

Waste Tire Pyrolysis Recycling with Steaming: Heat-Mass Balances & Engineering Solutions for By-Products Quality

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1. Introduction

Waste tires pyrolysis is well known method for their thermal recycling by heating at near 500°C with purpose of liquid oil and carbon black by-production as near 50% and 35% yield correspondingly, including about 10% combustible off-gas residual after oil condensing and 5% wire steel cord in rest (all relatively to tire mass). There are many patents claimed in the world such as [1-20] and others, as well as many research papers published in this field such as [21-42] and others since the 1980s mainly. Not considering such simplest as batch-battery type and such complicated as fluidized bed one and some others, the drum-kiln and screw-auger type of pyrolysis reactor should be noticed as most preferable for commercial use, being both of them operated continually with tire shreds as 2-3 inch size. The tire material is gasifying in a sealed pyrolysis reactor and volatile hydrocarbons (pyrolysis gases or simply pyrogas,) are piping from reactor to condenser for the liquid pyrolysis oil. A few of the oil as 5-10% is burning for heating the reactor, provided with all the off-gas fuel after condensing the oil is afterburning too. As a solid rest the tire carbon char is continually discharging from reactor for its powdering, separating off steel wires and producing the carbon black.

But even in 2000s with reference to [32] it has been concluded as there was not an operating commercial plant in the world that could be recognized as operated successfully with a high commercial productivity and quality of both by-products. Particularly, for the carbon black could be used commercially in the rubber industry again, its quality must be as 1-2 % tire oil volatile matters residual content. In recent years the tire pyrolysis plants of rotary-batch type are many referenced in the net as an alternative and widely used in China, Malaysia, Taiwan, etc., operating simply with a whole tire bulk and producing so way the carbon black of low quality as 5-6% and more of the residual content above, operating a priori with a low productivity as the batch-type.

In connection with the carbon black quality and with reference to [1, 2] the vacuum tire pyrolysis method should be mentioned as claimed in the 1980s, being performed under the low-pressure and resulted in 4% and less of oil residual content. It should be noticed as well

corresponded to the theoretical solution on such of dependence with pressure and pyrolysis temp condition considered just in the next part of the article. And specially concerning the steam use for tire pyrolysis in connection with that and with reference to U.S. Patent 866 758, it had been first claimed even in 1907, resulting in the pure carbon char yield with heating directly by steam at 315°C that was well enough for such of recycling (reclaiming in original), provided with the rubber particles intensively piping by the same steam flow. Much more late with reference to [9, 10, 33] the direct heating pyrolysis method by superheated steam feeding into reactor at 500-600°C has been claimed and published as a new idea of that in the 2000s. In accordance with that a multi-batch pyrolysis tunnel system has been elaborated in HMTI for recycling the whole tires in cartridges which continually moving through the long tunnel heating by this way. The idea was realized in a large scale commercial plant per 120 t/day in Lithuania, 2004-2005 but it was not effective as both low productivity and quality of carbon black because of low operating conditions as for heating the bulk of whole tires in cartridge, as for heating the large-long tunnel by steam feeding at all.

Independently the reactor type and heating system with references to [25, 28, 30, 31] some of catalytic pyrolysis methods could be noticed as proposed for enhancing the oil productivity and provided with such of solid or liquid additives as Na₂CO₃, AlCl₃, KOH, Y-, USY- or ZSN- zeolites etc. Being restricted in detail consideration on that for sake of the present article, it can be shortly characterized as no radical catalytic dependence was obtained for commercial use so as a little of addition could be used for its action without contamination of the oil or carbon black with rest of the same addition in kind of solid or gas. Proposing the steam actually is not a catalyst, but simply a carrier gas, nevertheless with reference to [24] it is interesting to notice that the oil yield with steam pyrolysis of the oily shale (in a laboratory scale) was increased by 34%, comprising that with nitrogen at the same operating and thermal conditions. In contrast, no real difference for oil yield rate was obtained with olefins or tires pyrolysis in [22, 27], but excluding only a high steam reactivity with tire char for its next purification with carbon black by-production.

As for the steam pyrolysis in the present article, it is obviously proposed that oil residual content in the carbon black is objectively corresponded to the pyrogas concentration in pyrolysis reactor where the gas is saturating all inside, including the carbon black porous structure too as considered next in the present article. Even the tire pyrolysis would be first performed ideally as 100% oil volatile matters gasified entirely, next pyrogas inside the carbon porous structure will be cooling and condensing there in kind of the same oil residual matters after the carbon discharge from reactor. To replace the pyrogas from the carbon and so way to clean that simply, it is also well known as an inert gas (e.g. nitrogen as most available) could be feeding into pyrolysis reactor finally, provided the gas feeding rate to be corresponded to the tire pyrolysis rate. If no such of inert gas blowing up the reactor theoretically it is about 3% oil residual matters in the carbon by-product by this way. But really it is not commercial solution because of high cost for any inert gas supply relatively to price of the carbon black by-product. A second thermal processing (firing) of the carbon black at 750-800°C is required after pyrolysis so to purify that off the oil residual for next treatment with commercial use, or even for its storage to be clean off the specific smell which is steady appeared at the oil residual content 5-6% and more.

In this connection with reference to [33-38] a new pyrolysis system for waste tire commercial recycling in the reactor of double-screw type with steam has been elaborated in HMTI (Belarus) for ENRESTEC Co. (Taiwan) in 2006, being next installed and applied by author's guidance in 2007-2008. The plant has been designed as a double-line pyrolysis system per 1 t/hr every (Pict.1, Fig.1) with carbon black quality as 1-2% oil residual matters, including more proof-explosion safety inside the reactor due to diluting the pyrolysis gases (pyrogas) with steam, as well as more sealing the reactor with steam feeding against air penetration into reactor under the low-operating pressure as required. Steam is self-producing in a second-heat boiler after heating the reactor provided by own pyrolysis oil-fuel combustion in a special furnace apart of reactor, including the pyrolysis off-gas afterburning therein too. For processing the steam is super-heating up to pyrolysis operating temp 400-450°C, being that performed in a steam coil tube around and along with reactor heating together, and feeding into reactor as shown and considered next bellow. With reference to [36] for all of unit numbers to be observed, the general design overview of the plant is shown in Pict.2 where only the units above are noticed in caption.



Pict. 1. ENRESTEC thermal units for waste tire pyrolysis with steam: 1 – oil fuel burner, 2 – furnace, 3 – pyrolysis reactor heating box, 4 – double-screw reactor in the box, 5 – second heat steam boiler.

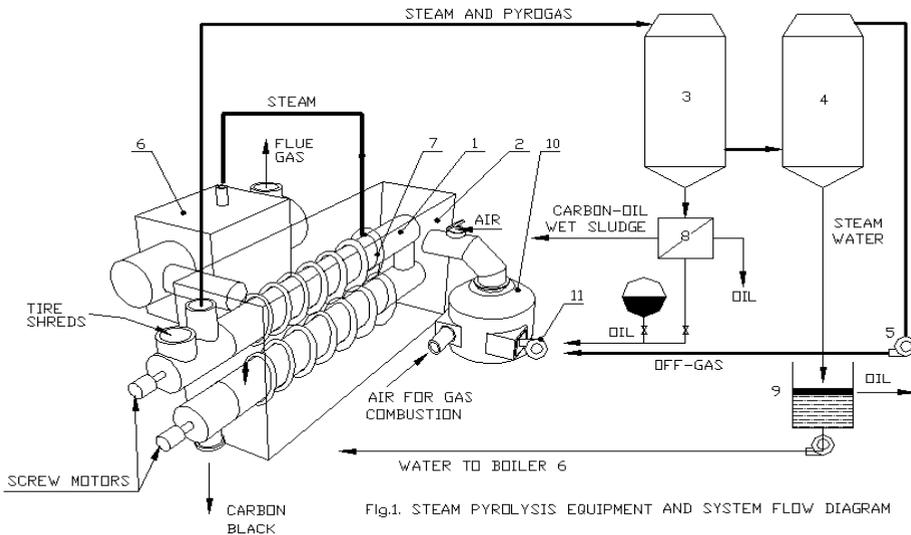
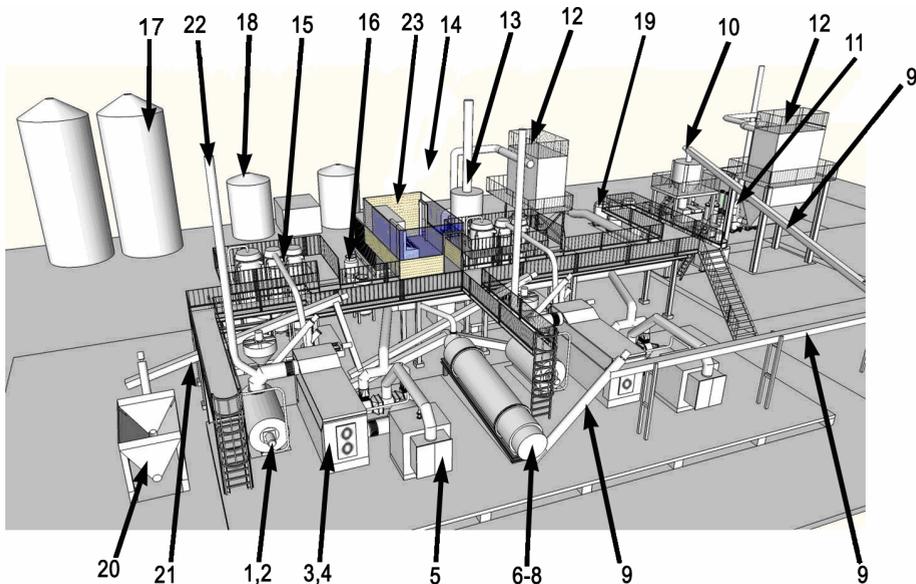


Fig. 1. Steam pyrolysis equipment and system flow diagram: 1 – pyrolysis reactor, 2 – reactor heating box, 3 – oil condenser, 4 – steam condenser, 5 – off-gas fan, 6 – second heat steam boiler, 7 – steam super-heating coil, 8 – oil Laval-separator, 9 – oil-water gravity separating tank, 10 – gas-oil furnace.



Pict. 2. Design overview of the ENRESTEC plant: 1,2 – both furnaces with oil fuel burners at front; 3, 4 – both heating boxes with every of double-screw reactor inside; 5 – heat utilizing steam boilers.

As for some history, the first steam use for rubber waste pyrolysis by U.S. Patent 866758 had been tested even in 1907, being concluded that the temp 600 F (315°C) is well enough for rubber vulcanized particles to be full pyrolyzed in the steam pneumatic flow condition at this temp. Comparing that to pyrolysis at 450–500°C as required without steam now, that is good evidence of steam effect by its diffusion with heat penetration inside every of the particles even at the lower temp. Being not so porous initially, with pyrolysis process in time the rubber is destructing and becoming as the carbon black of its fine porous structure that finally is well suitable for its cleaning by steam diffusion inside. In this connection it is all reason first to consider and evaluate even theoretically why and what is a limit on the carbon black quality by scrap tire pyrolysis recycling without steam (in terms of residual oil matters of its content).

2. Theoretical limit on carbon black quality without steam

By usual pyrolysis way as without steam, even all the tire volatile matters are proposed to be initially gasified, next there is to be objectively some of tire oil matters residual in carbon black (CB) because of its secondary contamination with the same volatilized matters that re-condensed in the CB porous structure after its cooling with discharge from reactor. Being some idealized and simplified, such of contamination can be theoretically formulated and estimated as bellow here. Let use the ideal gas law equation for the tire pyrolysis volatile matters (hydrocarbon vapors and inherent gases or simply pyrogas) which are proposed to be heated finally up to the temp $T = 450^\circ\text{C}$ (723 K) which is rather above all of pyrolysis liquid-gas phase transition points, and so allows the pyrogas can be considered as a super-heated one similar to an ideal gas, which molecular weight is proposed to be equal to that of tire pyrolysis oil condensed from the pyrogas as the same. With reference to [1.2] it is about $\mu = 210$ and we have the next pyrogas mean-total density in tire pyrolysis reactor at the temp 450°C and near the normal pressure operating conditions ($p = 10^5$ Pa):

$$pV = \frac{m}{\mu} RT, \quad (1)$$

$$\rho = \frac{m}{V} = \frac{p\mu}{RT} = \frac{10^5 \cdot 210}{8314 \cdot 723} \cong 3.4 \text{ kg/m}^3. \quad (2)$$

Pyrogas of the density above is saturating all inside the reactor operating volume, including the bulk between CB particles and inside every of the particles too, being these of the inner porous structure. By this consideration we have the next pyrogas quantity discharged with anyone particle of CB porous product which will be next condensed therein as the oil residual matters:

$$m_{oil(i)} = V_i \rho \cdot \sigma, \quad (3)$$

where V_i is volume of the particle, σ is factor of the particle structure porosity which is objectively proposed as not bellow $\sigma = 90\%$, and the pure mass of the particle solid-porous structure is a light as conveniently proposed by density not above $\rho_{cb} = 100 \text{ kg/m}^3$:

$$m_{cb(i)} = V_i \rho_{cb}, \quad (4)$$

by which relation the next simple estimation is obtained:

$$\frac{m_{oil(i)}}{m_{cb(i)}} = \sigma \frac{\rho}{\rho_{cb}} = 0.9 \frac{3.4}{100} \cong 3\%. \quad (5)$$

Concerning the theoretical limit on steam dilution with pyrogas as for its proof-explosive condition in reactor, with author's reference to [34] it is above 5 kg steam per 1 kg tire required so to provide such of condition with air. It is too much for real observation, comparing that to available steam self-producing rate by second heat after heating the reactor. And it is the question for analytical consideration and formulation bellow as it was realized in the operating process with steam in Taiwan.

3. Heat-mass balance analysis on waste tire pyrolysis with steam

Referencing namely to [35], the first version of the thermal units and flow diagram of the tire-steam pyrolysis process in Taiwan in 2007-2008 is shown in Fig.1, where steam is self-producing in the second heat boiler 6 with flue gas flow after heating the double-screw reactor 1 in the hot gas box 2 connected with the furnace 10 for oil combustion with off-gas after-burning together. Steam is super-heating in the tube coil 7 inserted as along-around the reactor in the hot box too, and next steam is feeding into the reactor for steaming the tire pyrolysis as considered above. The pyrogas with used steam flow together is piping to the oil and steam condenser 3-4 in line correspondingly, being provided by suction performance of the gas fan 5 that pipes the combustible pyrolysis off-gas residual after oil-steam condensing into the furnace. Flue gas from the furnace is piping for heating both reactor and steam boiler in line, and next to exhaust scrubber. The real view on these thermal units (furnace, reactor, steam boiler) is shown in Pict.1.

The tire scrap is moving and mixing by screw along-inside the reactor by usual way of such processing, being pyrolyzed and discharged to outside with the carbon black to be next cooling, screening and crashing for magnetic separation against some of steel cord wire residual. Pyrolysis oil is separating by Laval centrifugal unit 8 so to produce the own light oil for burning in the furnace and so heating the reactor and boiler. Ideally the pyrolysis oil and steam were proposed to be condensing in 3-4 separately and next steam water to be cycling and pumping to the boiler again simply as it is shown in Fig.1. Really it was not of such ideal proposition and steam was partially condensing with oil together, as well as all different benzene's and low-temp aromatic fractions of the pyrolysis oil were condensable and soluble with steam water too. Considering that especially for development next bellow in p.6, here we formulate and calculate simply the heat-mass balance of reactor and other thermal equipment above, not including the condenser as not involved with pyrolysis process. Due to the reactor heating is based on the off-gas afterburning, being the latter well available and corresponded to the pyrolysis rate, as well as the steam for the process is self-produced after heating the reactor and next super-heated along with reactor heating too, all of that is evidently depended on each other and so we can formulate analytically and calculate numerically the oil fuel specific consumption per 1 kg tire additively to the off-gas

burning. It is a novel question on the tire pyrolysis recycling because even without steam there is not such of general analysis in this field until now. With all references to [35, 36] the question on the oil fuel quantity to be combusted with pyrolysis off-gas together for heating the process with steam feeding and self-producing at the same time, it was answered by the heat-mass balance solution on that as following:

$$X = \frac{G_{oil}}{G_t} = \frac{q_t - (Q_{gas}E_rE_f - \alpha_2A) \cdot GAS}{Q_{oil}E_rE_f - \alpha_1A}, \quad (6)$$

$$A = q_{ss} \frac{q_g g_a}{q_s}, \quad (6')$$

$$Y = \frac{G_s}{G_t} = \frac{c_{p(g)}(T_{g2} - T_{g3})g_a}{c_{p(w)}(T_s - T_a) + h_s} (\alpha_1 X + \alpha_2 GAS) = \frac{q_g}{q_s} \left(\alpha_1 X + \alpha_2 \frac{GAS}{100} \right), \quad (7)$$

where $g_a \approx 15$ kg/kg is air stoichiometry index per 1 kg of liquid fuel, $\alpha_1 = 1.3-1.35$ is air excessive supply index for fuel combustion, $\alpha_2 = 1.05-1.1$ is the index for gas fuel combustion, $E_f = E_r = 0.95-0.97$ is the furnace and reactor thermal efficiency by every heat emission to outside 3-5% proposed, including the supplementary specific calculations as follows:

$q_t = c_{p(t)}(T_p - T_a) + h_t$ is a specific heat capacity per 1 kg pyrolysis,

$q_{ss} = c_{p(s)}(T_p - T_s)$ is a specific heat per 1 kg steam super-heating,

$q_s = c_{p(w)}(T_s - T_a) + h_s$ is a specific heat per 1 kg steam producing,

$q_g = c_{p(g)}(T_{g2} - T_{g3})$ is an enthalpy per 1 kg furnace gas flow.

With the same references to [35, 36] the question what is the off-gas burning rate to be for heating the pyrolysis reactor without oil fuel, it has been simply obtained from (7) with proposition $X=0$ which numerical solution at the pyrolysis conditions above is $GAS_{min} \cong 10\%$:

$$GAS_{min} = \frac{q_t}{Q_{gas}E_rE_f - \alpha_2A}, \quad (8)$$

The testing-operating data on the process with max 10% approximation are presented in the Table 1, including the standard analysis data on the pyrolysis oil and carbon black products quality referenced to [36]. It should be noted initially that testing the commercial process as considered above, as well as any other of such thermal processes with heat-mass balance calculation too, it is performed as 5-10 % discrepancy usually to be allowed. At the same time, concerning the carbon black recycling up to 1-2% of C_nH_m -residual quality as required for the market, it is clear that the latter can not be the subject for modeling, but only testing at the thermal parameters of the process under question. As for the non-calculating parameters which could be important for the carbon black quality, it is also clear that the

pyrolysis exposition time and tire chips-shreds size, and more exactly even the scrap thickness size, are both of most important, provided the size of the shreds was used as min 2 inches and some more. Really and simply the low, middle and high temp pyrolysis condition in range 350–450°C had been tested with tire processing rate within 0.5–1 t/hr, provided the reactor length and screw rotary speed resulted in the tire processing time as max 13 min so as carbon black quality to be near the same in specification range 1–2%. As for the scrap tire thickness, it was supplied in range of 5–15 mm.

Pyrolysis oil condensed heat value: 42 MJ/kg Off-gas heat value (without steam): 39 MJ/m ³	Tire pyrolysis rate, kg/hr		
	500	750	1000
Off-gas burning rate (10% tire mass at 55 C), m ³ /hr	50	75	100
Light pyrolysis oil mean-daily burning rate, kg/hr	40	30	20
Steam self-producing rate (feeding to reactor), kg/hr	200	250	300
Off-gas-oil furnace max operating temperature, °C	950	1100	1150
Furnace gas temp Tg1 for reactor heating inlet, °C	850	900	950
Furnace gas temp Tg2 for reactor heating outlet, °C	450	480	510
Pyrolysis operating temp Tp inside reactor, °C	350	400	450
Sulfur content in pyrolysis oil, %	-	1.15	-
Carbon content in pyrolysis oil, %	-	1.1	-
CnHm-content in carbon black, %	-	1.5	-
Sulfur content in carbon black, %	-	2.3	-

Table 1. Testing-Operating Data on Tire Pyrolysis Recycling With Steam (Taiwan-2008).

The process calculation by (6)–(8) is presented in Table 2 as carried out with low, middle and high-temp pyrolysis condition at 350, 400 and 450°C inside reactor correspondingly, correlating that to the tire shreds thickness 5, 10 and 15 mm proposed. The subject and result of the calculation is the oil fuel consumption and steam self-producing rate per 1 kg tire which is well corresponded to the testing data at the high-temp pyrolysis condition.

GAS (oil condensing corresponded temperature), %	Low-temps: 5 mm shreds, Tg1 = 850°C, Tg2 = 450°C, Tp = 350°C		Middle-temps: 10 mm shreds, Tg1 = 900°C, Tg2 = 500°C, Tp = 400°C		High-temps: 15 mm shreds: Tg1 = 950°C, Tg2 = 550°C, Tp = 450°C	
	X, kg/kg	Y, kg/kg	X, kg/kg	Y, kg/kg	X, kg/kg	Y, kg/kg
6 (35-40 C)	0.00896	0.164	0.0199	0.236	0.0333	0.330
7 (40-45 C)	0.00261	0.162	0.0111	0.232	0.0245	0.326
8 (45-50 C)	-	0.159	0.0024	0.229	0.0157	0.322
9 (50-55 C)	-	-	-	0.226	0.0069	0.318
10 (55-60 C)	-	-	-	-	-	0.314

Table 2. Calculating Data (6)–(7) on Oil Burning (X) And Steam Self-Producing Rate (Y) With Variable Pyrolysis Off-Gas Burning Rate at the Different Operating Temperatures .

The factor of steam feeding rate as required for pyrolysis reactor of the screw tubular type has been some tested in connection with the carbon black dusting by an excessive steam flow, being the pyrolysis oil next condensed with much of the carbon sludge after its centrifugal separation from the oil finally. To prevent the carbon dusting the steam feeding rate is appropriated as max 200-250 kg/hr with reactor diameter 0.6 m, or simply 1 t/hr per 1 m² of cross-section square of that in specific terms. So way it is enable to provide the steam feeding rate for carbon black purification and so on as considered next in p.6.

With reference to [35, 36] it was a few as 1-2% of wet carbon-oil slurry after its gravity and centrifugal separation from the pyrolysis oil with water. After the separation slurry was well marketable in Taiwan for use as the asphalt component in the road construction as they doing there. Otherwise, the slurry is proposed to be mixing with the scrap tire and recycling with pyrolysis too. The question concerning what is max possible sludge mixing-recycling rate with tire pyrolysis together (in percent relatively to tire), it has been obtained in [35, 36] by the similar heat-mass balance solution as following:

$$SLU_{\max} = \frac{\Delta X}{X} \cdot \frac{(Q_{\text{gas}} E_r E_f - \alpha_2 A) \cdot GAS}{wB}, \quad (9)$$

$$B = c_{p(w)}(100 - T_a) + h_s + c_{p(s)}(T_p - 100), \quad (9')$$

where ΔX is an additional oil fuel consumption for sludge pyrolysis together with tire by which calculation with conditions above it is obtained as $SLU_{\max} \cong 6\%$.

4. Process development with oil venturi condenser

As an imperfection of the first plant the steam was condensed with pyrolysis oil together and steam water after its gravity or centrifugal separation from the oil it was contaminated with different benzene and other low-temp aromatic fractions of the tire pyrolysis oil as well soluble with water. Such of contaminated steam water has become a regulation problem for its normal cycling to steam boiler again and so for the new process to be certificated in Taiwan and elsewhere, including some other operating problems considered in [36, 37] and being all the problems resulted simply from the water tube condensers applied and operated with water at 35-40°C. Moreover, operating by this way it was resulted in a low-quality of pyrolysis oil fuel in terms of the flash point temp which was about 40°C correspondingly.

With reference to [36, 37] in project for ALPHA RECYCLAGE FRANCHE COMTE (France) in 2009-2010 the tire-steam pyrolysis system has been developed and modernized so as a new condenser of venturi type with steam too is used (Fig.2), being first and only one referenced as without steam but namely for such of application in [2]. The new steam pyrolysis system is operating with oil condensing at near 100°C, proposing so way its quality in terms of the flash point temp to be high as near 80°C. Steam is not condensing and all piping with residual off-gas to furnace by which way only the oil condenser 4 is required (see Fig.2). And so way the furnace gas flow is rather enhanced with steam for heating reactor and next boiler where steam is acting in a new manner as a heating agent too which analyzed here.

With furnace flue gas together steam is piping to scrubber and condensing therein simply with water, being so way water is far from the oil and nothing of oil-water separating equipment is required.

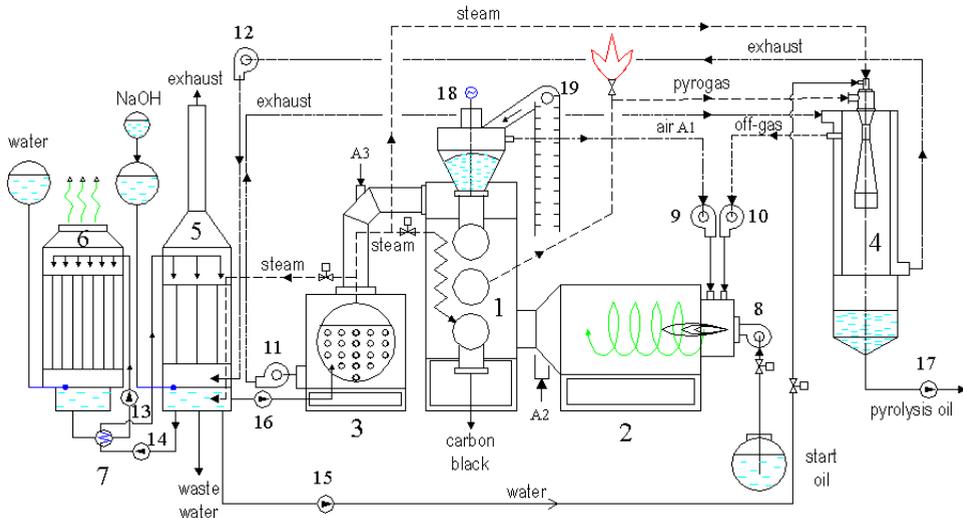


Fig. 2. Diagram of the modernized steam pyrolysis system: 1- reactor, 2 – furnace, 3 – steam boiler, 4 – venturi condenser, 5 – exhaust scrubber, 6 – cooling tower, 7 – water cooler for scrubber , 8 – oil fuel burner, 9-12 – air blowers and gas fans, 13-17 – water and oil pumps, 18-19 – scrap tire feeding system.

Basing and referencing to the data on the tire pyrolysis oil distillation with temp in [1, 2] and with the same reference to [36, 37] it is analytically obtained that the new process is characterized as *OIL* = 40-45% pyrolysis oil to be condensed at 100°C and correspondingly *GAS* = 17-18% incondensable off-gas to be residual (relatively to tire mass), being the latter well enough for the process heating without oil at all. By the analytical heat-mass balance it is resulted in the next formulation on the steam self-producing rate:

$$STEAM = \frac{G_s}{G_t} = \frac{Q_{gas} E_f}{[A_n c_{p(a)} + c_{p(s)}](T_{g1} - T_a)} \frac{GAS}{100}, \tag{10}$$

where the complex A_n is for the math compaction too:

$$A_n = \frac{G_a}{G_s} = \frac{c_{p(w)}(T_s - T_a) - c_{p(s)}(T_{g2} - 200) + h_s}{c_{p(a)}(T_{g2} - 200)}. \tag{10'}$$

By this way it is rather more steam self-producing rate then before in Taiwan and to avoid the off-gas would be diluted with steam too much as no ignition by [34] with reference to [36, 37] the steam self-producing rate is to be limited and reduced by $\Delta STEAM \geq 15\%$ which is formulated and calculated as follows:

$$\Delta_{STEAM} = \frac{\Delta G_s}{G_s} \geq 1 - \left(\frac{Q_{gas}}{Q_{gas(min)}} - 1 \right) \frac{\rho_s}{\rho_{gas}} \frac{GAS}{STEAM}, \quad (11)$$

provided simply by air injection into boiler (similar to its injection into furnace in Fig.1) that is also obtained by the analytical heat-mass balance as following:

$$\frac{\Delta G_a}{G_a} \geq \frac{T_{g2} - 200}{T_{g3} - T_a} \cdot \frac{0.15}{1 - \frac{c_{p(s)}(T_{g2} - 200)}{c_{p(w)}(T_s - T_a) + h_s}}, \quad (12)$$

where the total air injection rate (with combusting air and relatively to tire pyrolysis rate) per 1 kg tire is obtained:

$$AIR = \frac{G_a}{G_t} = \frac{A_n Q_{gas} E_f}{[A_n c_{p(a)} + c_{p(s)}](T_{g1} - T_a)} \frac{GAS}{100}, \quad (13)$$

Due to the more off-gas afterburning rate as $GAS = 17-18\%$ instead of around 10% before, including all the steam used and air injected as above, now it is a rather more furnace gas flow available for heating the pyrolysis reactor which results in rather less acting temp difference of the flow between the reactor inlet-outlet as follows:

$$T_{g1} - T_{g2} = \frac{c_{p(t)}(T_p - T_a) + h_t + c_{p(s)}(T_p - T_s)}{E_f E_r \left(c_{p(s)} + c_{p(a)} \frac{AIR}{STEAM} \right)}. \quad (14)$$

Calculating data on the modernized process by (10)-(14) with max 1% iterating discrepancy and max 5% calculating accuracy are presented in Table 3, where these are compared to operating data on the first steam pyrolysis system in Taiwan. Shortly it can be concluded as the new system is rather more capable for convective heating the pyrolysis reactor first by factor of the furnace gas flow than by its high temperature (i) in which accordance the reactor is also developed properly as a triple-screw design of a long heating surface (see Fig.2). In second, by more heating and 1.5 times longer process way the carbon black quality is proposed to be surely high as 1% and less of the tire residual matters. In third, steam boiler is correspondingly also heating much more and steam producing rate is proposed to be well enough as for feeding the reactor, as for injecting into the oil Venturi condenser (iii) as it is considered in the next p.5, including the oil quality is to be also high as noted yet above.

The numerical data on steam limitation with air injection by (13) are presented in the Table 3 so as the low-calorific heat value of the off-gas with steam mixture can be well increased as 5.5 MJ/m³ (1300 kcal/m³). In this connection and with the same reference to [36, 37] the special flow-vortex burner for the low-calorific gas fuel condition is proposed to be applied, being that well appropriated namely in the similar steam process with carbon black pyrolysis recycling from coal in Russia in commercial scale in 70-80-ths, where the similar off-gas was also much diluted by 80% with both steam and nitrogen as 3.3-3.8 MJ/m³ (800-900 kcal/m³), i.e. even bellow the critical value above. The burner is operating by the gas

pre-mixing and ignition with air in a vortex-flame tunnel just before the furnace (see Fig.3) by which way there is an area in the tunnel where the gas flame is every moment torching and so igniting just near from the furnace.

Pyrolysis oil heat value: 42 MJ/kg Off-gas heat value : 39 MJ/m ³	Operating process in Taiwan (1000 kg/hr)	Modernized process (1000 kg/hr)	
		Steam self-producing rate by (10)	Steam producing limited with air injection by (13)
Oil combustion rate, kg/hr	20	-	-
Off-gas burning rate, m ³ /hr	100	180	180
Combusting air flow, nm ³ /hr	2650	5000	5000
Furnace heat capacity, MW	1.2	1.95	1.95
Furnace gas temp inlet reactor, °C	900	800	800
Furnace gas temp outlet reactor, °C	500	590	590
Furnace gas temp inlet the boiler, °C	500	590	500
Air injecting rate in boiler, nm ³ /hr	-	-	1350
Steam self-producing rate, kg/hr	350	1300	1000
Steam residual with off-gas, kg/hr	15	1300	1000

Table 3. Modern Process Calculation in Comparison With Operating Process in Taiwan-2008

5. Oil venturi condenser with water spraying by steam jet

To prevent the condenser cooling surface could be contaminated with carbon soot the pyrogas is proposed to be condensing for oil in the condenser of venturi type which is operating now with cooling-spraying water instead of pyrolysis oil cycling before as it referenced in [2]. Water is well corresponded to the pyrolysis process with steam so as it is spraying and evaporating for steam too while the pyrogas cooling and condensing, including the carbon soot catching with oil droplets at the same time. The new condenser is developed with a steam jet for both spraying water and ejecting pyrogas from reactor (Fig.3).

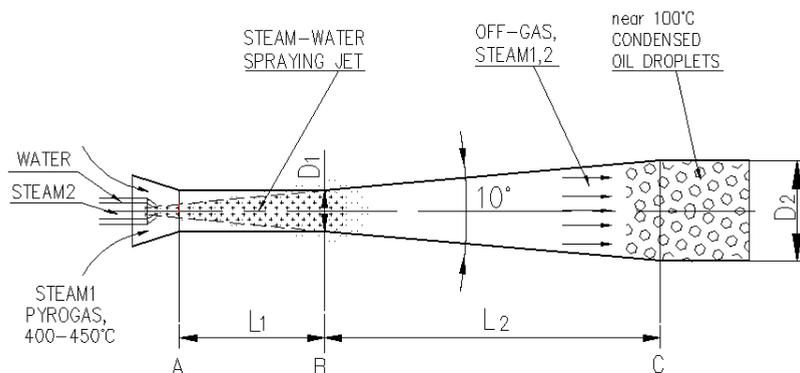


Fig. 3. The flow structure in the oil venturi condenser: pyrogas, steam, water, condensed oil.

With steam the oil condensing temp is well provided as near 100°C for the flash point to be at near 80°C. Moreover, the Venturi tube part is actively cleaning against the carbon soot by the same steam jet for spraying. There are three acting specific points with pyrogas-steam reactor flow mixing with steam-water jet and resulting in condensed oil droplets with incondensable pyrolysis off-gas and all steam residual flow in venturi tube as shown in Fig.3:

Inlet point A:

- pyrogas with used steam from pyrolysis reactor;
- cooling water flow spraying by boiler steam jet;
- steam jet self-wetting max 3% by throttle effect;
- water spraying by steam jet for droplets $\leq 10 \mu\text{m}$;

Mixing point B:

- water droplets mixing-heating with pyrogas flow;
- pyrogas flow mixing-cooling with water droplets;
- steam content is passive thermal agent of the flow;

Condensing point C:

- pyrogas is condensed for oil droplets at 100°C;
- water droplets are evaporated at the same temp;
- pyro-carbon soot is captured with oil droplets;
- incondensable pyro-off-gas is residual at 100°C.

Proposing a simple sonic type of steam nozzle for spraying water, initially a self-cooling and wetting effect with steam jet discharged at near the sonic velocity (throttle effect) to be considered, which can be maximally estimated by [40] under the next steam min pressure and temp conditions to be: $p_{\min} = 0.4 \text{ MPa}$ - steam pressure (abs), $T_1 = 142^\circ\text{C} = 415 \text{ K}$ - steam boiler temp, T_2 - steam temp after the throttle effect,

$$T_2 = T_1 \left(\frac{2}{k+1} \right) = 415 \cdot \left(\frac{2}{1.4+1} \right) \cong 72^\circ\text{C}. \quad (15)$$

Due to steam jet after its discharge is really cooling down only to 100°C and next a few steam is condensing at the same temp and normal pressure, it is acting for steam self-wetting as follows:

$$w_{s(\max)} = \frac{c_{p(s)}(100 - T_2)}{h_s} \cong 3\%, \quad (16)$$

where $c_{p(s)} = 0.5 \text{ kcal/kg}\cdot\text{C}$ is steam specific heat capacity, $h_s = 540 \text{ kcal/kg}$ is steam specific heat value at the normal (atmospheric) pressure.

5.1 Spraying water specific flow rate

With author's reference to [35-37] the tire (rubber) pyrolysis specific heat required for its thermal destruction at near to steady pyrolysis temp 400-450°C is experienced

approximately as $h_t = 640$ kJ/kg. Proposing the oil condensed is max 45% of tire pyrolysis mass, we have the next condenser heat capacity provided with spraying and evaporating water:

$$Q_{oil} = 0.45G_t h_t . \quad (17)$$

Heat with pyrogas condensing for oil and co-pyrolysis steam from reactor cooling down to Venturi operating temp 100°C is following:

$$Q_1 = Q_{oil} + c_{p(s)}G_{s1}(T_p - 100) , \quad (18)$$

heat for spray water heating-evaporating is following:

$$Q_3 = G_w [c_{p(w)}(100 - T_a) + h_s] , \quad (19)$$

heat for steam wetness evaporating is following:

$$Q_2 = w_s G_{s2} h_s = w_s r G_w h_s , \quad (20)$$

steam jet as ratio of spraying water rate is following:

$$G_{s2} = rW , \quad (21)$$

and condenser total heat-with-mass balance is following:

$$Q_1 = Q_2 + Q_3 . \quad (22)$$

By substitution-solution (10)-(15) we have:

$$\frac{W}{G_t} = \frac{0.45h_t + \frac{G_{s1}}{G_t} c_{p(s)}(T_p - 100)}{c_{p(w)}(100 - T_a) + h_s(1 - w_s r)} . \quad (23)$$

As noted here initially in 4 and with reference to [35, 36] the co-pyrolysis steam for reactor supply is self-producing after heating the latter and it is formulated, calculated and well tested relatively to tire mass in the next terms and rates:

$$\frac{G_{s1}}{G_t} = 25-30\%$$

With reference to steam common application for liquid spraying (e.g. for heavy oil fuel combustion), the factor of steam-water spraying mass ratio $r = 1$ is well enough. Taking that and all other given condition above into account, by (23) we have the next analytical solution on the water spraying for venturi condenser performance:

$$\frac{W}{G_t} \cong 0.2$$

5.2 Water droplets spraying and evaporating

With all reference to [39] and other fundamentals, the Nukiyama-Tanasawa equation can be applied for calculation on a liquid droplet diameter sprayed with a high-speed gas flow in venturi tube as follows:

$$d_i = \frac{0.585}{v_g^{\frac{1}{2}}} \sqrt{\frac{\sigma}{\rho}} + 59.7 \left(\frac{\mu}{\sqrt{\sigma \rho}} \right)^{0.45} \cdot \left(\frac{G}{G_g} \right)^{1.5}, \quad (24)$$

where v_g is gas flow velocity, ρ is liquid density and σ is liquid surface tension. Being both of the flows presented in terms of the volume flow rate, the liquid flow G is usually much less than that of spray gas G_g and equation is used conveniently as simplified to the first part only:

$$d_i \cong \frac{0.585}{v_{spr}} \sqrt{\frac{\sigma}{\rho}}. \quad (25)$$

Proposing the steam pressure could be so much as the jet velocity to be near of sonic as not less $v_s \cong 500$ m/s (water density is $\rho = 1000$ kg/m³ and water surface tension at near 100°C is a few as not above $\sigma \leq 0.05$ N/m), we have the next the water droplets by steam jet spraying way:

$$d_i \leq \frac{0.585}{500} \cdot \sqrt{\frac{0.05}{1000}} \leq 10 \mu\text{m}$$

There are many analytical and experimental data and references on that, concerning the liquid fuel combustion and specially considering the sphere droplet lifetime by its quick-transient heating and vaporizing (gasification) at the flame thermal condition, referencing that for example to [41]. And there is another approach which is all of near the same consideration but at quasi-steady thermal conditions - for example, in [42] concerning the wood particle combustion by its gasification too.

To estimate the time under question we use the latter as a method at quasi-steady thermal conditions, being there is not so evidence as weakness of that relatively to transient analyzing method. So way it can be analyzed by the convenient heat-mass transfer analogy, taking into account the heat for evaporating the water droplet of diameter $d_i = 2r$ is provided under the heat transfer criterion condition $Nu_{\min(i)} = 2$ which with reference to [9] is a minimal criterion value of that for spherical particle at a zero-flow velocity condition when the heat is transferred by the gas conductivity only. Due to near the same condition is proposed for a fine water droplet injecting and moving by steam at near the same flow velocity (zero-flow velocity relatively one other), it can be differentially formulated as bellow, beginning from the heat transfer coefficient by the criterion above and so on:

$$\alpha_{\min(i)} = \frac{Nu_{\min(i)} k_s}{d_i} = 2 \frac{k_s}{d_i}. \quad (26)$$

Evaporating surface of the water spherical droplet is following:

$$f_i = \pi d_i^2, \quad (27)$$

droplet mass evaporated with the surface layer dr is following:

$$dm_i = \rho_i f_i dr, \quad (28)$$

heat for the layer dr above to be evaporated is following:

$$dQ_i = dm_i h_s, \quad (29)$$

the same heat to be transferred during in $d\tau$ is following:

$$dQ_i = \alpha_i f_i (T_p - 100) d\tau. \quad (30)$$

By (26)-(30) substitution and integration we have the next solution on the question in title:

$$d\tau = \frac{\rho_i h_s}{k_s (T_p - 100)} r dr, \quad (31)$$

$$\tau = \frac{d_i^2 \rho_i h_s}{8 k_s (T_p - T_{oil})} \ln \frac{T_p - 100}{T_{oil} - 100}, \quad (32)$$

where $k_s = 0.02$ kcal/m·hr is steam thermal conductivity at 100 C, $T_{oil} = 105-110^\circ\text{C}$ is pyrolysis oil condensing temp to be proposed, and where the current arithmetic temp difference $(T_p - 100)$ by its integrating in (30) is logically resulted in a mean-logarithmic temp difference ΔT as following:

$$\Delta T = \frac{(T_p - 100) - (T_{oil} - 100)}{\ln \frac{T_p - 100}{T_{oil} - 100}} = \frac{T_p - T_{oil}}{\ln \frac{T_p - 100}{T_{oil} - 100}}. \quad (33)$$

So way we have the next numerical estimation on the droplet 10 μm evaporating time :

$$\tau = 3600 \cdot \frac{10^{-12} \cdot 1000 \cdot 540}{8 \cdot 0.02 \cdot (400 - 105)} \ln \frac{400 - 100}{105 - 100} \cong 0.015 \text{ sec}$$

With venturi condenser or scrubber under consideration, it is about 50 m/s of gas flow velocity as a minimal value of that to be in the narrow part of the venturi tube for its effective performance. Next in the conic part of the tube the flow is extending with a spherical angle about 10° so as the flow velocity dropping down about by one order as for an ordinary gas pipe to be. In particularly, considering the venturi condenser above, the narrow tube for 1 t tire pyrolysis per hour is proposed to be about 4 inches in diameter, proposing so the length of the conic tube to be not less then $L2 = 1$ m (see Fig.3). The minimal exposition time for water droplets evaporation in the venturi tube, even proposing

the droplets save the initial flow velocity as 50 m/s above, it is min 0.02 sec which is obtained simply by the conic length divided by the venturi velocity above.

6. Steam: Inner heating, carbon black cleaning & air sealing lock

6.1 Inner heating and increasing the tire pyrolysis rate with steam

The steam counter-feeding effect for the carbon black purification at the end of processing just inside the reactor of screw type is illustrated in Fig.4 where with author's reference to [38] the longitudinal diagram of scrap tire pyrolysis is presented and where a multi-tube reactor is simplified as one line. Steam is well penetrating into the moving-mixing bed of scrap tire simply by its diffusion, as well as into the every porous fragment or particle of that too, acting so for cleaning them off the volatile residue matters at the end of processing, even there is not convective steam flow inside the bed and most of steam is flowing above that. Along with such cleaning there is evidently some of inner heating the scrap tire by steam diffusion into the bed which question is a quite easy for estimation by value of inner specific surface per 1 m³ bulk of scrap tire minimally as $f_i = 20 \text{ m}^2/\text{m}^3$, including the standard mean-average thickness of chips $d_i = 10 \text{ mms}$, bulk density of tire scrap $\rho_{t(b)} = 500 \text{ kg/m}^3$ and Nusselt number for particle heating without convection is $Nu_{\min(i)} = 2$ to be taken into account:

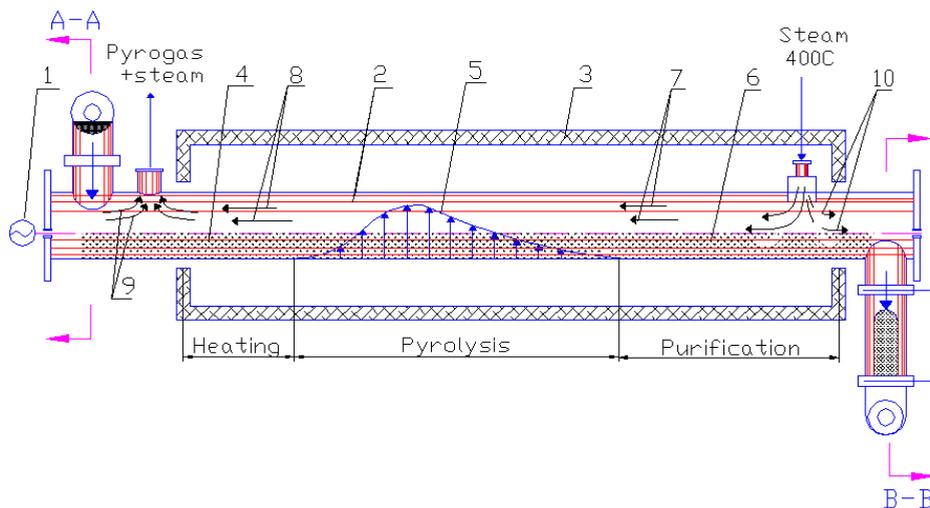


Fig. 4. The longitudinal and linearized diagram of scrap tire pyrolysis recycling in reactor of screw-tubular type with steam (the helix of the screw inside reactor is not shown):

1 - geared motor of screw, 2 - reactor tube shell, 3 - reactor heating box, 4 - scrap tire, 5 - release of tire volatile matters, 6 - carbon black, 7 - cleaning steam flow, 8 - resulting steam flow with pyrolysis gases (pyrogas), 9 - some of possible and allowed air inflow at reactor loading side, 10 - steam counter-flow pulse impact toward the air inflow as a steam seal-lock at the reactor unloading side.

$$\sum F_t = f_t \frac{G_t}{\rho_{t(b)}}, \quad (34)$$

$$\alpha_i = \frac{\text{Nu}_{\min(i)} k_{ss}}{d_i}, \quad (35)$$

$$\Delta T = \frac{T_p - T_a}{\ln \frac{T_{ss} - T_a}{T_{ss} - T_p}}, \quad (36)$$

$$\Delta Q_t = \alpha_i \sum F_t \Delta T, \quad (37)$$

where the inner tire heating by steam ΔQ_t to be provided by steam superheating as ΔQ_{ss} :

$$\Delta Q_t = \Delta Q_{ss}, \quad (38)$$

$$\Delta Q_{ss} = c_{p(s)} G_s (T_{ss} - T_s), \quad (39)$$

and the heat for tire pyrolysis is formulated as before too:

$$Q_t = G_t (c_{p(t)} (T_p - T_a) + h_t). \quad (40)$$

With reference to [38] the numerical data on that are presented in Table 4 where it is calculated by (34)-(40) per 1 t/hr tire rate at the minimal thermal pyrolysis condition as follows: ambient air temperature is $T_a = 20^\circ\text{C}$, boiler steam temperature is $T_s = 100^\circ\text{C}$, tire pyrolysis temperature is $T_p = 350^\circ\text{C}$, steam super-heating temperature is $T_{ss} = 400^\circ\text{C}$, steam feeding rate is $G_s = 300$ kg/hr, tire pyrolysis heat is $h_t = 630$ kJ/kg and others by the nomenclature:

$\sum F_t, \text{ m}^2$	$\alpha_i, \text{ W}/(\text{m}^2 \cdot ^\circ\text{C})$	$\Delta T, ^\circ\text{C}$	$\Delta Q_t, \text{ kW}$	$\Delta Q_{ss}, \text{ kW}$	$Q_t, \text{ kW}$
40	8	162	52	52	350

Table 4. Numerical Data (34)-(40) on Inner Heating with Steam per 1 t/hr Tire Pyrolysis.

The additional tire inner heating (37)-(39) could be objectively corresponded to increasing the pyrolysis rate, being that compared to the similar tire processing without steam and being all other conditions equaled. Taking into account the calculating accuracy of that as 2-3% the obtained result can be concluded as 10-15% which is a theoretical limit for increasing the tire pyrolysis rate with steam at the given conditions:

$$\frac{\Delta Q_{ss}}{Q_t + \Delta Q_t} = \frac{52}{350 + 52} = 13\%. \quad (41)$$

6.2 Steam feeding rate for reactor air-lock sealing

At last, with reference to [38] there is other effect with steam feeding into reactor of screw type which really acts as a hydrodynamic seal-lock preventing any possible air inflow through the reactor unloading system which is usually proposed to be seal but should be taken in mind as possible to be otherwise too. In any case the steam feed forms a local hydrodynamic counter-pressure pulse (steam seal-lock) which precisely keeps air from entering the reactor. With purpose of the uniform steam inlet and sealing impact all over the reactor cross-section in-side, it is feeding into there via the multi-jet deflector as shown in Fig.5. The same is shown by dashed arrows as a steam counter-flow acting for sealing toward the possible air inflow in the apposite direction in Fig.4. The steam pulse above is formulated usually as its dynamic pressure depended on the flow velocity:

$$\Delta p_1 = \frac{\vartheta_{ss}^2}{2} \rho_{ss} \quad (42)$$

where the velocity is to be calculated by half of reactor cross-section square whose second half is filled with scrap tire initially and carbon black finally (see Fig.5):

$$\vartheta_{ss} = \frac{2G_s}{S_r \rho_{ss}} = \frac{2g_s}{\rho_{ss}} \quad (43)$$

Proposing the reactor unloading system would be not sealed with a double-gate or double-flap valve etc., it would be a chimney draft effect acting as a static low-pressure by the temp difference between the reactor inside and outside which is additionally depended on the height of the reactor installation as shown in Fig.5:

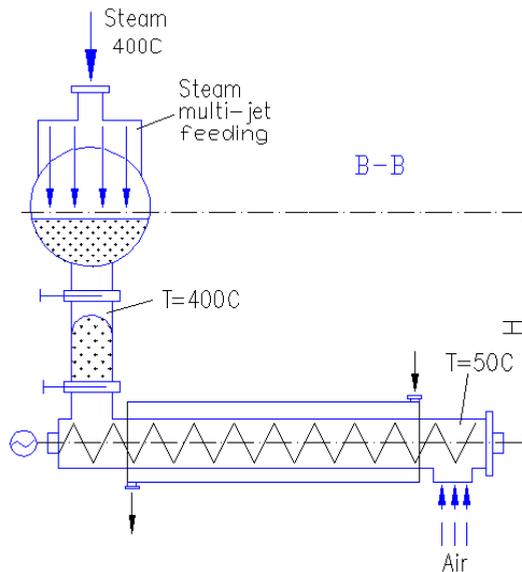


Fig. 5. Reactor unloading system with a water-cooling screw and double-gates as for consideration on the steam sealing effect against the possible air inflow from outside.

$$\Delta p_2 = \rho_a g H \left(1 - \frac{T_a}{T} \right), \quad (44)$$

which is to be equal to the dynamic pressure (42) with steam feeding above and by which substitution the steam feeding rate under question is following:

$$g_{s1} = \frac{G_{s1}}{S_r} = \sqrt{\frac{g \rho_a \rho_{ss} H}{2} \left(1 - \frac{T_a}{T} \right)}. \quad (45)$$

With reference to [38], as well as simply and evidently by equation (45), the steam feeding-sealing effect is to be objectively enhanced with cooling of the carbon discharge from reactor, being the opposite draft effect for air inflow is depended on the cooling temp just by another way. The numerical data on that are presented in Table 5 and theoretically it even would be nothing of sealing required if the carbon discharge temp could be entire equal to outside so as nothing of chimney effect appeared. At the same time in Table 6 there are numerical data on the steam feed required as obtained by (45) at the different ambient temperature which is other factor of the chimney draft effect simply by outside condition of the pyrolysis plant location in different region. With the same reference to [38] it was well experienced practically and particularly in Taiwan at about 30°C where it was no evidence of the air penetration inside with the steam feeding rate appropriated minimally as 200–250 kg/hr for the reactor diameter 0.6 m, or near 1 t/hr per 1 m² of cross-section square of that in specific terms.

carbon cooling temp $T, ^\circ\text{C}$	400	300	200	100	50
steam feeding rate by (45), t/(m ² ·hr)	3.7	3.45	3.0	2.3	1.55

Table 5. Steam Feeding Rate per 1 m² Reactor Cross-Section Square for Air-Lock Seal With Carbon Product Cooling Temp for Discharge.

ambient air temp $T_a, ^\circ\text{C}$	30	20	10	0	-10
steam feeding rate by (45), t/(m ² ·hr)	1.07	1.55	1.74	1.94	2.12

Table 6. Steam Feeding Rate per 1 m² Reactor Cross-Section Square for Air-Lock Seal With Air Ambient Temperature Outside Reactor.

7. Conclusion: Brief engineering-economy analysis on steam use way

In conclusion, in connection with possibility for steam self-producing along with tire pyrolysis recycling, it is a reason to analyze numerically and economically what is more effective way for steam use: power generation by turbine machine or carbon black production could be more as min 10% of tire rate additionally by inner heating with steam feeding into reactor as it is considered above in 6.1? By first way we have near to the next thermal data for steam generation after heating the pyrolysis reactor per 1000 kg/hr tire processing:

Pyrolysis off-gas combustion heat value (pure-dry gas as without steam) = 39 MJ/m³;
Heat capacity by max 18% off-gas after-burning (relatively to tire mass) = 1.7 MW;
Heat emission to outside with both of furnace and reactor by 5% totally = 0.1 MW;
Heat consumption for tire heating and pyrolysis (process without steam) = 0.35 MW
Heat capacity for 1000 kg/hr steam super-heating to 400°C (for turbine) = 0.175 MW
Heat residual and available for steam generation after all of these above = 1.075 MW;
Exhaust gas flow temperatures inlet/outlet the steam second-heat boiler = 600/200°C

Thermal efficiency of the boiler: $E = \frac{600 - 200}{600 - 20} \cong 70\%$;

Heat for steam generation: $0.7 \times 1.075 \text{ MW} = 0.7525 \text{ MW}$;
Steam rate (by index 1400 kg/hr per 1 MW) = 1050 kg/hr;
Thermal efficiency of small steam turbine (max) = 35%;

By the steam enthalpy operating range in turbine as max $h_1 = 770 \text{ kcal/kg}$ (4.0 MPa, 400°C) and $h_2 = 570 \text{ kcal/kg}$ (0.05 MPa, 40°C), it is the next power per 1000 kg/hr tire processing:

$$1050 \times (770 - 570) \times 0.35 \times 1.16 = 0.085 \text{ MW}$$

Proposing as max \$0.06 price per 1 kW-hr power, we have the next economy if to sale that:

$$\$0.06 \times 85 = \$5.1$$

By min 10% waste tire pyrolysis rate to be more by steaming way and with reference to [32] as the carbon black price is min \$0.3 per 1 kg, we have the next economy if to sale that more:

Carbon black (per 1000 kg/hr pyrolysis) = 350 kg/hr
Carbon black rate additionally: $0.1 \times 350 = 35 \text{ kg/hr}$
Economy for sale the carbon black: $\$0.3 \times 35 = \10.5

8. Acknowledgement

The author wishes sincerely and friendly to thank Mr. Wu Chun Yao (Morgan) and Mr. Horng Jiang (Rhine) for assistance and good co-operation in Taiwan.

9. Nomenclature

- w - wetness of components, %
- ρ - density of components, kg/m³;
- μ - molecular weight of components;
- m - mass of steam or gas components, kg;
- p - pressure of steam-gas components, bar;
- V - volume of steam-gas components, m³;
- c_p - specific heat of components, J/kg·°C;
- T - temperature of components and others, °C;
- T_{g1} - furnace gas temp for reactor heating inlet, °C;
- T_{g2} - furnace gas temp for reactor heating outlet, °C;

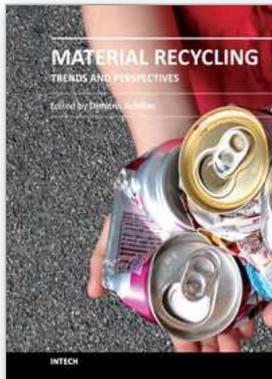
T_{g3}	- furnace gas temp for boiler heating inlet, °C;
T_p	- pyrolysis reactor operating temp inside, °C;
T_a	- ambient air temperature outside, °C;
G	- mass flow rate of components, kg/hr;
G_t	- tire pyrolysis mass flow rate, kg/hr;
G_{s1}	- steam feeding rate into pyrolysis reactor, kg/hr;
G_{s2}	- steam injecting rate into Venturi condenser, kg/hr;
G_g	- furnace (combusted) gas mass flow rate, kg/hr;
W	- spraying water rate for Venturi condenser, kg/hr;
d_i	- spraying water droplet diameter, m;
GAS	- off-gas flow rate relatively to tire, %;
OIL	- oil condensing rate relatively to tire, %;
AIR	- air mass flow rate relatively to tire, %;
$STEAM$	- steam mass flow rate relatively to tire, %;
SLU	- oil slurry mass rate relatively to tire, %;
Q	- heat flow capacity of components, MW
Q_{oil}	- condensed oil fuel heat value, MJ/kg;
Q_{gas}	- incondensable off-gas heat value, MJ/m ³ ;
Q_f	- combustion furnace heat capacity, MW.
Q_t	- heat capacity for tire pyrolysis, MW;
Q_s	- heat capacity for steam generation, MW;
Q_{ss}	- capacity for steam super-heating, MW;
Q_r	- pyrolysis reactor total heat capacity, MW;
q	- specific heat per 1 kg components, MW/kg
h_t	= 640 - tire pyrolysis specific heat, kJ/kg;
h_s	= 2260 - steam specific heat value, kJ/kg;
R	= 8314 - ideal gas constant value, J/kg·K

10. References

- [1] Solbakken A. et al. Process for Recovering Carbon Black & Hydrocarbons from Used Tires. U.S. Patent 4 250 158 (1981).
- [2] Solbakken A. et al. Process for Recovering Carbon Black & Hydro-carbons from Used Tires. U.S. Patent 4 284 616 (1981).
- [3] Cha Chang Y. et al. Pyrolysis Method with Product Oil Recycling. U.S. Patent 4 983 278 (1991).
- [4] Ledford C.D. Process For Conveying Old Rubber Tires Into Oil & Useful Residue. U.S. Patent 5 095 040 (1992).
- [5] Wu Arthur C. & Chen Sabrina C. Thermal Conversion Pyrolysis Reactor System. U.S. Patent 5 411 714 (1995).
- [6] Kanis D.R. Pyrolysis System and Method of Pyrolyzing. U.S. Patent 5 636 580 (1997).

- [7] Avetisian V. et al. Tire Liquefying Process Reactor Discharge System & Method. U.S. Patent 5 705 035 (1998).
- [8] Meador W.R. Tire Liquefying Process Reactor Discharge System & Method. U.S. Patent 5 720 232 (1998).
- [9] Zhuravsky G.I. et al. Method of Treating Plastic Waste. U.S. Patent 5 771 821 (1998).
- [10] Mulyarchik V.M. et al. Processing Waste Rubber by Steam. U.S. Patent 5 780 518 (1998).
- [11] Chang Y. Cha et al. Process for Co-Recycling Tires & Oils. U.S. Patent 5 735 948 (1998).
- [12] Bouziane R. Pyrolyzing Apparatus. U.S. Patent 5 820 736 (1998).
- [13] Denison G.W. Method & System For Recovering Marketable & Products From Waste Rubber. U.S. Patent 5 894 012 (1999).
- [14] Takegawa T. et al. Method For Recovering Carbon Black from Waste Rubber Such As Tires & Apparatus Therefore. U.S. Patent 5 961 946 (1999).
- [15] Faulkner et al. Pyrolysis Process For Reclaiming Desirable Materials From Vehicle Tires. U.S. Patent 6 221 329 B1 (2001).
- [16] Bullok B.P. Hydrocarbon Conversion Apparatus & Method. U.S. Patent 6653517 (2003).
- [17] Holden H.H. & Holden H.S. Continuous Temperature Variance Pyrolysis for Extracting Products From Tire Chips. U.S. Patent 6 657 095 B1 (2003).
- [18] Massemore B. & Zarrizski R. Process for Pyrolyzing Tire Shreds & Tire Pyrolysis System. U.S. Patent 6 736 940 B2 (2004).
- [19] Platz G.M. et al. Resource Recovery of Waste Organic Chemicals By Thermal Catalytic Conversion. U.S. Patent 6 683 227 (2004).
- [20] Nichols R.E. Low Energy Method of Pyrolysis of Hydrocarbon Materials Such As Rubber. U.S. Patent 6 833 485 (2004).
- [21] Day M. et al. Pyrolysis of Automobile Shredder Residue: Analysis of the Products of Commercial Screw Kiln Process. *Journal of Analytical & Applied Pyrolysis*. 1996. Vol. 37, pp. 49-67.
- [22] Simon C.M., Kaminsky W. & Schlesselmann B. Pyrolysis of Polyolefins With Steam To Yield Olefins. *Journal of Analytical & Applied Pyrolysis*. 1996. Vol. 38, pp. 75-87.
- [23] Cunliffe A.M. et al. Composition of Oils Derived From The Batch Pyrolysis of Tires. *Journal of Analytical & Applied Pyrolysis*. 1998. Vol. 44, pp. 131-152.
- [24] El-harfi K., Mokhlisse A. & Ben-Chanaa M. Yield & Composition of Oil Obtained By Isothermal Pyrolysis of the Moroccan Oil Shale With Steam Or Nitrogen as Carrier Gas. *Journal of Analytical & Applied Pyrolysis*. 2000. Vol. 56, pp. 207-218.
- [25] Teng H., Lin Yu-Chuan & Hsu Li-Yeh. Production of Activated Carbon From Pyrolysis of Waste Tires Impregnated With Potassium Hydroxide. *Journal of the Air & Waste Management Association*. 2000. Vol.50, No.11, pp. 1940-1946.
- [26] Kaminsky W. & Mennerich C. Pyrolysis of Synthetic Tire Rubber in Fluidized Bed Reactor To Yield Butadiene-Styrene Oil & Carbon Black. *Journal of Analytical & Applied Pyrolysis*. 2001. Vol. 58-59, pp. 803-811.
- [27] Zabaniotou A.A. & Stavropoulos. Pyrolysis of Used Automobile Tires & Residual Char Utilization. *Journal of Analytical & Applied Pyrolysis*. 2003. Vol. 70, pp. 711-722.
- [28] Williams P.T., Brindle A.J. Fluidized Bed Pyrolysis & Catalytic Pyrolysis of Scrap Tires. *Environmental Technologies*. 2003. Vol. 24, No. 7, pp. 921-929.
- [29] Barbooti M.M. et al. Optimization of Pyrolysis Conditions of Scrap Tires Under Inert Gas Atmosphere. *Journal of Analytical & Applied Pyrolysis*. 2004. Vol. 72, pp. 165-170.

- [30] Shen B., Wu C., Wang R., Guo B. & Liang C. Pyrolysis of Scrap Tires with Zeolite USY. *Journal of Hazardous Materials*. 2006. Vol. 137, No. 2, pp. 1065-1073.
- [31] Zhang X., Wang T. & Chang J. Vacuum Pyrolysis of Waste Tires with Basic Additives. *Waste Management*. 2008. Vol. 28, No. 11, pp. 2301-2310.
- [32] Kiser J.V. Scrap Tire Pyrolysis: Impossible Dream? *Scrap Magazine*. 2002. Vol. 59, No. 5. pp. 34-41.
- [33] Zhuravskii G.I., Matveichuk A.S. & Falyushin P.L. Obtaining of Fuels Based On Products Of Organic Waste Steam Thermolysis. *Journal of Engineering Physics and Thermophysics*. 2005. Vol. 78, No. 4, pp. 684-689.
- [34] Kalitko V.A. Steam-Thermal Recycling of Tire Shreds: Calculation on the Explosion-Proof Steam Feeding Rate. *Journal of Engineering Physics and Thermophysics*. 2008. Vol. 81, No 4, pp. 781-786.
- [35] Kalitko V. A., Morgan Wu Chun Yao et al. Steam Thermolysis of Discarded Tires: Testing and Analyzing of the Specific Fuel Consumption with Tail Gas Burning, Steam Generation and Secondary Waste Slime Processing. *Journal of Engineering Physics and Thermophysics*. 2009. Vol. 82, No 2, pp. 236-245.
- [36] Kalitko U. & Morgan Chun Yao Wu. Tire Scrap Pyrolysis Recycling By Steaming Way: Heat-Mass Balance Solutions and Developments. In: *Pyrolysis: Types, Processes, Industrial Sources and Products*. Edited by W.S. Donahue and J.C. Brandt. Nova Science Publishers. NY, 2009, pp. 79-115.
- [37] Kalitko V.A. Tire Shreds Steam-Thermal Recycling Process Modernization and Development by Inherent Gas Burning with Steam. *Journal of Engineering Physics and Thermophysics*. 2010. Vol. 83, No 1, pp. 179-187.
- [38] Kalitko V.A. A Thermal-Hydrodynamic Lock Sealing with Steam Feeding for Tire Scrap Pyrolysis in Reactor of Screw Type. *Journal of Engineering Physics and Thermophysics*. 2010. Vol. 83, No 2, pp. 324-330.
- [39] Perry's Chemical Engineers' Handbook. 8th ed./prepared by a staff under the editorial direction by D. W. Green, editor-in-chief, R. H. Perry, late editor. Printed in China by Copyright TP151. 2007.
- [40] Leonard John H. A Heat Transfer Textbook. Original American edition published by Prentice-Hall Inc., NJ, USA. Published and Reprinted by JWANG JUAN PUBLISHING CO., Taipei, Taiwan, 1981.
- [41] Schiller D., Li J. & Sirignano W.A. Transient Heating, Gasification and Oxidation of Energetic Liquid Fuel. *Combustion and Flame*. 1998. Vol.114, Issue 3-4, pp. 349-358.
- [42] Ouedraogo A., Mulligan J.C. & Cleland J.G. A Quasi-Steady Shrinking Core Analysis of Wood Combustion. *Combustion and Flame*. 1998. Vol.114, Issue 1-2, pp.1-12.



Material Recycling - Trends and Perspectives

Edited by Dr. Dimitris Achilias

ISBN 978-953-51-0327-1

Hard cover, 406 pages

Publisher InTech

Published online 16, March, 2012

Published in print edition March, 2012

The presently common practice of wastes' land-filling is undesirable due to legislation pressures, rising costs and the poor biodegradability of commonly used materials. Therefore, recycling seems to be the best solution. The purpose of this book is to present the state-of-the-art for the recycling methods of several materials, as well as to propose potential uses of the recycled products. It targets professionals, recycling companies, researchers, academics and graduate students in the fields of waste management and polymer recycling in addition to chemical engineering, mechanical engineering, chemistry and physics. This book comprises 16 chapters covering areas such as, polymer recycling using chemical, thermo-chemical (pyrolysis) or mechanical methods, recycling of waste tires, pharmaceutical packaging and hardwood kraft pulp and potential uses of recycled wastes.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Uladzimir Kalitko (2012). Waste Tire Pyrolysis Recycling with Steaming: Heat-Mass Balances & Engineering Solutions for By-Products Quality, Material Recycling - Trends and Perspectives, Dr. Dimitris Achilias (Ed.), ISBN: 978-953-51-0327-1, InTech, Available from: <http://www.intechopen.com/books/material-recycling-trends-and-perspectives/waste-tire-pyrolysis-recycling-with-steam-heat-mass-balances-and-engineering-solutions-for-by-product>

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