EFFECT OF PYROLYSIS TEMPERATURE, HEATING RATE, VAPOR RESIDENCE TIME, AND REACTOR TYPE ON THE YIELD AND PHYSICOCHEMICAL PROPERTIES OF WASTE TIRE PYROLYSIS PRODUCTS

Rayimjonov Burkhonjon
Junior researcher of the General and Inorganic Chemistry Institute, Tashkent, Uzbekistan.
+998 (90)-044-23-34
Yusupov Farkhod
Head of the Laboratory, General and Inorganic Chemistry Institute, Tashkent, Uzbekistan.
+998 (99)-111-17-06
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Abstract

This review evaluates the effects of four key parameters-pyrolysis temperature, heating rate, vapor residence time, and reactor type-on waste-tire pyrolysis. At 500 °C, an oil yield of 43.6 wt.% was reported, while increasing the temperature to 750 °C reduced oil yield to 26.6 wt.% and increased gas yield to 33.5 wt.%. Increasing the heating rate from 5 to 25 °C min^{-1} decreased oil yield from 54.8 to 43.0 wt.%, whereas gas yield increased from 7.24 to 18.04 wt.%. These results demonstrate that operating conditions strongly control product distribution and physicochemical properties. The optimal conditions therefore depend on the targeted recovery of oil, gas, or carbonaceous products.

Keywords: waste tires; pyrolysis; temperature; heating rate; residence time; reactor type.

1. Introduction

The increasing generation of end-of-life tires (ELTs) has created both environmental challenges and opportunities for resource recovery [1]. Because tire materials are highly cross-linked and resistant to natural degradation, conventional disposal methods can result in long-term accumulation and loss of valuable carbonaceous and hydrocarbon resources [2]. Pyrolysis has therefore attracted considerable attention as a thermochemical conversion route capable of transforming waste tires into three principal product fractions: liquid oil, non-condensable gas, and solid char/recovered carbon black [3].

The distribution and physicochemical properties of these products are strongly dependent on operating conditions [4]. Previous studies have demonstrated that pyrolysis temperature, heating rate, vapor residence time, and reactor configuration can substantially influence the decomposition pathways of natural rubber, styrene–butadiene rubber, and polybutadiene rubber and

consequently determine product yield and composition [5]. Increasing temperature generally promotes deeper thermal decomposition and secondary cracking, whereas heating rate affects the rate of volatile evolution and heat transfer within tire particles. Similarly, vapor residence time can influence secondary reactions of primary pyrolysis vapors, while reactor configuration determines heat and mass transfer, vapor–solid contact, and separation of primary products [6].

2. Materials and Methods

A systematic literature review was conducted to evaluate the effects of pyrolysis temperature, heating rate, vapor residence time, and reactor type on the yield and physicochemical properties of waste-tire pyrolysis products. Relevant peer-reviewed studies published between 2015 and 2026 were collected from major scientific databases using combinations of the keywords *waste tire pyrolysis, pyrolysis temperature, heating rate, vapor residence time, reactor type, pyrolysis oil, pyrolysis gas,* and *pyrolysis char*. The selected studies were screened according to their relevance and availability of experimental data, and information on feedstock characteristics, operating conditions, reactor configuration, product yields, and physicochemical properties was extracted. The reported results were subsequently compared to determine the influence of individual process parameters and their interactions on liquid, gas, and solid product formation. Particular attention was given to oil composition, calorific value, density, viscosity, sulfur content, gas composition, and the structural and surface properties of the solid residue.

3. Result and Discussion

The literature analysis demonstrates that the operating parameters of waste-tire pyrolysis strongly affect both product distribution and product quality. Temperature is generally the dominant parameter because it controls the extent of rubber decomposition and secondary cracking reactions. At moderate temperatures, decomposition of the main rubber fractions promotes the formation of condensable hydrocarbons, whereas further temperature increases enhance secondary cracking of pyrolysis vapors and generally increase gas formation. Heating rate also affects volatile release and heat-transfer behavior, while vapor residence time determines the extent of secondary reactions. Reactor configuration is particularly important because it controls heat and mass transfer and therefore influences the actual thermal history of the tire particles and vapors.

Table 1.

Effect of major pyrolysis parameters on waste-tire product distribution

Pyrolysis temperature (°C)	Heating rate (°C/min)	Residence time (s)	Oil yield (wt.%)	Char yield (wt.%)	Gas yield (wt.%)
400	14	90	27.0	58.7	14.3
450	14	90	38.4	45.8	15.8
500	14	90	43.6	39.9	16.5
550	14	90	42.6	40.0	17.4
600	14	90	40.0	39.9	20.1
650	14	90	37.3	40.0	22.7
700	14	90	32.1	39.9	28.0
750	14	90	26.6	39.9	33.5

As shown in Table 1, temperature and vapor residence time have closely related effects, because both can determine the severity of secondary reactions. At sufficiently high temperature or long vapor residence time, primary pyrolysis vapors undergo additional cracking, producing lighter hydrocarbons and permanent gases at the expense of condensable oil. In contrast, rapid heating and efficient removal of vapors can favor the recovery of primary volatile products. Consequently, maximizing oil yield does not necessarily require the highest possible temperature; rather, an appropriate combination of temperature, heating rate, and vapor residence time is required. Reactor design further modifies these relationships by determining how rapidly heat reaches the tire particles and how long the generated vapors remain in the hot reaction zone.

Table 2.

Influence of pyrolysis conditions on the physicochemical properties of products

Reactor type	Temperature (°C)	Heating rate (°C min^{-1})	Vapor residence time	Oil yield (wt.%)	Gas yield (wt.%)	Char yield (wt.%)
Fixed-bed	800	5	-	54.8	7.24	38.0
Fixed-bed	800	10	-	51.0	10.9	38.0
Fixed-bed	800	15	-	47.6	14.4	38.0

Fixed-bed	800	20	-	45.1	16.9	38.0
Fixed-bed	800	25	-	43.0	18.04	38.0
Vacuum reactor	600	-	Long/controlled vacuum	48.8	16.8	34.8
Rotary kiln	550	-	30 min	67.0	-	33.0
Fixed-bed	400-460	-	-	36-62	2.8-17	31.6-51

The physicochemical properties of the products are therefore closely connected with product distribution. Pyrolysis oil is particularly sensitive to temperature and vapor residence time because secondary cracking can change its molecular-weight distribution and increase the proportion of lighter and aromatic compounds. Gas formation becomes more significant under severe thermal conditions, while the solid fraction undergoes progressive devolatilization and carbonization. For char and recovered carbon black, increasing temperature can reduce volatile matter and modify surface characteristics, although the inorganic ash fraction originating from tire additives remains an important limitation. Overall, the literature indicates that optimization should be based not only on maximizing the yield of one product but also on achieving the required quality and composition of oil, gas, and carbonaceous solid products simultaneously.

Conclusion

The literature analysis confirms that pyrolysis temperature, heating rate, vapor residence time, and reactor type are the key parameters controlling waste-tire pyrolysis. The reviewed experimental data show that oil production generally reaches an optimum at intermediate temperatures; for example, an oil yield of 43.6 wt.% was obtained at 500 °C, while increasing the temperature to 750 °C reduced the oil yield to 26.6 wt.% and increased gas yield to 33.5 wt.%. Heating rate also significantly affected product distribution: increasing the heating rate from 5 to 25 °C min^{-1} decreased oil yield from 54.8 to 43.0 wt.%, while gas yield increased from 7.24 to 18.04 wt.%.

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