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Feasibility Study of Industrial-Scale Pyrolysis for Used Tire Recycling

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ABSTRACT

The increasing urban population and the rising number of vehicles have made the production of used tires a significant environmental concern. These tires, classified as non-degradable waste, pose a considerable challenge to nature, necessitating effective solutions for their collection and recycling. In response to this issue, a project has been developed to produce fuel from used tires, utilizing the pyrolysis method as the most suitable option for this process. Pyrolysis is defined as the thermal decomposition of tires in the absence of oxygen, an endothermic reaction that yields products categorized into three types: gaseous, liquid, and carbon solids. This project focuses on the liquid product, known as pyrolysis oil, which possesses a high calorific value. Additionally, various reactors were evaluated for the pyrolysis process, ultimately selecting the rotary kiln reactor due to its superior heat transfer capabilities, efficient space utilization, and cost-effectiveness. The main equipment utilized in this unit has been selected, and their specifications will be detailed. This project aims not only to address the issue of rubber waste but also to contribute to sustainable energy solutions.

Keywords: Worn tires, pyrolysis, rotary furnace, pyrolysis oil, diesel

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1- Introduction

Energy supply and environmental pollution are among the most pressing and challenging issues faced globally. One significant problem in this context is the accumulation of worn tires and rubber waste, the disposal of which poses considerable risks to both the environment and human health. The unique properties of rubber—such as its resistance to mechanical damage, long lifespan, and immunity to various weather conditions—render these materials difficult to biodegrade. Tires are notably resistant to abrasion, water, heat, electricity, and many chemicals; microorganisms require over 100 years to decompose them. Moreover, worn tires can lead to hazardous fires due to their high volume and can serve as habitats for mosquitoes and rodents, potentially facilitating the spread of various diseases. The uncontrolled burning of tires has severe consequences, producing smoke and toxic substances that can contaminate air, soil, and surface and groundwater resources. However, it is essential to recognize that tires also present numerous opportunities for resource conservation, as they are a source of valuable materials and fuels. Therefore, this section will review the properties and compositions of tires, as well as the reasons for their potential as a valuable fuel source. Additionally, the physical characteristics of the materials involved in this process will be analyzed to provide effective solutions for managing rubber waste. A typical tire consists of three primary materials: rubber, metal, and textiles. The percentage composition of these materials determines the tire's strength and flexibility. Table 1 presents the percentage composition utilized in the European Union for the production of car and truck tires [1].

Table 1: Components of car and truck tires [1]

Rubber compounds	Car tire	Heavy vehicle tire
Carbon black	28%	20%
Natural rubber	22%	30%
Metal	13%	25%
Synthetic rubber	23%	15%
Fabric, Filters, …	14%	10%

Natural rubber is derived from plant sap, specifically from the Hevea Brasiliense’s tree. Despite the advent of synthetic rubber, natural rubber remains the most crucial element in rubber production due to its unique properties. Synthetic rubber, on the other hand, is produced from petroleum derivatives. The most commonly used types of synthetic rubber include butyl rubber and styrene-butadiene rubber. Important components of tires that enhance their resistance to wear and tear are carbon black and amorphous silica. Vulcanization is a chemical process that transforms natural rubber into more durable polymers through the addition of sulfur and its compounds. Vulcanized materials exhibit reduced adhesion and improved mechanical properties. Consequently, two other vital ingredients in rubber composition are sulfur and zinc oxide, which typically serve as vulcanization activators. The second primary material utilized in tire production is metal. Steel wire, often of high quality, incorporates brass, tin, and zinc to provide strength and resistance to tires. The final type of material used in tires is textiles. Reinforcing fabrics are employed to impart structural strength to the tire carcass and can be either synthetic or natural. Commonly used materials for this purpose include polyester, rayon, and nylon. Worn tires should not be classified as municipal solid waste. The elemental and proximate analysis, along with the calorific value of various tires compared to other solid fuels, is presented in Table 2 [1].

Table 2: Characteristics of tire types and comparison with biomass

	Percentage of							Thermal Value (MJ/kg)
	Carbon	Hydrogen	Nitrogen	Sulfur	Oxygen	Ash	Moisture	
Car tire	83.92	6.83	0.78	0.92	3.39	4.16	0.75	38.6
Heavy vehicle tire	83.20	7.70	1.50	1.44	6.16	5.00	1.40	33.4
Motorcycle tire	75.50	6.75	0.81	1.44	15.50	20.10	1.53	29.18
Municipal solid waste	15-30	2-5	0.2-1	0.02-0.1	12-24	10-30	10-40	8.9-13.4

Approximately 80% of the weight of tires consists of carbon. The composition includes 65% volatile matter, 30% fixed carbon, and about 5% ash. Additionally, the calorific value of tires ranges from 30 to 40 MJ/kg. Worn tires contain a minimal amount of moisture, which is negligible compared to sources such as municipal solid waste. As illustrated in Table 2, various types of worn tires exhibit a significantly higher calorific value and a greater carbon content than biomass waste. This characteristic is why used tires are increasingly regarded as a valuable energy source rather than mere waste today. Fuels derived from worn tires are commonly referred to as Tire-Derived Fuel (TDF). Given these factors, converting worn tires into solid, liquid, and gaseous fuels presents a more advantageous option than simply burning them and losing this valuable fuel source. Considering that the percentage composition of different types of tires (for light and heavy vehicles) is relatively similar, this project has opted to treat a mixture of light and heavy vehicle tires as a single input. The specifications of this mixture are detailed in Table 3 [2].

Table 3: Compositions and properties of light and heavy tire mixtures

Main ingredients	Weight percentage	Properties	
Nitrogen	0.59	Heat value (MJ/Kg)	33.4
Carbon	70.55	Particle size (mm)	5-20
Hydrogen	7.65		
Sulfur	1.36		
Oxygen	2.55		
Ash	5.51		
Other	1.96		

The output from the pyrolysis process includes solid, liquid, and gaseous products, the main compositions of which is provided in Tables 4 [2].

Table 4: Composition of pyrolysis process output products

Liquid product		solid product		gas product	
Main ingredier	Weight percentage	Main ingredients	Weight percentage	Main ingredients	Weight percentage
Methane	14.86	Nitrogen	0.38	Nitrogen	0.45
Ethane	15.18	Carbon	83.90	Carbon	78.00
Ethylene	10.01	Hydrogei	1.30	Hydrogei	8.40
Butane	4.41	Sulfur	3.00	Sulfur	1.31
Butadiene	25.05	Ash	11.75		
Nitrogen	6.60	Metal	21.1		
Carbon monox	4.15				
Carbon dioxic	18.38				
Hydrogen	1.35				
Hydrogen sulfi	0.01				

Figure 1 shows the feed and final products.

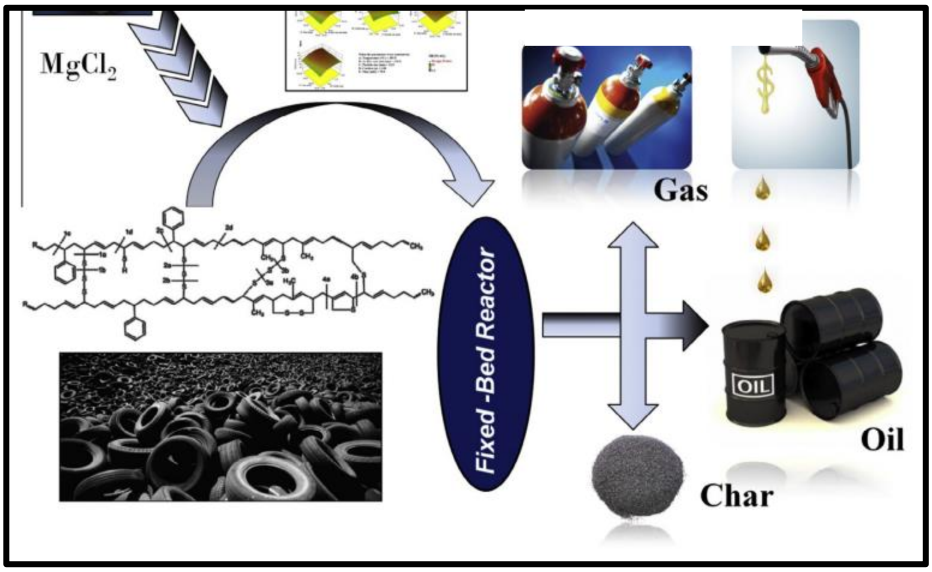

Figure 1: Scheme showing the overview of this work [3]

2- Materials and methods

3-1- Comparison of Methods and Selection of Appropriate Method

Around the world, due to the impact of rising oil prices and the reality of decreasing oil supplies, many steps are being taken to replace petroleum-based fuels. Additionally, the disposal of waste tires has become increasingly challenging. Waste management must be addressed in an economical manner that is also environmentally and health-acceptable, preferably employing skilled labor. The disposal of waste automobile tires is one of the most pressing problems to be solved. It is estimated that more than one billion waste tires are produced worldwide annually. Furthermore, tires do not easily degrade in the natural environment. The combustion of tires produces harmful pollutants detrimental to human health, including polycyclic aromatic hydrocarbons (PAHs), benzene, styrene, phenols, and butadiene. This makes landfilling and incineration illegal waste disposal options. Pyrolysis of used vehicle tires to produce fuel for internal combustion engines can be considered a hygienic, environmentally friendly, and efficient method for their disposal.

Since flash, arc, and plasma pyrolysis systems operate at high temperatures, the liquid product yield is reduced compared to gaseous and solid products. Additionally, autoclave and vacuum pyrolysis operate at high and low pressures, respectively, which limits their applicability in commercial production. We utilize pyrolysis to increase oil products while easily controlling the conditions [3].

The main commercial pyrolysis technologies with acceptable liquid product yields include fluidized bed reactors (FBR), circulating fluidized bed reactors (CFBR), conical bed reactors (CSBR), rotary kiln reactors (RKR), and spiral reactors (AR). Each of these reactors has distinct advantages and disadvantages concerning technical, economic, and ecological indicators and is suited for different applications. Depending on the primary goal of pyrolysis—whether it be heat production, electricity generation, or fuel production (liquid fuels and coal)—a specific type of reactor should be selected. Generally, each reactor type offers unique characteristics regarding heat transfer processes, mass flow, and capacity. The RKR is a suitable choice for large-scale operations. It achieves a higher oil yield when operating at temperatures between 550-650°C while producing the lowest gas yield. When optimizing for liquid product yield while minimizing gas yield, the CSBR reactor is preferred; higher liquid yields have been achieved with a CSBR compared to other technologies. Additionally, it has been observed that operating at higher temperatures increases the aromaticity of the liquid product fraction as well as the quality of the coal produced. FBR and CFBR have been extensively studied from laboratory scale to pilot scale and finally to industrial scale. Compared to other tire pyrolysis technologies, the oil yield from derived oil varies from 32% to 60%, which is influenced by factors such as pyrolysis temperatures, tire powder particle size, feed position, fluid gas type, and residence time [4]. Ultimately, the rotary kiln was chosen as the reactor type for pilot scale operations due to its superior heat transfer capability, better space utilization ratio, and cost-effectiveness. The raw material used in this study is car tires, specifically focusing on light or heavy vehicle tires, or a mixture of both, considering the industrial scale of the project and the lack of significant differences in the percentage of compounds between passenger car, motorcycle, and heavy vehicle tires [5]. The particle size of the raw material can affect the final percentage of products. To meet the feed standards of pyrolysis reactors, the raw materials are crushed using mechanical methods to reduce their size. Samples with a particle size of 5-20 mm are utilized in the actual operation of the pyrolysis furnace. In all work conducted, the final products include a liquid product, a gas product, and solid carbon materials. If the wires in the tire are not separated at the beginning of the process, they become part of the solid metal product. Since the presence of these wires in the rubber plays a catalytic role in the process, we do not separate the metal from the rubber at the outset.

Consequently, the output from the reactor consists of three streams: one is a gas stream, another is a two-phase gas-liquid stream, and the third is a solid stream that includes carbon and metal materials. The percentage of output products is determined according to operating conditions. It is important to note that the aim of this study is to enhance the efficiency of the liquid product. The characteristics of the final liquid product are such that they bear many similarities to diesel fuel, as detailed in Table 5.

Table 5: Liquid product specifications

	Density (kg/m^3)	Viscosity (eSt-̇c)	Flash point	HHV (MJ/Kg)	GCV (MJ/Kg)
Diesel	975	2.11	50	-	-
TPO (tire pyrolysis oil)	968	3.88-40	15	40-37	41.5

By comparing the operating conditions of different projects and paying attention to the industrial scale of this project, it is possible to determine the appropriate operating conditions for production purposes.

Table 6: Process operating conditions

REF.	Operational scale	Percentage of output products			Operating pressure	Operating temperature	Reactor type
		Char	Gas	Oil			
[3]	LAB				atmospheric	500°C	Fixed bed batch
[3]	LAB	45.74	16.2	33.8	atmospheric	407°C	fixed bed
[3]	LAB	31.61	42.43	25.72	atmospheric	475°C	fixed bed
[3]	LAB	76.7	1.5	21.86	atmospheric	301.4°C	fixed bed
[6]	LAB	47.88	11. 87	55	atmospheric	600-720°C	Fixed bed batch
[7]	LAB				atmospheric	425°C	Fixed bed batch
[8]	LAB	10	13.5	40.26	atmospheric	500°C	Fixed bed batch
[9]	LAB	40.6	17.9	41.5	atmospheric	600°C	Rotary kiln
[10]	pilot	49.09	2.39	38.12	atmospheric	550°C	Rotary kiln
[11]	LAB	39.9	15	45.1	atmospheric	500°C	Rotary kiln
[12]	LAB	34	10	55	atmospheric	450°C	Fixed bed batch
[1]	commercial	45±4	15±3	40±4	95-100 KPa	420±20°C	Rotary kiln
[13]	pilot	41.3	13.6	45.1	atmospheric	500°C	Rotary kiln
[14]	pilot	40.5±0.3	16.9±0.3	42.6±1	1 bar	550°C	Rotary kiln

According to Table 6 and the type of reactor selected in this process, the appropriate operating conditions for this project are as follows:

Table7: Operating conditions selected for the process

REF.	Percentage of output sulfur			Percentage of output products			Reactor type	Operating temperature	Operating pressure
	Char	Gas	Oil	Char	Gas	Oil			
[1]	1.98	0.01	0.88	42	18	40	atmospheric	420°C	Rotary kiln

The capacity of the unit is set at 1,000 tons per year, based on discussions in the market study section. Considering the semi-continuous operation of the unit, the annual operating factor is estimated to be 315 days per year, with an assumed continuous operation of 24 hours. The feed flow rate is calculated to be 138.88 kg/h. In addition to these operating conditions, safe nitrogen gas is utilized for cleaning the unit before initiating operations, with a cleaning gas flow rate set at 32 Nl/hr, corresponding to the unit's capacity of 1,000 tons per year [9].

3- Results

In this process, the metals in the tire are not separated, as they are intended to be used as a catalyst in the pyrolysis reactor. A mixture of worn tires from light and heavy vehicles is fed into a shredder as the input for the unit. After being crushed to a particle size of 5-20 mm, the tires are transferred to a sieve using conveyor-1. Particles larger than 5-20 mm are separated and returned to the shredder. The appropriately sized tires then enter the pyrolysis reactor, which is of the rotary kiln type. The operating temperature in the furnace is maintained at approximately 420±20°C, with a pressure of 95-100 kPa. The output streams from the rotary kiln (pyrolysis reactor) consist of 42% solid, 3% gas, and 55% gas-liquid mixture. The focus of this project is on the liquid phase, which includes both light and heavy hydrocarbons.

First, the gas and liquid outlet from the pyrolysis reactor at a temperature of approximately 420±20°C is fed by gear pump-1 to a shell and tube cooler-1. This stream is cooled to a temperature of 165°C to facilitate the separation of diesel (liquid phase). The separation of the liquid and gas phases occurs in a horizontal gas and oil separator. The diesel outlet temperature from the gas and oil separator is 165°C. After separation, the diesel temperature is further cooled to ambient temperature (25°C) in cooler-2 before being transferred to the storage tank by centrifugal pump, pump-2. The ninth stream exiting the two-phase separator consists of non-compressible gases, which are cooled to ambient temperature (25°C) in cooler-3. The output stream from the pyrolysis reactor (stream 3) contains metals from the tire and carbon black, which are removed using conveyor-3.

A diagram of this process, including the main equipment, is shown in Figure 2.

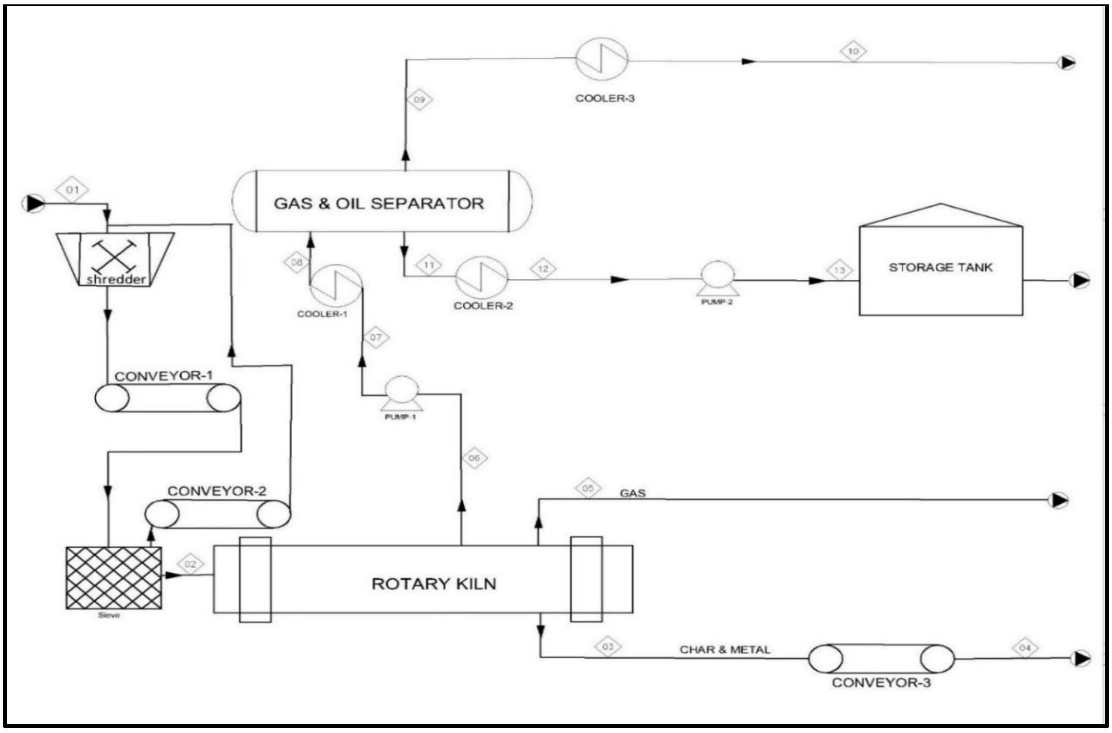

Figure 2: Process diagram

3-1- Selection of Applicable Devices in the Process

3-1-1- Shredder

Shredders come in various types and categories, generally including mills, shredders, and shear shredders. To reduce the size of worn tires and bring them to the desired dimensions, it is essential to use equipment suitable for rubber and polymer materials that are not hard and abrasive but flexible. For this purpose, shear shredders were examined among all the equipment suitable for size reduction. Shredders used for reducing the size of worn tires come in various types, including mills, shredders, and shear shredders. Since tires are made of flexible rubber and polymer materials rather than hard, abrasive substances, equipment suitable for such materials must be selected. Among these, shear shredders are commonly used for size reduction. The two main types of rubber shear shredders in industry are those with fixed solid cutting blades and those with replaceable cutting blades, both capable of cutting whole tires into specific-sized pieces. The fixed blade shear shredder operates at low speed and is versatile, able to process various materials such as tires, municipal solid waste, and bulky refuse. It features two counter-rotating shafts with interconnected shredders that grip and compress the tire, with the size of the output pieces controlled by the number of hooks and shredder width. Its advantages include flexibility in shredding different materials, a simple design with easily removable blades, adjustable piece size, and the ability to feed raw materials in bulk. However, its cutting edges tend to dull quickly, which can be mitigated by using harder steels at a higher cost. On the other hand, the shear shredder with replaceable cutting blades is specifically designed for tires and uses star rolls to feed one tire at a time into the cutting area. The blades are made of high-quality steel alloy and can be replaced as needed. Despite this, it has the drawback of limited feeding capacity and difficulty in adjusting particle size. Considering these factors, the fixed blade shear shredder is deemed more suitable for the process, especially since tires are fed with metal wires still attached. The fixed blade shredder offers greater flexibility, bulk feeding capability, and cost and time savings, making it a better choice than the shredder with replaceable blades designed solely for tires [15].

3-1-2- Conveyor

Three conveyors are needed to transport and move solid materials and shredded tire particles throughout the process. The first conveyor moves rubber pieces from the shredder to the sieve. The second conveyor transfers coarse rubber particles from the sieve section back to the shredder section. Finally, the third conveyor removes solid carbon black particles resulting from the pyrolysis process at high temperatures. Depending on various factors—including particle type and material being moved, conveyor speed, slope, weight of particles, volume and size of particles, temperature of particles, and distance of movement—the appropriate type of conveyor is selected from among its different types to ensure it is both effective and economical for this process.

The different types of conveyors include:

- Screw conveyors
- Drag conveyors
- Belt conveyors
- Bucket elevators

- Pneumatic conveyors
- Vibratory conveyors

After examining the characteristics and operation of each conveyor type, it was concluded that all three conveyors should be belt conveyors. Belt conveyors are generally suitable for moving polymeric and adhesive materials with high capacities over long distances (for example, several hundred feet in a factory). Most conveyor belts are made from fabric or rubber; at high temperatures (up to 150°F), they may also incorporate wire mesh or sheet metal. The maximum allowable slope for these conveyors is 30 degrees with widths ranging from 14 to 60 inches and speeds between 100 to 600 ft/min. It should be noted that power consumption is lower in belt conveyors [16][17].

3-1-3- Two-phase Separator

In this process, a separating device is required to separate the two-phase flow exiting the rotary kiln into gas and liquid components. A two-phase gas-liquid separator is an appropriate choice for this purpose. Considering that the mass percentage of liquid exceeds that of gas in the feed stream and that the feed is hydrocarbon-based, a horizontal two-phase gas-liquid separator is recommended. This type of separator is available in both high-pressure and low-pressure variants; given that our process operates at atmospheric pressure, a low-pressure separator is suitable [18].

3-1-4- Liquid Product Storage Tank

The main product of this process is liquid (diesel), necessitating a separate storage tank. Selecting an appropriate tank requires consideration of temperature and pressure conditions. The liquid exiting this process is at ambient temperature (25°C) and atmospheric pressure. Another important characteristic affecting tank selection is vapor pressure; in this case, it must be less than 1.5 psia. Based on these criteria, an atmospheric storage tank with a fixed roof will be chosen as the final option [18][19].

3-1-5- Pumps

As previously mentioned, the main product of this process is liquid, necessitating the use of pumps to transfer and move it. When selecting a pump, several characteristics of the fluid must be considered, including temperature, pressure, viscosity, corrosiveness, and fluid phase. A centrifugal pump is employed to transfer the single-phase liquid (diesel) flow exiting the two-phase separator to the storage tank. The choice of this pump type is due to the widespread use of centrifugal pumps for petroleum fluids. Additionally, this flow is at ambient temperature and pressure, making it suitable for this type of pump. A gear pump is utilized for the gas-liquid flow exiting the pyrolysis reactor, which operates at a temperature of 420 °C and atmospheric pressure. Given the two-phase nature of this flow, a pump that does not suffer from cavitation—such as a centrifugal pump—is appropriate. Furthermore, due to the viscous nature of this flow, the pump must be capable of transporting viscous fluids; gear pumps are designed to handle fluids within a viscosity range of 2-400,000 cSt [17][20].

3-1-6- Sieve

The purpose of using a sieve is to separate particles larger than 20 mm. For this application, the Chattooti sieve type is recommended as it is suitable for small-scale operations and has low depreciation and maintenance costs [21].

3-1-7- Heat Exchangers

In this process, heat exchangers are used to cool the gas, gas-liquid, and liquid flows. For both gas-liquid and liquid flows, a shell-and-tube type exchanger has been selected due to the high heat load of these flows. Water is used as the cooling fluid within the tubes, and fans are employed to cool the gas flow [22].

A diagram of this process on an industrial scale, including the main equipment and output products, is shown in Figure 3.

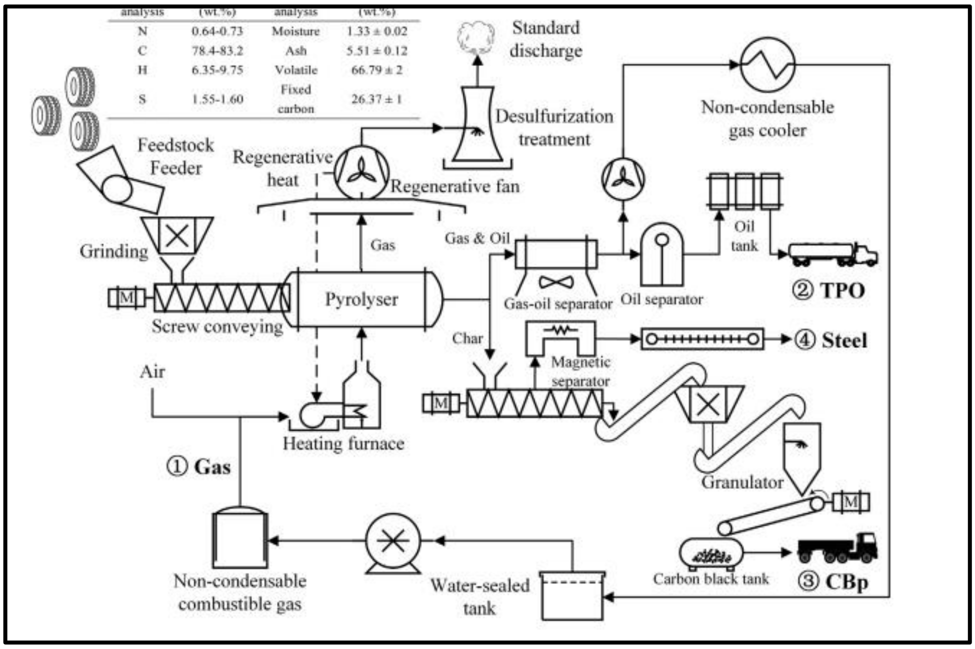

Figure 3: Commercial scale waste tires pyrolysis [1].

4- Conclusion

At the, the results obtained from this process are summarized as follows: Based on sources and references, it was determined that 80% of the weight of tires consists of carbon, with volatile matter accounting for 65% by weight, fixed carbon at 30% by weight, and ash content approximately 5% by weight. Additionally, the calorific value of tires is about 30 to 40 MJ/kg. Considering these materials, it is concluded that converting worn tires into fuel is a more advantageous option than burning them and losing this valuable energy source. Furthermore, given that the percentage composition of the types of tires (light and heavy vehicles) is similar, a mixture of light and heavy vehicle tires is deemed more suitable as the input for the feed unit based on a review of articles related to industrial-scale operations.

It should be noted that the particle size of the raw material can affect the final percentage of products. The raw materials are mechanically crushed to reduce their size in accordance with the feed standards of pyrolysis reactors. Samples with a particle size of 5 to 20 mm are utilized in the actual operation of the pyrolysis furnace. According to studies, the final products include a liquid product, a gas product, and solid carbon materials. If the wires in the rubber are not separated at the beginning of the process, they play a catalytic role in the reaction. Consequently, the output from the reactor consists of a two-phase gas-liquid flow and a solid flow that includes carbon and metal materials.

The capacity of the unit is set at 1,000 tons per year based on discussions in the market study section. Considering the semi-continuous operation of the unit, an annual operating factor of 315 days per year was established, with a feed flow rate of 138.88 kg/h. Additionally, harmless nitrogen gas is used for cleaning the unit before starting operations, with a flow rate of 32 Nl/hr. To select an appropriate reactor type based on the main purpose of pyrolysis-whether for electricity production, fuel generation, or heat-a specific reactor must be chosen. The rotary kiln reactor is deemed suitable for large-scale operations due to its higher heat transfer capability, better space utilization ratio, and cost-effectiveness.

In selecting a shredder, it was concluded that a fixed blade shredder is more suitable for this application. After examining the characteristics and operation of each conveyor type, it was determined that all three conveyors would be belt conveyors. A separating device is needed to separate the two-phase flow exiting the rotary kiln. A two-phase gas-liquid separator is considered appropriate for this purpose. Given that the mass percentage of liquid exceeds that of gas in the feed stream and that it is hydrocarbon-based, a horizontal two-phase gas-liquid separator is recommended. This type of separator is available in both high-pressure and low-pressure variants; considering that our process operates at atmospheric pressure, a low-pressure type is suitable.

As mentioned earlier, since liquid is the main product of this process, pumps are required to transport it. Several characteristics of the fluid must be considered when selecting a pump-including temperature, pressure, viscosity, corrosiveness, and fluid phase. A centrifugal pump is used to transfer the single-phase liquid (diesel) flow from the two-phase separator to the storage tank. The purpose of using a sieve is to separate particles larger than 20 mm. For this application, the Chattooti sieve type is recommended due to its suitability for small-scale operations as well as its low depreciation and maintenance costs.

In this process, heat exchangers are employed to cool gas, gas-liquid, and liquid flows. For gas-liquid and liquid flows, a shell-and-tube type exchanger has been selected because these flows have high thermal loads. Additionally, due to the flammability of process materials, product flow is contained within pipes while water serves as a cooling fluid in the shell; fans are also utilized to cool the gas flow.

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