific heat of the steam and the tire rubber, kJ/(kg·^{o}C); d_t = 10 mm, average thickness of the tire scrap; ΣF_t, total surface of the tire-scrap charge in pyrolysis, m^2/h; f_t, specific surface of 1 m^3 of the tire-scrap charge, m^2/m^3; G_t, production rate of tire pyrolysis, kg/h; G_s, steam output and feed to the reactor, kg/h; g_s, specific steam feed per 1 m^2 of the reactor's cross section, kg/(m^2·sec); g, free-fall acceleration; H, height of the reactor above the unloading screw conveyer along the axis of their arrangement, m; h_t, 630 kJ/kg, heat of thermal destruction of the tire rubber; $\mathrm{Nu_d}$, diffusion Nusselt number; Δp_1, dynamic steam head in the reactor, Pa; Δp_2, static rarefaction in the reactor's unloading screw conveyer, Pa; ΔQ_{s1}, heat of steam heating of the tire scrap; kW; ΔQ_{s2}, heat of superheating of the steam, kW; Q_t, heat of tire pyrolysis, kW; S_r, cross-sectional area of the reactor, m^2; T_p, T_s, and T_{ss}, temperature of pyrolysis, of the steam in the boiler, and of the superheated steam in the reactor respectively, ^{o}C; ΔT, temperature head of the steam in heating the pyrolysis material in the reactor, ^{o}C; T and T_a, temperature inside and outside the reactor's unloading screw conveyer, ^{o}C; v_{ss}, steam-flow velocity in the reactor above the charge bed, m^2/sec; α_{ss}, coefficient of heat transfer of the superheated steam in the reactor's charge bed, W/(m^2·^{o}C); ρ and ρ_a, air density inside and outside the screw conveyer, kg/m^3; ρ_{ss}, density of the superheated steam, kg/m^3; λ_{ss}, thermal conductivity of the superheated steam, W/(m·^{o}C); $\rho_{t(b)}$ = 0.5 ton/m^3, bulk density of the tire scrap. Subscripts: a, air; b, bulk; d, diffusion; p, pyrolysis; s, steam; ss, superheated steam; t, tires; r, reactor.

REFERENCES

1. J. V. L. Kiser, Asphalt rubber: overcoming the obstacles, *Scrap Magazine*, **60**, No. 1, 46–54 (2003).
2. K. Kiser, Tire recycling gains traction, *Scrap Magazine*, **64**, No. 2, 157–168 (2007).
3. J. V. I. Kiser, Scrap tire pyrolysis: the impossible dream?, *Scrap Magazine*, **59**, No. 5, 34–41 (2002).
4. V. A. Kalitko, Steam-thermal recycling of tire shreds: calculation of the rate of explosion-proof feed of steam, *Inzh.-Fiz. Zh.*, **81**, No. 4, 750–754 (2008).
5. V. A. Kalitko, Morgan Chun Yao Wu, V. A. Zhdanok, and Benson Tsai Ching Yu, Steam thermolysis of discarded tires: testing and analysis of the specific fuel consumption with tail gas burning, steam generation, and secondary waste slime processing, *Inzh.-Fiz. Zh.*, **82**, No. 2, 242–251 (2009).
6. Patent U.S. 6221329. Pyrolysis Process for Reclaiming Desirable Materials from Vehicle Tires.
7. Patent U.S. 6657095. Continuous Temperature Variance Pyrolysis for Extracting Products from Tire Chips.
8. Patent U.S. 6736940. Process for Pyrolyzing Tire Shreds and Tire Pyrolysis System.