Journal Of Research Technology & Engineering
www.jrte.org
ISSN 2714-1837

Rotary kiln tire pyrolysis towards greener waste management.

Udara S.P.R. Arachchige, S.D.N. Udayanga*, P.M.P. Madawa

Faculty of Technology, University of Sri Jayewardenepura.

*nipunaudayanga12@gmail.com

Received: 25 Sep 2023; Revised: 02 Oct 2023; Accepted: 02 Oct 2023; Available online: 10 Oct 2023

Abstract: Due to the use of non-biodegradable garbage, such as plastics and tires, which threaten the environment, people, and animals, the world population is fast expanding; it will reach 8 billion in 2023. As a result, this assessment is anticipated to address one of the current tire waste solutions while also considering their economic value. The primary products of Pyrolysis produced at the rotary kiln factory include steel, carbon black, gas, and oil. Numerous studies have examined the procedures, variables, and traits and how to maintain the circumstances and overcome difficulties with the composition, characteristics, and uses of the pyrolysis products. And they can be successfully applied in a variety of industrial settings after undergoing various post-treatment procedures.

Keywords: rotary kiln, tire pyrolysis, waste tire

1 INTRODUCTION

Tire waste is a global environmental problem that has kept increasing over the past decades due to the population's growth and continuous social and economic developments worldwide. More than 1.4 billion waste tires are generated annually from various vehicular sources, with nearly 166 million US tons discarded yearly[1]. In Thailand, 400,000 to 600,000 tons of scrap tires are generated[2]. Over 1 billion end-of-life tires (ELTs) are produced yearly. Further, it is estimated by 2040, there will be 2 billion cars and 790 million trucks on the road[3]. The tire waste is non-degradable. It needs over 1000 years to decompose in nature completely; therefore, this waste seriously threatens the ecology worldwide[4]. Hina Industrial Information Network 2018 and China Rubber Association statistics have summarized comprehensive data on recycling waste tires since 2011.

The primary information comprises the production of tires and waste tires and the value and volume of the recovery, as presented in Fig. 1. It may be noted that the total production of tires from 2011 to 2018, in terms of weight, was around 172.82 million tons. New tires weighed 4.493

billion, while the waste tires weighed 96.41 million tons. But, only 37.2 %, i.e., 35.87 million tons, is needed to devise innovative techniques to recycle these waste tires for environmental protection [5]. Recently, many attempts to recycle tires in navel methods: Shredding or grinding and crumbling to rubber powders, Reconstruction of waste tires, The utilization of incineration for generating thermal energy in utility boilers with the purpose of electricity generation, as well as its application in cement kilns and brickfields. Its usage in various building-related scenarios. Other disposal methods such as landfilling, heaping, and abandonment. Different alternative treatment approaches. However, the grinding process is relatively costly due to its execution under cryogenic temperatures and the need for mechanically intensive equipment. Conversely, incineration might result in the formation of hazardous substances like polycyclic aromatic hydrocarbons (PAHs) and soot during the combustion procedure[6]. Sustainable use of energy resources is necessary for properly managing the planet's natural resources and reducing environmental pollution. Thus, obtainment of renewable fuels is an issue among current challenges. This should be done at affordable costs with economically feasible applications to reduce pollutant emissions, including NO_x, CO_2, and particulate matter (PM). C_xH_y Studies stated that water pollution caused by runoff from tire fires could last up to 100 years. In addition, toxic incineration exhausts from waste tires are far more mutagenic than those from well-designed and adequately operated coal-fired plants emissions[7].

The waste tires possess both a non-decomposed and non-biodegradable material. Thus, the waste tires disposed of at dump sites cause serious human health, environmental, and atmospheric problems due to improper management. Besides, in such places, waste tires keep destroying the ecology through bacteria growth, hosting mosquitoes, insects, and pests through soil and groundwater. Additionally, it causes high fire risk, which cannot be quickly extinguished, and uncontrolled fire emissions potentially affect the environment. The harmful compounds emitted from decomposing waste tires pollute the groundwater and atmosphere, damage the ozone layer, absorb excessive sunlight, and so on [1],[8],[7].

Further, Alternative fuel production is already commercialized in the transportation sector, with the introduction of ethanol, methanol, biodiesel, LPG, CNG, waste material, etc. Among them, waste materials such as tires, plastics, and electronics have suddenly increased in the environment and become the largest solid waste in many countries. Thus, the waste material must be recycled for fuel[8]. Therefore, many researchers have been studying converting the waste tire into a helpful energy material in either gas, liquid, or solid forms. Many have been working on various utilization techniques, such as Pyrolysis and co-pyrolysis[8]. Pyrolysis, essentially an endothermic process, is a method for treating tire wastes in an environmentally friendly way[6].

JRTE©2023

Fig. 1. Production and recycling of tires from 2011 to 2018 [5]

In contrast to the widely used traditional technology, Pyrolysis (Pyro = heat. Lysis = break down) breaks down chemical bonds and decomposes the compound structure under a non-oxygen atmosphere at high temperatures, producing minimal emissions of nitrogen oxide and sulfur oxide[6]. The high molecular weight polymers in tire rubber are reduced to low ones in the forms of gas, solid, and liquid that can be used as chemical energy resources, as shown in Fig. 2. The inorganic residues such as steel and carbon black remain solid at this process's end[9],[6],[10]. Pyrolysis occurs under low pressure and high temperatures around 400 ~ 500 C. Practically. Pyrolysis cannot be performed oxygen-free since a limited quantity of oxygen is present in the reactor, and oxidation will occur at a limited amount[11]. The composition of waste tires makes them a desirable source for producing carbon-based materials. The high calorific value (28–37 MJ kg^{-1}) and low mineral content of tires make them valuable potential energy sources[11].

The employment of waste tires as fuel in advanced thermal-conversion processes with low contaminant emissions is a promising alternative in the current market, which allows the energy use of such wastes at affordable costs and reduces the environmental impact regarding waste tire disposal. Processes of Pyrolysis could be categorized according to applied pressure as vacuum, atmospheric, and fast or slow according to the heating rate. Some advantages of a pyrolysis process are low energy requirements, simple devices for volatile product condensation, and high liquid yield. Pyrolysis processes reduce solid carbonaceous residues, condensable fraction (pyrolytic oil), and non-condensable gas fraction. The mass distribution of each phase is determined by operation parameters, such as temperature profiles, pressure, heating rate, fuel dimensions, heating system, and catalysts, among others[7].

JRTE©2023

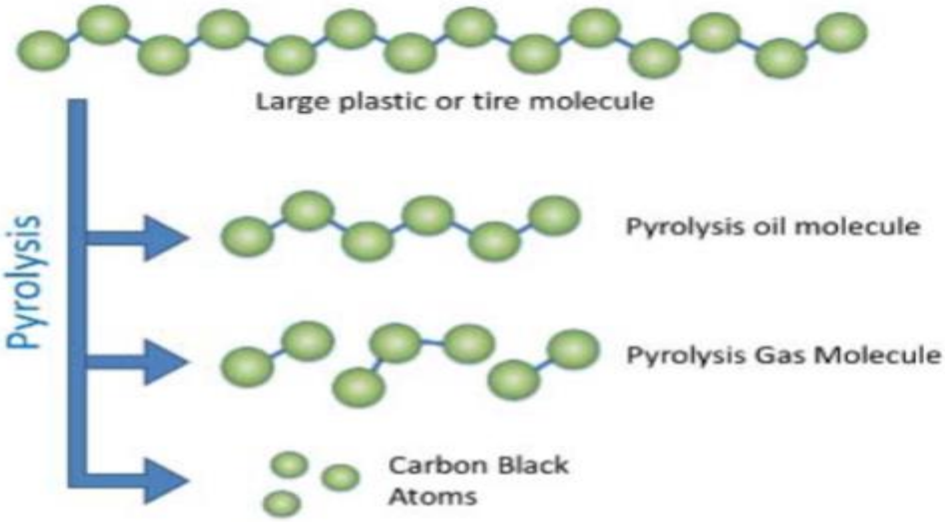

Fig. 2. pyrolysis [12]

Three types of pyrolytic reactions are categorized by the processing time and temperature. Slow Pyrolysis is low temperatures and slow biomass heating rates characterized by lengthy solids and gas residence times. In this mode, the heating temperatures range from 0.1 to 2°C /s. The prevalent temperatures hover around approximately 500°C (932°F). Gas tends to remain within the system for more than five seconds, while biomass may undergo residence times spanning from minutes to days. In gradual Pyrolysis, the principal outputs consist of tar and char, released as biomass undergoes gradual devolatilization. Following the initial reactions, re-polymerization and recombination reactions come into play. Pyrolysis: Flash pyrolysis is characterized by swift heating rates, and temperatures varied from 400 to 600°C. Nonetheless, the vapour's residence time within this process remains under 2 seconds. Compared to gradual Pyrolysis, flash pyrolysis yields reduced quantities of gas and tar. Fast Pyrolysis: This technique is predominantly employed to generate bio-oil and gas. During this procedure, the feedstock undergoes rapid heating to temperatures ranging from 650 to 1000°C, with variations based on the targeted production of bio-based or gas-related outputs. The process results in the accumulation of substantial amounts of char, necessitating frequent removal. Fast Pyrolysis has demonstrated its potential to capitalize on microwave heating. Biomass exhibits a notable propensity for absorbing microwave radiation, thereby facilitating highly efficient material heating. This phenomenon, akin to the microwave heating of food, expedites the initiation of pyrolysis reactions and significantly curtails the energy demand for the process, courtesy of microwave-induced initiation[12].

The waste tire can be converted to oil, gas, and carbon black through pyrolysis technology, which has high economic value. Customers even get other byproducts (steel wire). Therefore, investing in a waste pyrolysis plant contributes to economic progress and environmental development. There are many, but according to the type of rotary kiln will be considered in this review[13].

JRTE©2023

2 ROTARY KILN REACTOR

A pyrolysis plant is a device that puts waste tires in a closed container heats and cracks them at a specific temperature and pressure to produce liquid oil, non-condensable combustible gas, and solid products. The plant's many components will be introduced along with the latest design from the Beston group; each plays an essential role in the process, as shown in Fig. 3 [14].

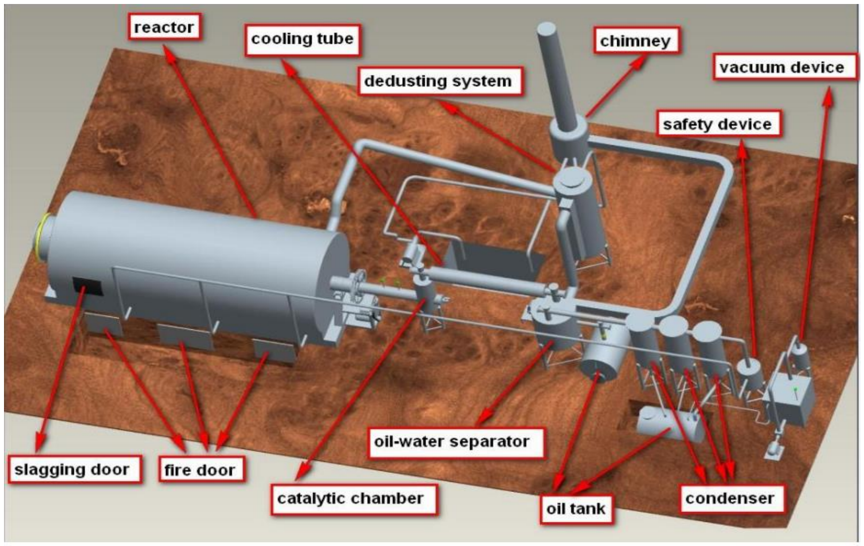

Fig. 3. Component of pyrolysis plant [15]

The rotary kiln pyrolysis of a waste tire was founded in the Adiyaman region, Kudret Inkar Waste Tire Recycle Co., Turkey. In this system, the waste tire is pyrolyzed and then condensed by a heat exchange system containing three heat exchangers: high (250–400 °C), medium (100–250 °C), and low (75–200 °C), for separating the sample into three types of liquid. The rotary kiln reactor consists of an electric and electronic control panel; its other parts are installed in the system[8], as shown in Fig. 4. N_2 is supplied to maintain the reactor's inert atmosphere and sweep away the pyrolyzed vapour product to the condensers. Furthermore, purging the system with nitrogen minimizes secondary reactions in the hot zone[16].

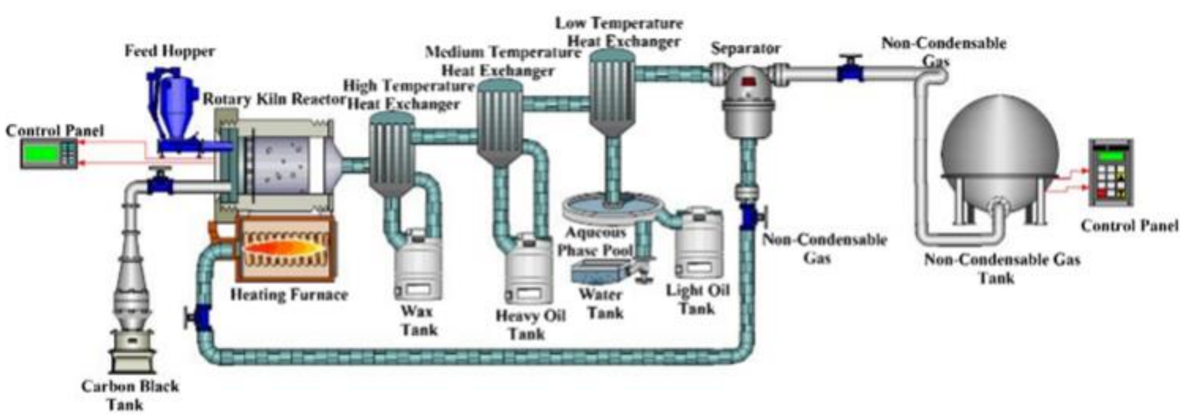

Fig. 4. schematic of the rotary kiln reactor pyrolysis system [8]

JRTE©2023

The utilization of the rotary kiln reactor has gained extensive traction in the field of waste tire pyrolysis. This is attributed to the reactor's capability to effectively handle the diverse shapes and sizes of waste tires during the pyrolysis process. The design of rotary kiln drums typically involves the creation of a horizontally or inclinedly oriented cylinder that revolves around its axis. The successful application of the rotary kiln reactor in solid waste pyrolysis can be attributed to its capacity to facilitate reasonable management of process variables, particularly emphasizing the residence time of solid waste within the reactor[17].

Rotary kiln pyrolizer offers many unique advantages over other reactors. For instance, The slow rotation of the inclined kiln enables uniform pyrolytic products but a mixing of the materials. Also, the residence time of solids can be easily adjusted to provide the optimum conditions of pyrolysis reaction. Solid wastes of various shapes, sizes, and calorific values can be used in a rotary kiln either in batches or continuously[18]. Heating in the same place will always damage the pyrolysis rotary kiln reactor if the reactor does not rotate. Therefore, uniform rotation extends the oil machine's waste tire pyrolysis service life. In addition, during the tire pyrolysis process, the rotation speed of the pyrolysis rotary kiln reactor is not fast, and each rotation takes 2.5 minutes, so it runs smoothly. It is heated evenly, which can meet the requirements of smooth machine operation[19]. The typical rotary kiln processes include the Kobe Steel commercial one tonnes/h plant, the Italian ENEA Research Center Trisaia pilot-scale plant, and the Kassel University laboratory-scale setup[18].

3 COMPONENTS/ UNITES

The component of the pyrolysis plant mainly consists of eight parts. Pretreatment, feeding, reactor, condensing, tail gas treatment, slag discharge, electronic control, and others. For a complete process with high efficiency, all the systems work together[14].

3.1 Part I – pretreatment system

The primary objective of the pretreatment system is predominantly centered on transforming waste tires into particles ranging in diameter from 20 to 50mm. This is achieved through a sequence of machinery, ultimately enhancing the reactor's capacity utilization while concurrently diminishing the duration of the reaction. Generally encompassing elements like a tire-cutting machine, dicing machine, tire wire drawing machine, plastic crusher, fine crusher, and other related equipment, the system can be customized based on specific customer requirements and various available equipment alternatives[14].

Cutting machine: The tire-cutting machine (also called tire shredder) separates the tire tread and the bead. It severs the bead steel ring, streamlining the subsequent stages of production. The Working Principle is The pneumatic cylinder supports and employs the expansion claw to secure the tire. A motor propels the tire via a coupling. The operational process manages the expansion and contraction of the cutter, effectively severing the bead from both sides of the tire[14].

Wire drawing machine: This apparatus extracts the steel wire within the discarded tires' bead under ambient conditions. Its principal aim is to extend the operational lifespan of the ensuing crusher equipment blades and simplify the process of crushing and cutting. The device comprises

JRTE©2023

key elements such as an electric motor, draw hook, hydraulic cylinder station, control handle, frame, guide wheel, and other integral components[14].

Dicing system The shearing dicing machine is used to cut waste plastic, rubber, and other large-volume wastes into smaller pieces by shearing the material. It gets ready for the upcoming crushing operation. This process is not essential if the tire's diameter is less than 1.2 meters. This concerns necessary parts like hydraulic stations, electric control cabinets, and oil cylinders[14].

Crushing Machine:The material undergoes reprocessing primarily through cutting, tearing, and squeezing, aiming to decrease its size. The refined raw materials then undergo a secondary processing phase to attain the necessary size of approximately 50mm, which is suitable for the pyrolysis reactor[14].

3.2 Part II – Feeding system.

The feeding system incorporates either mechanical apparatus or human effort to introduce raw materials into the reactor. It predominantly utilizes three methods: screw feeder, hydraulic feeder, and manual feeding, often accompanied by a corresponding belt conveyor[14]. When investors opt for the screw feeder, they benefit from a brief feeding duration and minimal labour demands. This option proves advantageous in nations with elevated labour costs. However, it's important to note that raw materials must be pre-cut into smaller fragments before being fed into the screw feeder[13].

3.3 Part III – Reactor system

The reactor system has four parts as the core equipment in the whole pyrolysis system for waste [14]. as shown in Fig. 5.

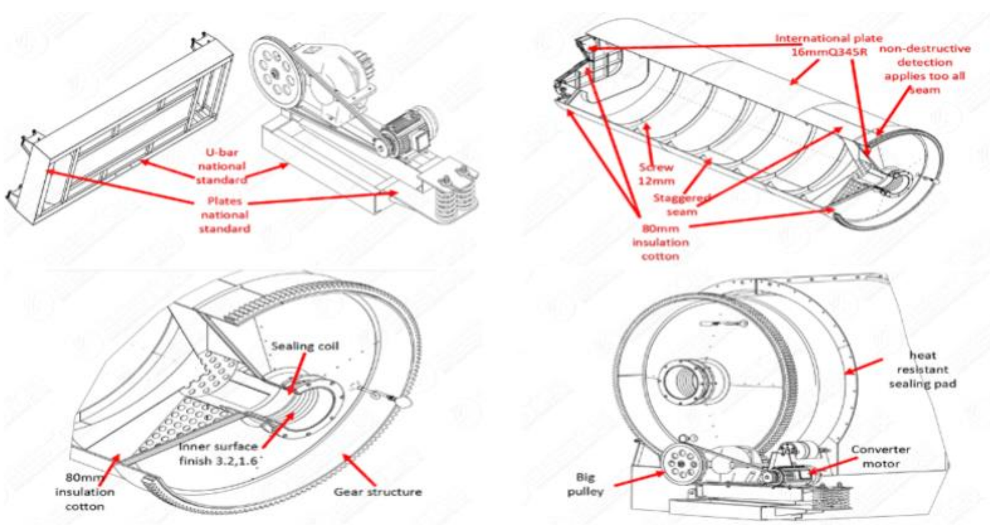

Fig. 5. Reactor system [14]

Drive device: The propelling mechanism comprises a driving motor, a reducer, and a spring base, collectively supplying the energy necessary for the reactor's rotation. An electric control cabinet oversees the reactor's forward and reverse motion. The main furnace is set in motion through a motor that drives the cylindrical gear reducer, ensuring a seamless operational flow. A spring compensation system is integrated to guarantee precise gear meshing[14].

JRTE©2023

Base :The fuel ignites within the foundation, supplying the necessary heat for the pyrolysis reactor. This mitigates a portion of the heat dissipation, offering structural support and stabilization to the primary furnace. Beston Group customizes diverse heating strategies depending on the specific site conditions of the customer. Frequently employed fuels encompass coal, wood, fuel oil, natural gas, and non-condensable combustible gas reclaimed during production[14].

Reactor: The reactor is the system's main component, shown in Fig. 6, which rotates, allowing raw materials to absorb heat. Once it reaches the cracking temperature, it produces oil and gas. It has either a cylindrical or spherical shape (internal diameter of 2.2 m and a length of 6.6 m). The capacity of the reactor is roughly 4 tonnes. Quality and reasonable design directly affect the operation of the entire pyrolysis unit and the safety of personnel and equipment in the production process[14].

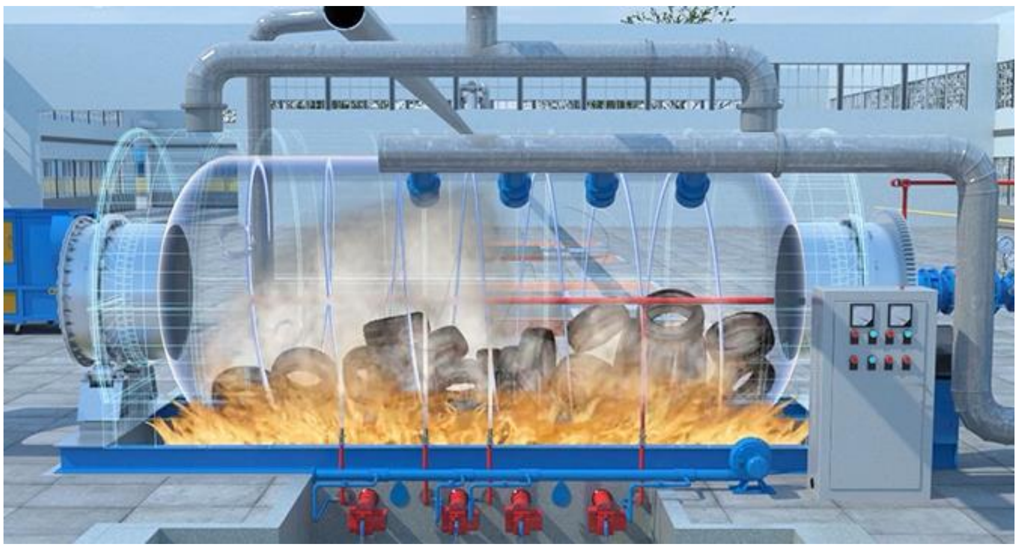

Fig. 6. reactor [20]

Casing: The primary function of the casing is to keep warm, reduce the pyrolysis oil reactor's heat loss and fuel consumption in the heating process, and ensure that the pyrolysis reaction continues [14][21]. The heat loss through the reactor can be slowed down during the process[13].

3.3.1 Condensing system

The oil gas processing system (condensing system) separates and collects the pyrolysis oil gas in the reactor[22], including manifold, residual oil tank, oil gas condenser, oil and gas separation tank, and cooling water heat dissipation system[14].

JRTE©2023

Manifold: The manifold serves two primary functions. Firstly, it acts as a buffer for the oil gas emerging from the pyrolysis reactor as it enters the oil passage condenser. This ensures a uniform entry of oil gas into the condenser. Secondly, it facilitates gas-liquid separation, effectively segregating gas from heavy oil. During production, the manifold segregates the gas generated within the reactor from the liquid oil formed upon cooling. The gas ascends into the oil-gas condenser within the manifold while the liquid oil descends. Upon the reactor's gas entry into the manifold, the latter's temperature is relatively low, causing a portion of the gas with a low freezing point to condense into liquid and separate within the manifold. The condensed gas proceeds upwards into the oil gas condensing system, while the separated liquid descends into the residue tank. This liquid compound encompasses both oil and water components[14]. shown in Fig. 7. During the transformation of oil vapour into liquid oil through the cooling process, certain impurities are prone to be assimilated into the liquid oil. Subsequently, the remaining residue is expelled by means of the ball valve positioned below[14].

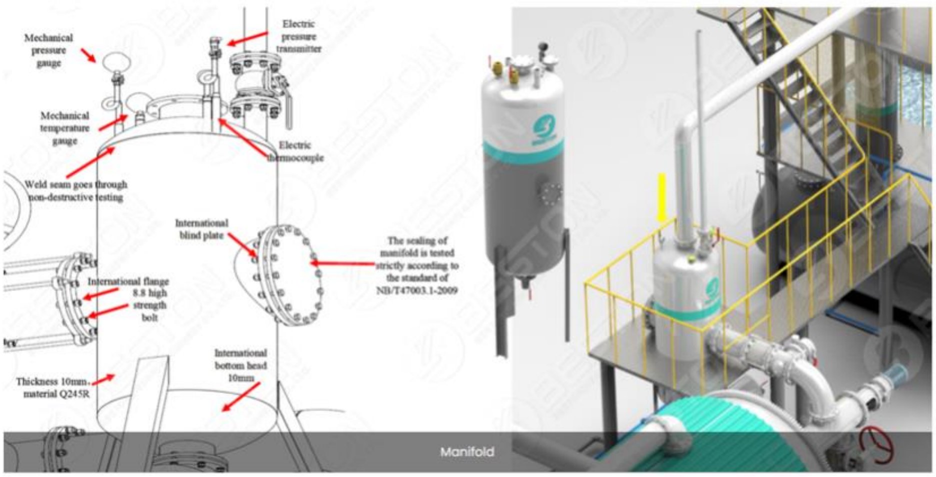

Fig. 7. manifold [14]

Oil gas condenser

NO.1 Vertical Condenser Fulfills the vital task of cooling down oil gas. It holds a significant position within the pyrolysis oil equipment and directly influences its output rate. Beston employs a traditional tube-and-tube configuration for its oil gas condenser. This design boasts straightforward construction, easy maintenance, and a substantial cooling surface area. Its widespread application is prevalent within the petrochemical sector. Employing water as the cooling medium, the condenser effectively transfers heat[14].

Oil vapour is introduced into the oil passage condenser via the airbag, where it undergoes cooling to transition into liquid oil and non-condensable combustible gas. This resulting mixture then proceeds into the oil tank. Simultaneously, as the oil gas flows, cooling water is drawn through the condenser's bottom water inlet by the cooling water circulating pump. The heat dissipation tower facilitates the discharge of heat from the circulating cooling water, maintaining the cooling water's temperature within an established range to ensure the consistent functioning of the condensing system. Throughout this process, the circulating cooling water remains consistently clean[14] shown in Fig. 8. NO_2. Integrated Condenser An oil passage condenser, an oil storage tank, and a hydro seal are all included in the three-in-one integrated condenser as a single functional component. This innovative design is the brainchild of Beston company. The most recent iteration of this condenser boasts several advantages, including ease of transportation and installation, leading to a reduction in installation time. The condensing pipe is robust and less susceptible to blockages, ensuring simple cleaning procedures. Additionally, its compact footprint occupies less floor space, offering enhanced oil storage capacity. Moreover, the incorporation of double water seals enhances anti-tampering capabilities[14] shown in Fig. 9.

Fig. 8. Vertical condenser [14]

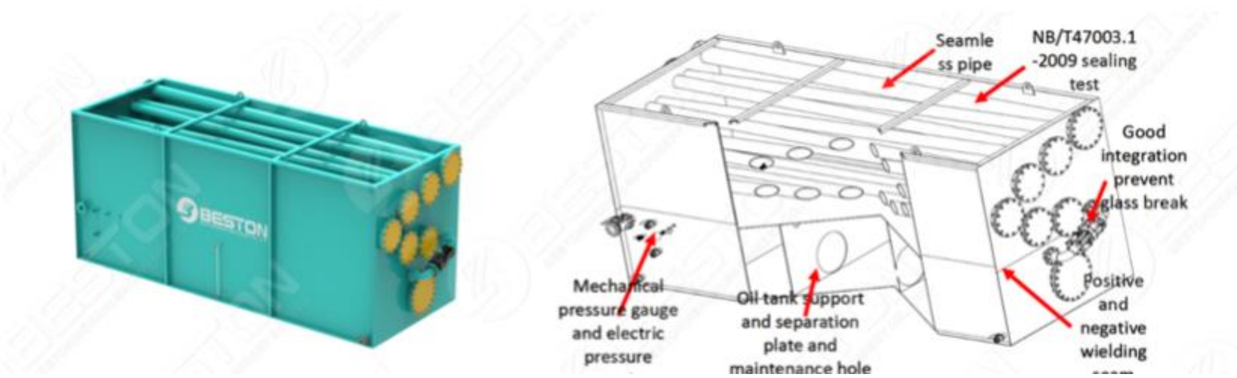

Fig. 9. Integrated condenser [14]

Oil tank: The oil tank serves a dual function of storing oil and facilitating gas-liquid separation. The liquid oil from cooling is directed into the oil tank for storage through gravity. Simultaneously, driven by the reactor's pressure, uncooled combustible gas enters the combustible gas recovery system to undergo gas-liquid separation. Equipped with a level gauge, the oil tank enables the monitoring of stored oil quantities[14].

Hydroseal: The hydroseal serves two purposes: averting backfires and refining the combustible gas. In the event of a backfire following the flame's entry into the hydroseal tank via the combustible gas pipeline, the flame's propagation is halted due to the combustible gas inlet pipe being submerged beneath the water surface. This design minimizes the risk of hazardous incidents. Operationalizing the anti-backfire mechanism relies on water pressure within the hydroseal tank, with the water surface positioned slightly higher than the combustible gas inlet, typically around 5-7 cm higher. However, maintaining an excessively high water level could lead to internal pressure within the combustible gas inlet pipe. Throughout production, any factors lead to incomplete cooling in the oil gas cooling system, and a small quantity of liquid oil may accumulate in the water-sealed tank. Before resuming production, this oil accumulation must be drained[14], as shown in Fig. 10.

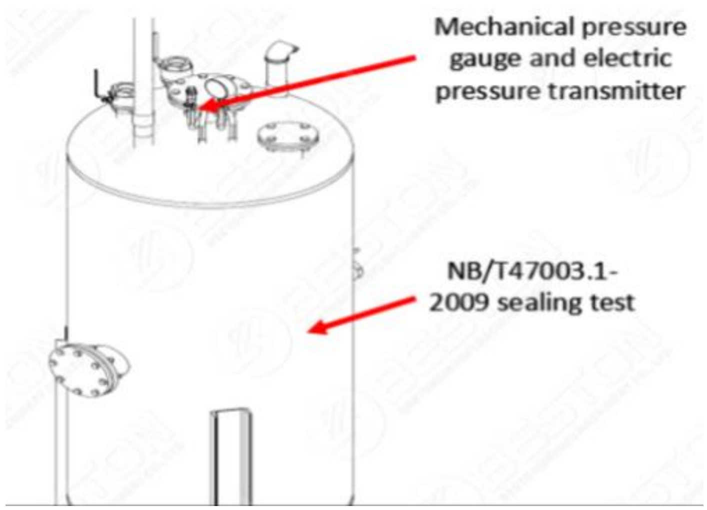

Fig. 10. hydro seal [14]

3.3.2 Tail gas treatment system

The tail gas treatment system is responsible for gathering and refining the exhaust gas from the reactor to ensure compliant emissions. Key components encompass a flue condenser, atomization water tank, atomization tower, chimney, and induced draft fan (centrifugal fan)[14].

Fue condenser: The flue condenser functions as a dual-pipe heat exchanger. A dedicated water pump facilitates the circulation of cooling water from the pool. Heat is exchanged with the cooling water as the high-temperature hot air transits through the flue condenser. Consequently, the hot air's temperature decreases, safeguarding the induced draft fan's bearings and prolonging the operational lifespan of the induced draft fan, enhancing its efficiency over time[14].

Induced draft fan: The fan operates based on the rapid rotation of the impeller inside the fan. This rotation generates centrifugal force within the fan casing, propelling the air away from the impeller and expelling it through the air outlet, thereby creating a "pressure discharge" effect. Simultaneously, the expelled air generates "negative pressure," prompting a continuous influx of "fresh air" through the air inlet. This process establishes the fan's standard operational state[14]. During the operation of the induced draft fan, it exhausts the hot air flue gas produced within the reactor while maintaining a specified negative pressure. This configuration is commonly referred to as a suction fan. The induced draft fan's air inlet is equipped with an air valve. This component regulates the effective cross-sectional area of the air inlet by means of various valve settings, enabling the adjustment of hot air flow. Typically, the middle setting is favoured. The underlying principle is that the higher the hot air flow rate, the lower the heat the hot air imparts to the reactor [14].

Water tank: The primary role of the water tank is to supply water and facilitate water recovery for the spray system within the upper atomization tower. The water tank is designed with a mechanism for separating impurities, ensuring a cleaner water source for the upper air supply[14].

Spray de-dusting tower: The atomization tower, also known as a dust removal tower, offers two techniques: Bohr magnetic ring packing adsorption and water spraying. For Bohr magnetic ring packing dust removal, ceramic Bohr magnetic rings are employed as packing material. These rings bring advantages like high throughput, low resistance, efficient particle separation, and operational flexibility. Their size is generally 50%-100% larger than standard Raschig rings. As hot air passes through, the magnetic rings within the packing dampen the air, separating larger dust particles. Simultaneously, spray water wets the magnetic coil's surface. When hot air flows through, the wet magnetic ring surface attracts and captures smaller dust particles while simultaneously spraying water. An evenly distributed shower pump washes the magnetic rings.Regarding spray water dust removal, the dedicated spray water pump draws water from the base of the dust removal tower. The dust removal device transforms This water into mist through nozzles. The resulting mist captures, collides with, and condenses dust particles, causing them to fall alongside the droplets. This dust removal method boasts a simple structure, low resistance, and user-friendly operation. A uniform spray head within the tower separates fine particles from the hot air. In the dust removal base, dust and impurities accumulate, with partitions separating clean water. This segregated water is recycled for mist-based dust removal[14].

Chimney: A chimney facilitates the ventilation of hot smoke or fumes emanating from a boiler, furnace, stove, or fireplace. Typically, chimneys are oriented vertically, or as close to vertical as feasible, to ensure a streamlined flow of gases into the atmosphere[14].

3.3.3 Slag discharge system

As shown in Fig. 11, the slag discharging system employs an internal screw mechanism within the slag discharging device to expel carbon black from the reactor to an external container provided by the customer for storage. This setup achieves an enclosed carbon black discharge process characterized by straightforward operation and full automation. This method guarantees a clean, pollution-free, time-efficient, and labor-saving process. The system components comprise a screw discharge device, a high-temperature ball valve, and a water-cooled discharge device (typically outfitted with two sets of water-cooled slag discharges)[14].

JRTE©2023

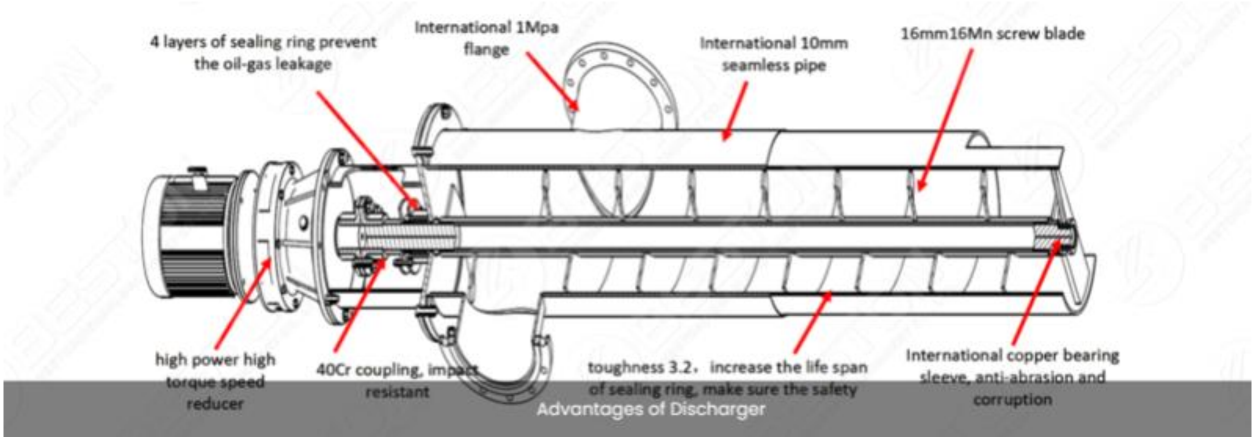

Fig. 11. sludge discharger [14]

Screw discharging: The principle of screw discharging is the same as that of a screw conveyor. This machine employs a motor to drive a rotating screw that pushes materials to accomplish their conveyance. Its primary components encompass driving devices, screw shafts, screw blades, and screw shells. The structure is uncomplicated and compact, ensuring reliable operation and convenient transportation. In coordination with the reactor, this mechanism effectively facilitates the discharge of carbon black[14].

High-temperature Ball Valve: During production, the high-temperature ball valve remains closed, effectively preventing oil and gas leakage through the slag tap. When the slag discharge operation is initiated, the valve is opened, facilitating the extraction of carbon black from this specific juncture[14].

Water cooling discharging system: The collaboration with the screw-discharging extractor is discretionary. When coupled with a water cooling system, the production of carbon black can be achieved at elevated temperatures. This water-cooling setup, comprising circulating water pumps and pipelines, has the potential to share the same water-cooling system as the oil gas condenser. The incorporation of corresponding valves, pumps, and pipelines enables this integration[14].

3.3.4 Electronic control system

The power control cabinet is the central control hub for the complete pyrolysis system. It governs the activation and functioning of each motor as outlined in the design. Additionally, it provides real-time displays of key component temperatures and pressures, offering vital data for efficient production operations[14]. The internal control circuit within the electric control cabinet is pre-connected before the equipment leaves the factory. Your responsibility lies in connecting the power circuit and the transmission signal circuit based on the designated indicators present on the terminals[14].

3.3.5 Part VIII. Other accessories

Cooling tower: A cooling tower is a mechanism designed to disperse waste heat produced by industries through the interaction between water and air, resulting in evaporation. Cooling the water within a cooling tower involves a heat and mass transfer process. This cooled water is then conveyed to the interior of the cooling tower, where it meets fillers, nozzles, water distributors,

JRTE©2023

or water distribution trays. These elements substantially enhance the surface area for interaction between water and air. Fans draw air into the cooling tower. A portion of the water assimilates heat and undergoes vaporization under consistent pressure, leading to a decrease in temperature for the surrounding liquid water[14].

The underlying principle follows: The fan draws in dry air, which enters the cooling tower through the air inlet system. Water molecules, rich with high-pressure saturated steam, flow from high to low-pressure regions within the tower, ultimately entering the lower-pressure atmosphere. This hot and humid water is evenly dispersed throughout the tower using a self-seeding system. When water droplets come into contact with the air, two primary mechanisms take place. Firstly, direct heat transfer between the air and water ensues. Secondly, due to the pressure variance between the water vapour's surface and the surrounding air, evaporation transpires through pressure-driven action. This entails the transfer of heat through contact with unsaturated dry air, which removes sensible heat from the water. In addition, a portion of the water evaporates, effectively extracting latent heat from the water. These combined processes work to accomplish the objective of cooling the circulating water[14].

Burner: A burner encompasses a range of devices designed to facilitate the controlled mixture and combustion of fuel and air. Upon activation, the automated fuel supply triggers the release of ignited flames, which then burn in the presence of air to achieve the desired flame configuration and power output. Burners commonly utilize various fuel types, including diesel, heavy oil, natural gas, liquefied petroleum gas, coalbed methane gas, and biogas. The primary function of a burner is to create and sustain controlled combustion for specific applications[14].

Blower and Exhaust Gas Spray Gun: The blower and exhaust gas spray gun can utilize the combustible gas generated by the reactor as fuel for heating purposes. This approach enables heating of the reactor while allowing for the possibility of turning off the burner. This strategy decreases energy consumption for the customer, leading to reduced production costs[14]. The blower supplies air to the combustion chamber, with an airflow rate of approximately 8 cubic meters per minute. Within the exhaust gas spray gun, stationary black bricks are positioned to ignite the combustible gas and facilitate the heating of the reactor[14].

Burning room: During the operation of the pyrolysis plant, a portion of the produced combustible gas is utilized to heat the reactor by burning in the base. The remaining can be stored in an airbag or directly combusted within the exhaust combustion chamber. Beyond its role in reactor heating, the surplus flammable gas generated during Pyrolysis requires appropriate disposal. Discharging it directly could lead to environmental pollution and potential safety risks. However, by conducting controlled burning, these safety concerns are mitigated, ensuring the elimination of potential hazards[14].

Airbag: The combustible gas generated during Pyrolysis can also be accumulated within an airbag. This stored gas can then be utilized as fuel for future production cycles, leading to decreased reliance on external fuel sources and preventing environmental contamination. To facilitate this storage, a fan and a small hydroseal are coordinated with the system[14].

JRTE©2023

4 EFFECTING FACTORS

The composition of pyrolysis products is subject to the influence of various process operating conditions. These factors encompass feed size, operating temperature, pressure, residence time, heating rate, and the presence of a catalytic medium[16].

4.1 Temperature

Temperature is a key factor in tire recycling pyrolysis plants. Our tire recycling pyrolysis plant generally adopts low-temperature pyrolysis technology and keeps the pyrolysis degree at an average of 380 degrees [23]. Pyrolysis can be carried out through the fast or slow pyrolysis process. Fast Pyrolysis is known for its high heating rate (1000 °C/s), short residence time of about 3 seconds, and the gaseous products' fast quenching. The characteristics of this process cause a minimal secondary reaction, leading to a high pyro-oil yield. In contrast, slow Pyrolysis, characterized by its low heating rate and long residence time, promotes secondary reaction, thus increasing the yield of gas and char products[24],[16]. It has been recorded that the low to medium-temperature pyrolysis process favours the production of tire pyrolysis oil, while the high-temperature process favours the production of gases[24]. If the temperature is too high, the tire pyrolysis oil gas will run quickly out of the cooling system without condensing, so the oil output cannot be higher[23].

Waste tires mainly comprise rubber, carbon black, and other organic components. After thermal Pyrolysis, rubber and other organic components are pyrolyzed into oil gas. The residual solid substances after cracking include recovered carbon black filler, inorganic ash, and steel wire. Waste tires begin to decompose at about 290°, and the Pyrolysis ends at about 570°[23]. These components undergo distinct weight loss patterns and experience varying temperature thresholds during Pyrolysis. A comprehensive analysis of global literature and laboratory findings indicates that decomposition occurs within the temperature range of approximately 150-350°C for processing oils, plasticizers, and other organic additives. For NR (natural rubber), the range lies between 330-400°C, while for SBR (styrene-butadiene rubber) and BR (butadiene rubber), the decomposition takes place within the interval of 400-480°C[6].

4.2 Size of the particle

The use of tire chips instead of whole tires may also increase the efficiency of the process by 20-30% Smaller feed size particles provide more reaction surface, giving a high heating rate and rapid decomposition of rubber. The oil product vapours undergo extended periods for secondary reactions within the reactor, leading to decreased liquid and char yields and heightened gas yield. Conversely, the slower heating rate observed in processing whole tire feed is due to its reduced thermal conductivity. Moreover, heat can penetrate only to a certain depth within the available pyrolysis time, in contrast to smaller pieces' more comprehensive thermal decomposition. Consequently, the rubber core of larger pieces undergoes carbonization, hindering complete decomposition and resulting in elevated char yield alongside decreased liquid and gas yields[16].

Fig. 12 illustrates how the size of waste tire granules affects the production of solid, liquid, and gaseous pyrolysis products. All specimens underwent uniform heating at a rate of 14 ◦C/min until reaching 750 ◦C. As the granule size of the tested samples increased, there was a marginal uptick

JRTE©2023

in the solid residue (char) yield, rising from 39.9% for WTS1 to 41.3% for WTS3. This subtle change in char yield suggests that the thermal decomposition rate may decrease with larger granules, owing to their reduced heat exchange area. This slowdown in heat transfer toward the center of larger granules is primarily due to tires' inherently low thermal conductivity. Furthermore, the size of the granules also influences the production of liquid and gaseous phases in the pyrolysis process[25].

M. Rofiqul et al. [26] studied the effect of changing particle size on the yield of pyrolytic oil under fixed applied conditions, temperature at 475°C, and residence time of 5 seconds. They found that with an increase in the particle size from 2 cm3 to 12 cm3, the pyrolytic oil yield increases until the particle size is 4 cm3 with 51%. After that, the yield decreases. They concluded that smaller particle size provides more reaction surface, causing a high heating rate and too quick decomposition of the rubber. Conversely, larger particle sizes experience a reduced heating rate due to their lower thermal conductivity. Within the available pyrolysis timeframe, heat can only penetrate to a certain depth compared to the nearly comprehensive thermal decomposition achieved in smaller pieces. Thus, the core of the larger pieces become carbonized and can't be decomposed, ultimately resulting in an increase in char and a decrease in liquid and gas yield."

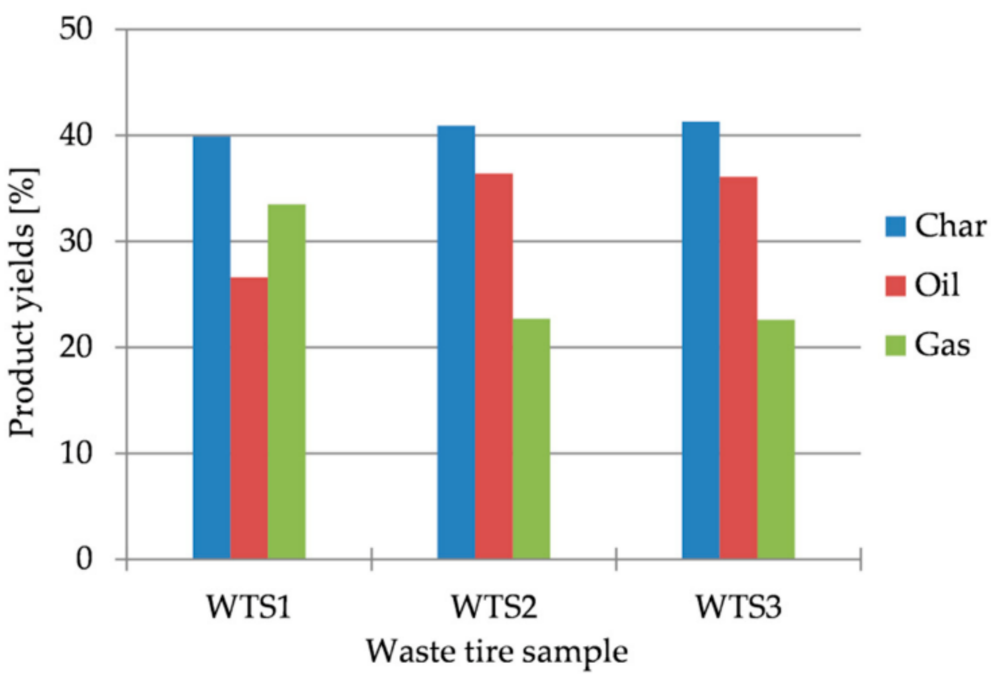

Fig. 12. The percentage of pyrolysis products relative to the granule size[25]

4.3 Speed

The speed of the process and the efficiency of heat transfer also impact the distribution of products. Slow Pyrolysis, known as carbonization, can be employed to optimize the generation of solid char. This approach involves gradual pyrolytic decomposition at lower temperatures. Rapid quenching is frequently applied to enhance the production of liquid products, which

JRTE©2023

condenses gaseous molecules into liquid form. In specific pyrolysis procedures, a product yield of up to 80% by weight in liquid form can be achieved[27].

Effect of rotating speed: The investigations on pyrolysis were conducted at 300°C. We looked at how product distribution and oil properties including viscosity, density, and heating value were affected by rotating speed and lifter presence[22]. Fig. 13(a) the influence of rotational speed on the mass yield produced by the pyrolysis of the used tire. According to the results, the rotating speed of 15 rpm generated the most liquid. Higher rotating speed will result in greater material mixing inside the reactor, which will increase the amount of heat that is transferred from the reactor's outside to the materials. However, in any circumstance, the amount of liquid generated is still little. This may be as a result of the low temperature not being high enough to convert used tire waste into pyrolysis gas. The solid product, which is still high at more than 50%, demonstrates this[22].

The lifter installed in the rotary kiln reactor can better mix the waste tire and increase heat transfer due to more comprehensive surface contact between the waste tire and reactor surface. Fig. 13(b) shows the mass yield of waste tire pyrolysis with lifter installation in the reactor. From Fig. 13, we can see that the use of a lifter reduced the liquid and solid products while the gaseous product increased[22].

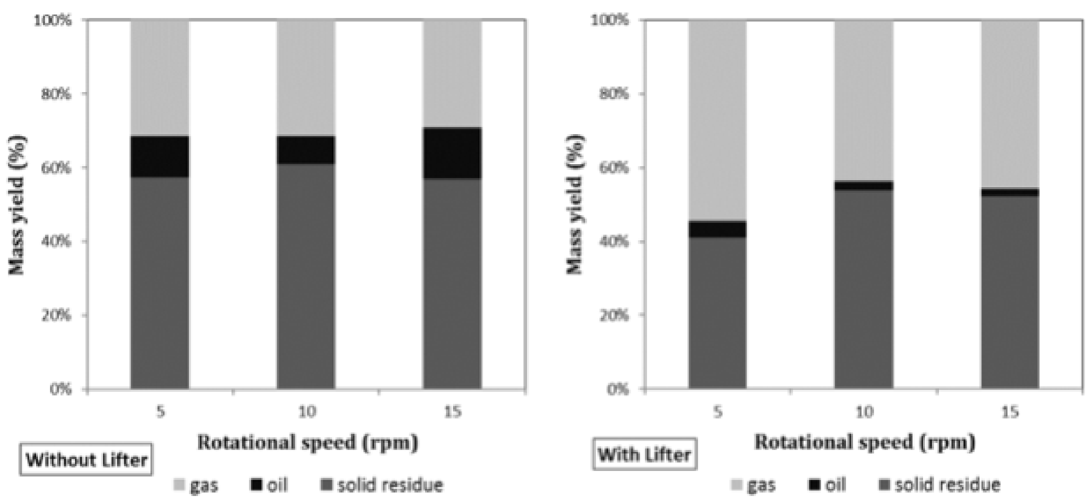

Fig. 13. (a) effect of rotational speed (without lifter) and (b)the lifter presence of the product distribution at the temperature of 300 ℃ [22]

4.4 Residence time

As the vapour residence time extends, there's a concurrent reduction in liquid and char yields, accompanied by a slight increase in gas yield. This effect emerges due to the decomposition of specific oil vapour into secondary permanent gases. The process begins with forming primary vapours through tire pyrolysis at the optimal temperature. Subsequently, these primary oil vapours transform secondary gases. As an illustration, this process encompasses the transformation of oil vapours into a combination of heavy hydrocarbons and light hydrocarbons

JRTE©2023

($CH_4 + C_2H_4 + C_3H_6 + \ldots$), in addition to the generation of gases, including CO, CO_2, H_2. This transformation leads to a decrease in oil content and an increase in gaseous products. Furthermore, the prolonged interaction between volatiles and char facilitates another concurrent secondary pyrolysis reaction that reduces the char yield. Moreover, Table 1 presents a typical tire composition. Given the diverse range of tire manufacturers and their distinct formulations, the yield and composition of waste tire pyrolysis are inherently influenced by the source and quality of the tires used[16].

4.5 Thermogravimetry and Differential Thermogravimetry

Thermogravimetry (TG) and differential thermogravimetry (DTG) represent highly potent and efficient methodologies for ascertaining fuel combustion profiles. Given the characteristic of tires possessing remarkably low thermal conductivity, it is advisable to utilize TG with a heating rate not exceeding 20 ◦C/min. This precaution is necessary because, at higher heating rates, the actual temperature of the sample can deviate significantly from the measured temperature due to the unique thermal properties of tires[28],[25]. As depicted in Fig. 14, the TG and DTG curves for waste tire samples provide valuable insights. The TG curve demonstrates that the thermal decomposition of the sample occurs within the range of 200–500 ◦C. In parallel, the DTG curve reveals the presence of three distinct phases in the thermal decomposition process of the sample. The first phase unfolds between 200–350 ◦C, representing the devolatilization of additives like extender oils, stearic acid, and similar components. The second phase of thermal decomposition transpires within the temperature range of 350–420 ◦C, primarily corresponding to the decomposition of NR (natural rubber). Finally, the third phase occurs in the temperature range of 420–500 ◦C, aligning with the decomposition of SBR (styrene-butadiene rubber) and BR (butadiene rubber). Notably, there is no discernible change in the mass of the solid sample residue throughout the temperature range spanning from 500–750 ◦C[25].

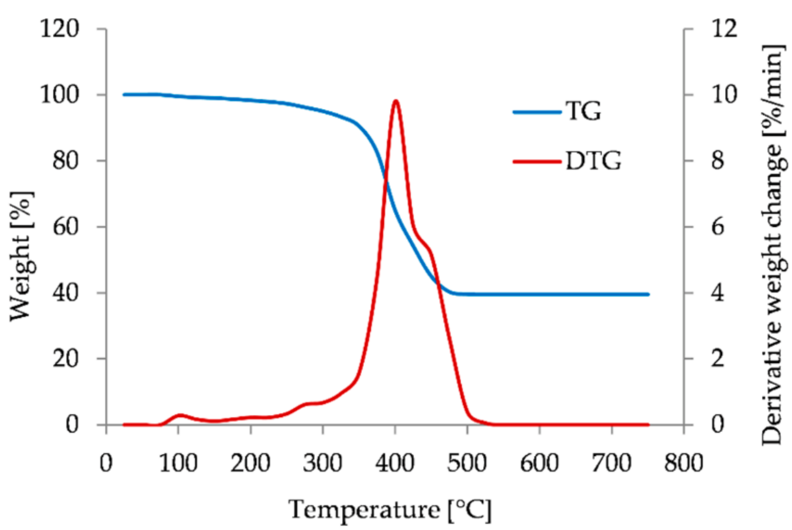

Fig. 14. The waste tire's TG and DTG curves[25]

5 MATERIALS

The composition of tires exhibits variability influenced by factors such as tire grade, age, and manufacturer. Radiant Renewable Energy Ltd. sources used tires locally from suppliers dealing

JRTE©2023

with discarded materials. The specialized team encountered used tires from 20 brands in the plant yard, as outlined in Table 1[6].

Table 1. Tire brands were discovered in the pyrolysis plant yard of Radiant Renewable Energy Ltd.[6]

SI No.	Tire brands	Tire types	Country of origin	SI No.	Tire brands	Tire types	Country of origin
1	Dunlop	Truck/bus and car	Japan	11	Pioneer	Truck/bus and car	China
2	Bridgestone	Truck/bus and car	Japan	12	Kendoa radial	Truck/bus and car	China
3	Continental	Truck/bus and car	Great Britain	13	GAJAH TUNGGAL	Truck/bus and car	Indonesia
4	Goodyear	Truck/bus and car	South Africa	14	MAXXIS	Truck/bus and car	Taiwan
5	Courier	Truck/bus and car	Italy	15	DEESTONE	Truck/bus and car	Thailand
6	Michelin	Truck/bus and car	Italy	16	Road star	Car	Bangladesh
7	Eurotour	Truck/bus and car	Korea	17	Gazi	Car	Bangladesh
8	MRF	Truck/bus and car	India	18	HT super	Car	Bangladesh
9	XPL	Truck/bus and car	India	19	HT army	Car	Bangladesh
10	Birla	Truck/bus and car	India	20	MUSAFIR	Autorickshaw	Bangladesh

Tires contain vulcanized rubber (60-65 wt.%) and carbon black(25-35 wt.%). The remaining comprises accelerators, fillers including non-homogenous distributions of carbon black, steel, sulphur, zinc oxide, processing oil, and vulcanization accelerators [8], reinforcing textile cords, fabric belts, steel wire reinforcing beads, etc., which are added during manufacturing[29]. The compositions vary depending on the application, manufacturer, etc. For example, the rolling friction is high in vehicles, so additives that reduce the rolling friction are added to the components used to prepare tires. The essential parts of tires are synthetic rubber or natural rubber, wire, fabric, tread, carcass, sidewall, shoulder, bead, bead wire, bead filler, and liner[29], as shown in Fig. 15 and the continent, the material of them is in table 2[30].

JRTE©2023

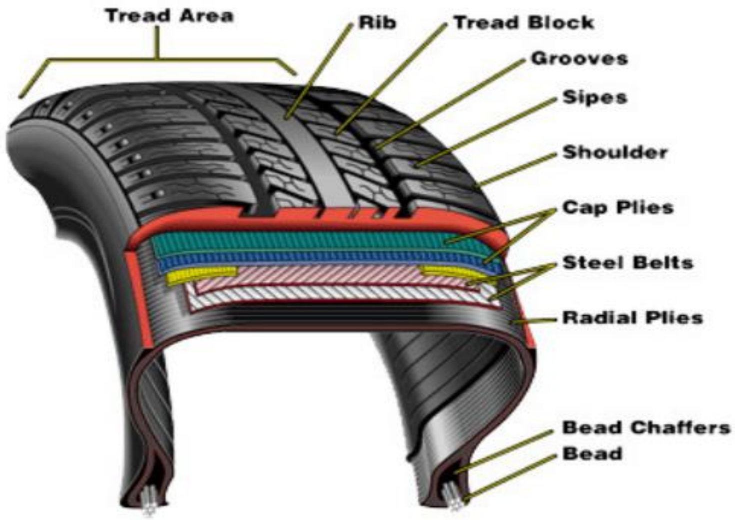

Fig. 15. Components that make up a tire [30]

Table 2. Typical tire elements and their constituent materials [30]

Element	Composition
Liner	Inner coating of synthetic rubber
Plies	Layers of rubber, nylon and metal reinforced rubber piled together
Bead heel	Ringed steel wires surrounded by hard rubber
Sidewall	Natural and synthetic rubber mixed with small amounts of carbon black and additives
tread	Natural and synthetic rubber

Tires are characterized using proximate and ultimate (elemental) analyses. Depending on the specific literature's intention, the tire's calorific values can also be included[30]. As shown in Table 3 and Table 4, the proximate and ultimate analyses of some tires in the literature.

Table 3. Typical approximate analysis of a waste tire

Component (wt.%)	Literature source		
	Qiang Yao et al. [31]	Choi et al. [32][a]	Williams et al. [33]
Moisture	1.14		0.8
Volatile matter	62.24	73.9± 0.66	66.5
Fixed carbon	32.28	21.8± 0.6	30.3
Ash	4.35	4.3± 0.07	2.4
Steel			
Calorific value (MJ/Kg)	34.9		40.0

[a]dry basis

Table 4. Typical ultimate analysis of a waste tire

Element (wt.%)	Literature source		
	Qiang Yao et al. [31]	Choi et al. [32][a]	Williams et al. [33]
C	84.08	89.2±0.00	85.9
H	6.71	7.7± 0.01	8.0
N	0.49	0.5± 0.02	0.4
S	1.51	2.6± 0.08	1.0
O	1.73		2.3
ASH			2.4

[a]dry and ash-free basis.

Truck tires (TT) generally contain more natural rubber than passenger car tires (PCT), and the amount of added compound can vary from region to region, as shown in Table 5 [30].

Table 5. shows the typical composition of passenger and truck tires [30].

Material(wt.%)	PCT		TT	
	USA	EU	USA	EU
Natural rubber	14	22	27	30
Synthetic rubber	27	23	14	15
Carbon black	28	28	28	20
Steel	14-15	13	14-15	25
others[a]	16-17	14	16-17	10

fillers, accelerators, Nylon, and sulphur, among others.

composition with some characteristics is 19% Natural rubber, usually from trees in Southeast Asia. 38% Synthetic rubber (butadiene, styrene, halo butyl rubber) and additives to prevent damage from ozone and oxygen and to promote curing, 4% synthetic- -polymer fabric belts (Nylon, rayon, and aramid) for reinforcement, 12% Wire (high-carbon steel), for more reinforcement 26% Fillers (carbon black, silica) [34].The waste tires are a better material for Pyrolysis due to the obtained values stated by others [35],[36],[37],[25]. Plus, the tested sample's GCV was 32 MJ/kg, which is higher compared to the calorific value of biomass or the calorific value of most coals [38],[39] exploring the possibilities of producing energy from waste tires are worthy for the future[25].

6 PRODUCT ANALYSIS

The market of pyrolysis products will govern the method used for the process for this characterization of pyrolysis products, and the possibilities of their application in other processes are essential [15]. The general analysis of products is given in Table 10.

6.1 Pyrolysis oil

The main product from waste tire recycling pyrolysis plant is pyrolysis oil, which usually has a yield of 40-50%, [40]with the density of the Pyrolysis of the waste tire is in the range of 0.79-

JRTE©2023

0.94 g/cm3 as It is shown in table 6. Density determines the energy content in the fuel per unit of the same volume. According to Indonesian standards for diesel fuel, the density values are 0.815-0.870 g/cm3 for diesel fuel. In general, most of the pyrolysis oil of waste tire are in that range[22].

The heating value is the most important parameter in the Pyrolysis of waste tires into alternative fuels. This parameter describes the energy content present in the fuel. The amount of calorific value of WTPO can be seen in Table 7 compared with other fuels. It can be seen that the heating value of WTPO was still lower than diesel fuel and plastic pyrolysis oil. However, the value was higher than bio-oil from bagasse[22]. It can be seen that the viscosity of WTPO is in the range of 0.79 – 6.50 cSt. Based on the standards of diesel fuel in Indonesia, the viscosity values are in the field of 2.0 – 5.0 cSt for diesel, as shown in Table 6.

Table 6.density of liquid oil produced from Pyrolysis of waste tire [22]

Property		**Rotational speed (RPM)**		
		5	10	15
Density (g/cm^3)	Without lifter	0.94	0.86	0.85
	With lifter	0.83	0.86	0.79
Viscosity (cSt)	Without lifter	1.39	2.63	1.55
	With lifter	2.94	6.50	0.79

Table 7.The heating value of WTPO and other fuels. Fuel

Fuel	**Heating value (MJ/Kg)**	**Reference**
WTPO	32.43	[22]
Plastic pyrolysis oil	44.00-46.00	[22]
Diesel fuel	41.45-46.67	[6]
Bio-oil from bagasse	23.50	[6]

Applications: Given the rising cost of oil and the difficulty in reducing emissions, there are several possible uses for the liquids produced by tire pyrolysis[26]. Product applications are shown in Fig. 16. Pyrolytic oil is a mixture of parafins, olefins, and aromatic compounds that can be used directly as fuel or added to petroleum refinery feedstocks [18].

JRTE©2023

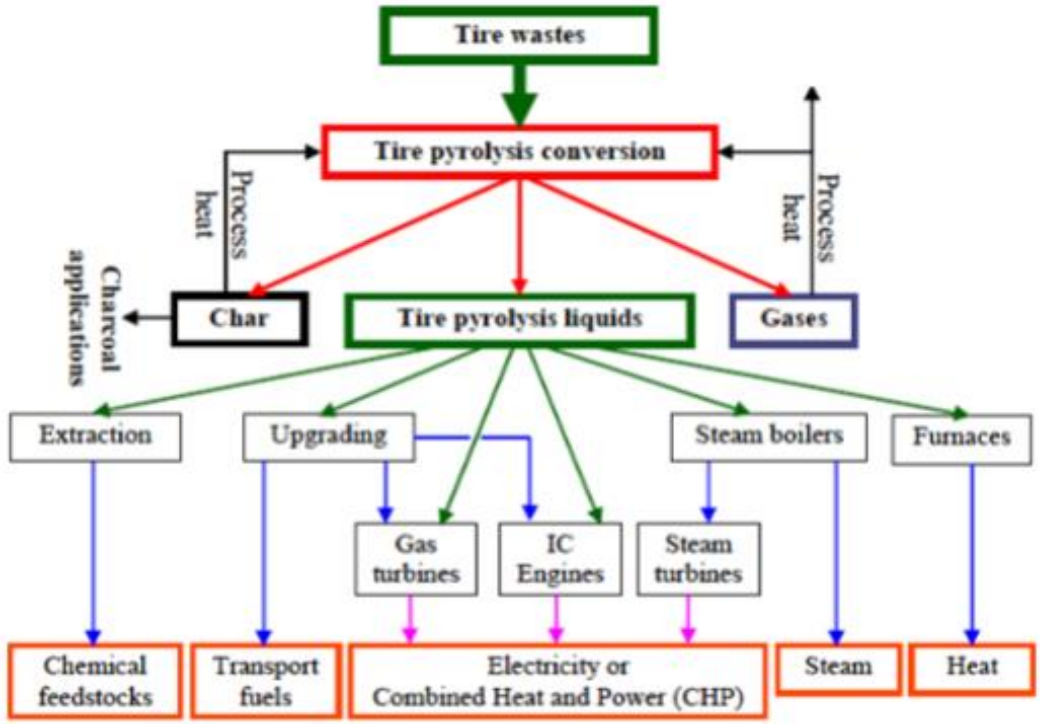

Fig. 16. tire pyrolysis conversion and product applications [26]

6.2 Activated carbon

Activated carbon derived from pyrolytic char finds versatile applications, including water purification and air filtration. Moreover, it serves purposes in batteries and fuel cells. The calorific value of pyrolytic char is comparable to high-grade coal, making it suitable for use as fuel in pulverized or briquette forms. The potential use of pyrolytic char as low-grade carbon black for thermoplastics manufacturing and as an economical adsorbent for treating industrial effluents has also been proposed. Activated carbon can adsorb substances such as metals, phenols, p-chlorophenols, butane, basic dyes, and natural gas. Studies have explored carbon black's production, characterization, and applications, including its role as a base for printing ink and a filler for recycled tires[16].

Carbon black: Carbon black from Pyrolysis is much more economical with respect to carbon black from petroleum. It is more price-efficient to be used as an ingredient in industries such as Electric cable jacketing, Conveyor bands, Carrier Bands, Hose and doormats, Black nylon bags, Rubber additives, Automotive spare parts, Heat isolation, Black colourant in rubber material[15].

Table 8: Element analysis of carbon black [15]

Weight %	**Element**
71	Carbon
13.3	Oxygen
5.4	Iron
2.8	Sulphur
2.3	Zinc
1.3	Calcium

JRTE©2023

0.3	Aluminium

6.3 Gas

Through gas chromatography analysis, the gaseous fraction amounts to approximately 10 – 15 wt%[6]. The primary constituents of pyrolysis gas encompass alkane, alkene, benzene, methylbenzene, xylene, hydrogen, nitrogen, carbon monoxide, carbon dioxide, and hydrogen sulphide. The gas distribution primarily comprises ethylene, propylene, butane, and isobutene. Except for hydrogen and methane, the predominant components are primarily C2, C3, and C4 compounds. Due to its consistent quality and minimal sulphur content, pyrolysis gas finds direct applicability as an industrial and household fuel. The heating value of pyrolysis gas is akin to that of natural gas, rendering it suitable for steam or turbine-based power generation applications.[38]. As shown in Table 9, it increases with increasing pyrolysis temperature. The pyrolysis-derived gas has a calorific value of approximately 30-40MJ N/m^{-3} [41],[18] and can be sufficient to provide the energy required for a small-scale process plant. The carbon oxide components (CO_x) predominantly arise from the oxygenated organic compounds in tires, including substances like stearic acid and extender oils. Hydrogen sulphide (H_2S) is a byproduct of the decomposition of sulphur-containing links within the vulcanized rubber structure, and its concentration tends to be low. Notably, the most significant gas products are C4 and >C4, originating from styrene-butadiene rubber (SBR) depolymerization. For a comprehensive view of the gas composition resulting from tire pyrolysis at varying temperatures (400, 500, 600, and 700°C), please refer to Fig. 17 [16].

Table 9. Pyrolysis gas constituents [16]

Component	Component
Carbon monoxide	CO
Carbon dioxide	CO_2
Hydrogen sulphide	H_2S
Methane	CH_4
Ethane	C_2H_6
Ethene	C_2H_4
Propane	C_3H_8
Propene	C_2H_6
Butane	C_4H_{10}
Butene	C_4H_8
Butadiene	C_4H_6
Pentane	C_5H_{12}
Pantene	C_5H_{10}
Hexane	C_5H_{14}
Hexene	C_6H_{12}

JRTE©2023

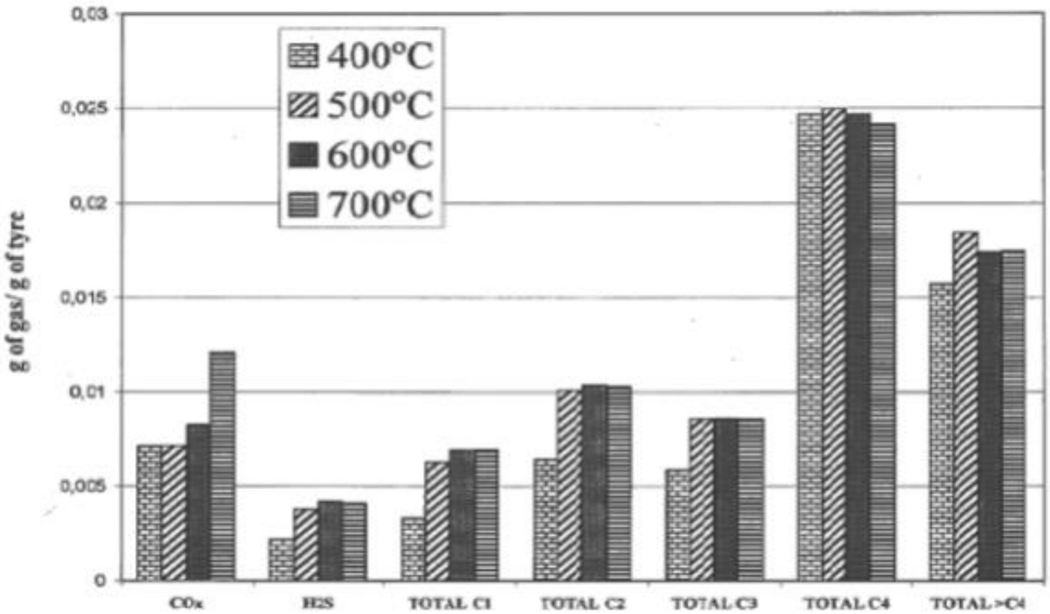

Fig. 17. Gaseous product distribution with temperature [16]

6.4 *Steel*

The pyrolysis-derived steel wire marketing depends on the product's cleanliness, quantity, and packaging. The cleanliness of the reclaimed steel is evaluated based on the extent of rubber contamination. Steel containing less than 10% rubber content is deemed acceptable within the market standards[16].

Table 10. production rate when using the following materials [13],[15]

Material	Item	Fuel Oil	Steel Wire	Carbon black	Combustible gas
Tires	truck tires	45%-50%	15%-20%	30%	5%-10%
	car tires	40-45%	10%-15%	40%	5%-10%
	motorbike bike tires	30%-35%	5%-10%	10%	5%-10%

Venturing into the waste tire pyrolysis machinery sector can yield profitable returns. Assessing the advantages involves considering various factors, such as equipment expenses, raw material costs, shipping expenses, and the selling price of the end products[42]. The basic parameters for the pyrolysis plant and Analysis of the BLJ-6 Pyrolysis Plant To Process Waste Tyres are shown in Tables 11 and 12, respectively.

Table 11. Basic Parameter of Beston Pyrolysis Plant [13]

Model	BLJ-3	BLJ-6	BLJ-10	BLJ-16	BLL-16		BLL-30
Capacity	1-3t/d	4-6t/d	8-10t/d	12-16t/d	8t/d (only for rubber powder)		30-35t/d
Working Process	Batch	Batch	Batch	Batch	Semi-continuous		Fully continuous
Reactor Size	φ1400*4900mm	φ2200*6000mm	φ2600*6600mm	φ2800*7100mm	φ2800*7100mm		φ1800*18500mm
Reactor Material	Q245R	Q245R	Q245R	Q245R	Q245R		310S stainless steel
Drive System	350 reducer+4kw drive motor	400 reducer+5.5kw drive motor	400 reducer+5.5kw drive motor	500 reducer+7.5kw drive motor	500 reducer+7.5kw drive motor		ZQH650-50 reducer+15kw frequency conversion motor
Land (L*W*H)	18m*4.2m*6m	30m*12m*8m	30m*13m*8m	33m*13m*8m	33m*13m*8m		70m*20m*10m
Power	16.65kw	37.85kw	44.3kw	55.6kw	55.6kw		256kw
Burner	2*200,000 kcal	2*300,000 kcal	2*300,000 kcal	2*400,000 kcal	2*400,000 kcal		2.5 million kcal per set
Total Weight of Shipped Materials	About 18t	About 24.5t	About 28t	About 34.5t	About 34.5t		About 150t
Number of Containers	1*40HQ	1*40FR+1*40HQ+1*20 GP	1*40FR+2*40HQ	1*40FR+2*40HQ	1*40FR+2*40HQ		25m*8m bulk cargo+8*40HQ
Noise (dB)	≤60	≤60	≤60	≤60	≤60		≤60
Heating Materials	Fuel oil (including tire/plastic pyrolysis oil), natural gas, LPG, diesel, etc.						
Condensing System	Vertical Condenser	φ426*3000 Single-piece condensing area 7.58m2	φ630*3600 Single-piece condensing area 17.8m2	φ630*3600 Single-piece condensing area 17.8m2	φ820*3600 Single-piece condensing area 35.6m2	φ820*3600 Single-piece condensing area 35.6m2	φ920*3200 Two sets of vertical condensers
	3-in-1 Condenser	3000*2200*2250 Condensing area 17.51m2	5800*2260*2500 Condensing area 35.85m2	5800*2260*2500 Condensing area 35.85m2	8000*2260*2500 Condensing area 49.5m2	8000*2260*2500 Condensing area 49.5m2	

Table 12. Analysis of BLJ-6 Pyrolysis Plant for Waste Tire Processing[43]

Items	Unit	Consumption	Unit price	Total
Material	Tyre	6MT/Day	$46/MT	
Fuel	Pyrolysis oil	100kg/Day	$0/kg	
Electricity Pyrolysis	42.4KW (70%)	18Hour	$0.14/KWH	Daily consume 534kwh
Labour	6 person	1 day	$15/person/day	
Pyrolysis oil	45% oil yield	2.7MT	$410/Ton	
Carbon black	30% yield	1.8MT	$50/Ton	
Steel wire	15% yield	0.9MT	$150/Ton	
Daily Input				
Items	**Unit**	**Consumption**	**Unit price**	**Total**
Tyre	Ton	6	$46.00	$276.00
Pyrolysis oil	KG	100	$0.00	$0.00
Electricity Pyrolysis	KWH	534	$0.14	$74.76
Labour	Person	6	$15.00	$90.00
Total				**$440.76**
Daily Output				
Items	**Unit**	**Consumption**	**Unit price**	**Total**
Pyrolysis oil	Ton	2.7	$410.00	$1,107.00
Carbon black	Ton	1.8	$50.00	$90.00
Steel wire	Ton	0.9	$150.00	$135.00
Total				**$1,332.00**
Daily Profits				
Output – Input	$891.24			
Month Profits (25 working days)		$22,281.00		
Annual (10 Months)		$222,810.00		

7 CHALLENGES AND FUTURE DEVELOPMENTS

To ensure optimal operation and further expansion of the plant, as well as a commitment to environmental safety, the following guidelines should be rigorously followed: 1. Thorough Cleaning of Solid Tire Wastes: Solid tire wastes must undergo thorough cleaning before loading into the reactor. This practice maintains product liquid quality and minimizes emissions from the plant.2. Manage Excess Gaseous Products: Prevent the release of excess gaseous products into the atmosphere. Consider storing surplus gas in containers for controlled combustion in the furnace or for supplying to local communities as a cooking fuel. 3. Closed Handling and Transportation: Product liquid, char handling, and transportation should occur within closed conduits/systems to minimize environmental impact. 4. Environment-Friendly Diesel Production: Incorporate demister filters and wet scrubbers with CaOH/NaOH columns to ensure eco-friendly alternative diesel production from tire wastes. Their operation requires meticulous monitoring.5. Chimney Design Compliance: Adhere strictly to the standard design of the chimney to ensure safe exhaust of flue gas into the atmosphere.6. Wastewater Treatment: Thoroughly treat and dispose of plant-generated wastewater sincerely and responsibly.7. Regular Inspection of Mountings: Conduct routine inspections of plant mountings and promptly replace them as needed for safer plant operation.8. Enhance Sustainability: Focus on upgrading liquid products and optimizing char utilization to ensure the long-term sustainability of the technology.9. Skilled Operators: Employ operators with expertise in tire pyrolysis to ensure efficient plant operation.10. Monitor Sulfur and Chlorine Content: Regularly check solid tire waste's sulphur and chlorine content biannually. This practice aids in controlling SOx and dioxin emissions from the plant, plus sulphur and chlorine-containing compounds in the liquid and char products.11. Location Considerations: As the plant is populated, consider the challenges of further expanding operations in the exact location.12. Continuous Monitoring and Consultancy: Recognize that due to the involvement of new technology and waste material concerns, the plant requires continuous monitoring and specialized tire pyrolysis team support for effective and safe operation. By diligently following these guidelines, the waste tire pyrolysis plant can uphold efficient and responsible operation, prioritize environmental safety, and contribute to the surrounding community's well-being. [6].Uneven temperature distribution and hysteresis in rotary kiln reactors create challenges, leading to suboptimal Pyrolysis of waste tires. This produces tire char with higher volatile matter, ash, and sulphur content. The rotational movement of the reactor causes uneven heating, hindering complete decomposition. Addressing these issues through improved heating techniques and uniform temperature conditions can enhance pyrolysis efficiency, yielding char with reduced impurities and improved quality [17],[44].

The studies found no recommendable pyrolysis conditions as they vary from author to author, making it difficult for industrial application. The major drawback of Pyrolysis is the poor quality of the products. The char produced is a heterogeneous material with high ash content, poor particle size, absorption properties, structure, surface chemistry and activity. It cannot be sold as carbon black or activated carbon, affecting the economic feasibility of tyres. On the other hand, the oil produced is composed mostly of heavy cyclic olefins, not attractive enough to be sold as high-value fuel. However, much of the current research is focused on producing activated carbon

JRTE©2023

and carbon black, upgrading pyrolysis oil, and maximizing the limonene concentration in the pyrolysis oil to improve the industrial viability of waste tyre pyrolysis. [44].

Hita et al.[45] explored the challenges of the liquid product of Pyrolysis that prevent the direct use of Pyrolysis is listed below: (1) contain a very high sulphur content, (2) high content of aromatic hydrocarbons, and (3) a great proportion of molecules with similar boiling point range (BP of 350 ◦C). This means waste tire pyrolysis oil requires major upgrading before use. The methods used for upgrading the oil suggested were hydro-cracking (HC), hydrodesulfurization (HDS), and hydrodearomatization (HAD). Therefore, studies on Pyrolysis have moved to investigate methods of upgrading the oil during and as additional treatment steps.

8 CONCLUSION

In this review, full attention was given to the rotary kiln pyrolysis process, its parameters and the product's characteristics with their yield according to mentioned details. Truck tires are producing more oil, around 45% to 50%, which is more with respect to car and motorbike tires. The oil is not in standard condition, making it difficult to use in industries by the time it is produced, even though it has the higher calorific value than the other waste type generation, which was 32 MJ/kg. Plus, there are many gaps in the field due to temperature, particle size, used conditions, and their effect on yield. This literature review has gone through the rotary kiln reactor with its components, the effecting factor for that, the materials, the product analysis with their application, challenges, and what needs to be maintained in the process have been mentioned.

9 REFERENCES

[1] B. E. Rogachuk and J. A. Okolie, "Waste tires based biorefinery for biofuels and value-added materials production," *Chem. Eng. J. Adv.*, vol. 14, no. March, p. 100476, 2023, doi: 10.1016/j.ceja.2023.100476.

[2] D. Mmereki, B. Machola, and K. Mokokwe, "Status of waste tires and management practice in Botswana," *J. Air Waste Manag. Assoc.*, vol. 69, no. 10, pp. 1230–1246, 2019, doi: 10.1080/10962247.2017.1279696.

[3] "The merits of tyre pyrolysis | Engineer Live." https://www.engineerlive.com/content/merits-tyre-pyrolysis (accessed Jul. 18, 2023).

[4] G. Chen *et al.*, "Pollutants formation, distribution, and reaction mechanism during WT pyrolysis: A review," *J. Anal. Appl. Pyrolysis*, vol. 157, no. January, p. 105218, 2021, doi: 10.1016/j.jaap.2021.105218.

[5] Q. Z. Wang, N. N. Wang, M. L. Tseng, Y. M. Huang, and N. L. Li, "Waste tire recycling assessment: Road application potential and carbon emissions reduction analysis of crumb rubber modified asphalt in China," *J. Clean. Prod.*, vol. 249, 2020, doi: 10.1016/j.jclepro.2019.119411.

[6] M. R. Islam, M. N. Islam, N. N. Mustafi, M. A. Rahim, and H. Haniu, "Thermal recycling of solid tire wastes for alternative liquid fuel: the first commercial step in Bangladesh," *Procedia Eng.*, vol. 56, pp. 573–582, 2013, doi: 10.1016/j.proeng.2013.03.162.

JRTE©2023

[7] E. B. Machin, D. T. Pedroso, and J. A. de Carvalho, "Energetic valorization of waste tires," *Renew. Sustain. Energy Rev.*, vol. 68, no. September 2016, pp. 306–315, 2017, doi: 10.1016/j.rser.2016.09.110.

[8] A. Ayanoɪlu and R. Yumrutaş, "Rotary kiln and batch pyrolysis of waste tire to produce gasoline and diesel like fuels," *Energy Convers. Manag.*, vol. 111, pp. 261–270, 2016, doi: 10.1016/j.enconman.2015.12.070.

[9] J. Ma, Q. Zhong Advisor, N. J. Themelis, and A. C. Bourtsalas, "Comparison of Operating Pyrolysis Processes in China," no. December, 2018.

[10] H. B. Tosun, "Production and characterisation of waste tire pyrolytic oil – Investigating physical and rheological behaviour of pyrolytic oil modified asphalt binder," *Heliyon*, vol. 9, no. 1, p. e12851, 2023, doi: 10.1016/j.heliyon.2023.e12851.

[11] K. Frikha *et al.*, "Potential Valorization of Waste Tires as Activated Carbon-Based Adsorbent for Organic Contaminants Removal," *Materials (Basel).*, vol. 15, no. 3, pp. 1–24, 2022, doi: 10.3390/ma15031099.

[12] "What is pyrolysis?__Waste Tire/Plastic Pyrolysis Plant." https://www.wastetireoil.com/Pyrolysis_faq/Pyrolysis_Plant/pyrolysis_plant_351.html (accessed Jul. 25, 2023).

[13] "Pyrolysis Plant | Factory Price from Top Manufacturer." https://bestonmachinery.com/pyrolysis-plant/ (accessed Jul. 26, 2023).

[14] "Components of Pyrolysis Plant - Beston Group's." https://www.bestongroup.com/components-of-pyrolysis-plant/ (accessed Jul. 20, 2023).

[15] B. Hills, "Technical proposal for 10TPD Scrap Tire Processing Unit," no. 10.

[16] N. Nkosi and E. Muzenda, "A review and discussion of waste tyre pyrolysis and derived products," *Lect. Notes Eng. Comput. Sci.*, vol. 2, pp. 979–985, 2014.

[17] N. Gao, F. Wang, C. Quan, L. Santamaria, G. Lopez, and P. T. Williams, "Tire pyrolysis char: Processes, properties, upgrading and applications," *Prog. Energy Combust. Sci.*, vol. 93, no. June, p. 101022, 2022, doi: 10.1016/j.pecs.2022.101022.

[18] S. Q. Li, Q. Yao, Y. Chi, J. H. Yan, and K. F. Cen, "Pilot-scale pyrolysis of scrap tires in a continuous rotary kiln reactor," *Ind. Eng. Chem. Res.*, vol. 43, no. 17, pp. 5133–5145, 2004, doi: 10.1021/ie030115m.

[19] "What is a pyrolysis rotary kiln reactor and what are its advantages?_Waste Tyre Recycling Pyrolysis Plant." https://www.recyclingpyrolysisplant.com/FAQ/pyrolysis_plant/pyrolysis_rotary_kiln_reactor_860.html (accessed Jul. 25, 2023).

[20] "temperature and pressure requirement during the operation of waste tire pyrolysis plant?_Pyrolysis machine FAQ." https://www.doinggroup.com/index.php?u=show-2152.html (accessed Sep. 07, 2023).

[21] "Pyrolysis Plant Design ." https://plasticpyrolysisplants.com/plastic-pyrolysis-reactor-design/ (accessed Aug. 27, 2023).

JRTE©2023

[22] M. Syamsiro, M. S. Dwicahyo, Y. Sulistiawati, M. Ridwan, and N. Citrasari, "Development of a rotary kiln reactor for pyrolytic oil production from waste tire in Indonesia," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 245, no. 1, 2019, doi: 10.1088/1755-1315/245/1/012044.

[23] "What is approximate temperature in tyre pyrolysis reactor?_Waste Tyre Recycling Pyrolysis Plant." https://www.recyclingpyrolysisplant.com/FAQ/pyrolysis_plant/approximate_temperature_tyre_pyrolysis_reactor_861.html (accessed Jul. 25, 2023).

[24] D. T. Dick, O. Agboola, and A. O. Ayeni, "Pyrolysis of waste tyre for high-quality fuel products: A review," *AIMS Energy*, vol. 8, no. 5, pp. 869–895, 2020, doi: 10.3934/ENERGY.2020.5.869.

[25] Z. Čepić *et al.*, "Experimental analysis of temperature influence on waste tire pyrolysis," *Energies*, vol. 14, no. 17, 2021, doi: 10.3390/en14175403.

[26] J. L. Kenna, "Innovation in Pyrolysis Technology for Management of Scrap Tire: a Solution of Energy and Environment," *J. Soc. Stud. Educ. Res.*, vol. 10, no. 3, pp. 1–16, 2010.

[27] M. F. Laresgoiti, I. De Marco, A. Torres, B. Caballero, M. A. Cabrero, and M. J. Chomón, "Chromatographic analysis of the gases obtained in tyre pyrolysis," *J. Anal. Appl. Pyrolysis*, vol. 55, no. 1, pp. 43–54, 2000, doi: 10.1016/S0165-2370(99)00073-X.

[28] J. Wnorowska, S. Ciukaj, and S. Kalisz, "Thermogravimetric analysis of solid biofuels with additive under air atmosphere," *Energies*, vol. 14, no. 8, 2021, doi: 10.3390/en14082257.

[29] N. Kapilan, K. A. Kumar, and B. P. H. Chandra, "Studies on pyrolysis oil derived from waste tires as fuel for diesel engine," *J. Phys. Conf. Ser.*, vol. 2070, no. 1, 2021, doi: 10.1088/1742-6596/2070/1/012232.

[30] L. Mulaudzi, "Process modelling and economic evaluation of waste tyres to limonene via pyrolysis," no. December, p. 218, 2017.

[31] S. Q. Li, Q. Yao, S. E. Wen, Y. Chi, and J. H. Yan, "Properties of pyrolytic chars and activated carbons derived from pilot-scale pyrolysis of used tires," *J. Air Waste Manag. Assoc.*, vol. 55, no. 9, pp. 1315–1326, 2005, doi: 10.1080/10473289.2005.10464728.

[32] G. G. Choi, S. H. Jung, S. J. Oh, and J. S. Kim, "Total utilization of waste tire rubber through pyrolysis to obtain oils and CO2 activation of pyrolysis char," *Fuel Process. Technol.*, vol. 123, pp. 57–64, 2014, doi: 10.1016/j.fuproc.2014.02.007.

[33] P. T. Williams, S. Besler, and D. T. Taylor, "The pyrolysis of scrap automotive tyres. The influence of temperature and heating rate on product composition," *Fuel*, vol. 69, no. 12, pp. 1474–1482, 1990, doi: 10.1016/0016-2361(90)90193-T.

[34] Roy Berendsohn, "Our Waste Tire Problem Is Getting Worse," Aug. 14, 2017. https://www.popularmechanics.com/cars/car-technology/a22553570/waste-tires/ (accessed Jul. 18, 2023).

[35] J. F. González, J. M. Encinar, J. L. Canito, and J. J. Rodríguez, "Pyrolysis of automobile

JRTE©2023

tyre waste. Influence of operating variables and kinetics study," *J. Anal. Appl. Pyrolysis*, vol. 58, no. 59, pp. 667–683, 2001, doi: 10.1016/S0165-2370(00)00201-1.

[36] J. I. Osayi, S. Iyuke, M. O. Daramola, P. Osifo, I. J. Van Der Walt, and S. E. Ogbeide, "Evaluation of pyrolytic oil from used tires and natural rubber (Hevea brasiliensis)," *Chem. Eng. Commun.*, vol. 205, no. 6, pp. 805–821, 2018, doi: 10.1080/00986445.2017.1422493.

[37] Y. Kar, "Catalytic pyrolysis of car tire waste using expanded perlite," *Waste Manag.*, vol. 31, no. 8, pp. 1772–1782, 2011, doi: 10.1016/j.wasman.2011.04.005.

[38] G. Maj, "Emission factors and energy properties of agro and forest biomass in aspect of sustainability of energy sector," *Energies*, vol. 11, no. 6, 2018, doi: 10.3390/en11061516.

[39] K. Król and D. Nowak-Woźny, "Application of the mechanical and pressure drop tests to determine the sintering temperature of coal and biomass ash," *Energies*, vol. 14, no. 4, 2021, doi: 10.3390/en14041126.

[40] "Waste Tyre Recycling Pyrolysis Plant for sale, manufacturer of Waste Tyre Recycling Pyrolysis Plant, factory price_Waste Tyre Recycling Pyrolysis Plant low cost." https://www.recyclingpyrolysisplant.com/product/tyre-to-oil/ (accessed Jul. 25, 2023).

[41] F. Fortuna, G. Cornacchia, M. Mincarini, and V. K. Sharma, "Pilot-scale experimental pyrolysis plant: Mechanical and operational aspects," *J. Anal. Appl. Pyrolysis*, vol. 40–41, pp. 403–417, 1997, doi: 10.1016/S0165-2370(97)00026-0.

[42] "Tyre Pyrolysis Plant Project Report | Get Custom Plan." https://bestonmachinery.com/tyre-pyrolysis-plant/project-report/ (accessed Jul. 27, 2023).

[43] "Small Pyrolysis Machine - Batch Type Pyrolysis Plant." https://www.bestongroup.com/small-pyrolysis-machine/ (accessed Jul. 27, 2023).

[44] A. enkosi Mavukwana and C. Sempuga, "Recent developments in waste tyre pyrolysis and gasification processes," *Chem. Eng. Commun.*, vol. 209, no. 4, pp. 485–511, 2022, doi: 10.1080/00986445.2020.1864624.

[45] I. Hita, M. Arabiourrutia, M. Olazar, J. Bilbao, J. M. Arandes, and P. Castaño Sánchez, "Opportunities and barriers for producing high quality fuels from the pyrolysis of scrap tires," *Renew. Sustain. Energy Rev.*, vol. 56, pp. 745–759, 2016, doi: 10.1016/j.rser.2015.11.081.

JRTE©2023