

Simulation of gas condensation process from pyrolysis of used tires

Simulación del proceso de condensación de gases de la pirólisis de neumáticos usados

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Abstract

Waste tires, composed of rubber, have caused negative environmental problems. There have been problems regarding an increase in the accumulation of tires in different sectors, together with the fact that waste management methods are obsolete. These problems have awakened interest in their study and thermal degradation. Tires composed of rubber represent a material with an important potential for recycling and utilization, together with the conversion of these wastes into energy, value-added products or for the improvement of raw materials. The technique used to carry out thermal degradation is called pyrolysis and consists of heating the organic matter in the absence of oxygen at a specified rate or heating rate, up to a maximum temperature known as pyrolysis temperature, and maintaining it there for a specified time. The products of pyrolysis correspond to: liquid, condensable gases and solid char or ash; for its part, the condensable gas can be further decomposed into non-condensable gases ([CO, CO₂, H₂ and CH₄), liquid and char. This work aims to contribute with the design and simulation of the condensation cycle of the gases obtained from pyrolysis. Particularly, for the condensation of these gases, the ASPEN HYSYS process simulator was used, where the adaptation of a shell and tube heat exchanger allowed to carry out the condensation. The feed containing these gases comes from tests in a pyrolytic reactor with favorable results. As a result of this condensation and the operating conditions, it is observed that, for a range between 80 and 90 °C, the condensation of gases such as i-Butene and Propylene is favored. This study aims to take up existing research in this area and make a proposal for the condensation of pyrolysis gases, generating an idea of the feasibility and recovery of tire waste with a circular economy approach.

Resumen

Los neumáticos de desecho, compuestos por caucho, han causado problemas ambientales negativos, se han registrado problemáticas respecto a un aumento en la acumulación de llantas en diferentes sectores aunado a que los métodos de gestión de los residuos son obsoletos. Estos problemas han sido tan evidentes que han despertado el interés para su estudio y la degradación térmica de estos mismos. Las llantas compuestas por caucho representan ser un material con un potencial importante para el reciclaje y su aprovechamiento, aunado a la conversión de estos desechos en energía, productos de valor agregado o para la mejora de materias primas. La técnica por la cual se lleva a cabo esta degradación térmica se denomina pirólisis y consiste en calentar la materia orgánica en ausencia de oxígeno a una velocidad especificada o tasa de calentamiento, hasta una temperatura máxima conocida como temperatura de pirólisis, y mantenerla allí durante un tiempo especificado. Los productos de la pirólisis corresponden a: líquido, gases condensables y carbón sólidos o ceniza; por su parte, el gas condensable puede descomponerse aún más en gases no condensables (CO, CO₂, H₂ y CH₄), líquido y carbón. Este trabajo tiene como objetivo contribuir con el diseño y simulación del ciclo de condensación de los gases obtenidos de la pirólisis. Particularmente, para la condensación de estos gases, se emplea el simulador de procesos de ASPEN HYSYS en donde se realiza la adaptación de un intercambiador de calor de tubo y coraza que permitirá llevar a cabo la condensación. La alimentación que contiene a estos gases es proveniente de pruebas en un reactor pirólítico con resultados favorables. Resultado de esta condensación y de las condiciones de operación se observa que, para un rango entre 80 y 90 °C, se favorece la condensación de gases como lo son el *i-Buteno* y el *Propileno*. Este estudio pretende retomar las investigaciones existentes en este rubro y realizar una propuesta para la condensación de los gases de pirólisis, generando una idea de la viabilidad y la valorización de residuos de llantas con un enfoque de economía circular.

Recycling, Waste, Tires, Pyrolysis, Condensation

Reciclaje, Residuos, Llantas, Pirólisis, Condensación

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Introduction

Tires composed of rubber are materials with a growing negative environmental impact, both for the city of Bogotá and for the country itself; according to the statements of Cardona-Gómez and Sánchez-Montoya [1], 1% of the total waste generated in Colombia comes from rubber. In the work carried out by Castillo-Viveros and Simancas-Robles [2] it is highlighted that, in the City of Bogotá, there have been problems regarding an increase in the accumulation of tires in different sectors and their final disposal. Furthermore, in 2016, Durán [3] states that around 30 million tires were discarded in the country and, particularly in Bogotá, an estimated 4 million in that year alone. Rubber waste is a major global concern, due to its slow decomposition, which is estimated that outdoors this process takes between 500 and 3000 years [2]. Waste management methods are obsolete, based on combustion or accumulation in landfills, clandestine deposits, residential yards or even public spaces, also due to the high elasticity of tires that impairs their compaction.

The increase in vehicle use has accumulated thousands of tons of waste, which can cause the accumulation of gases that can lead to fires, generation and spread of pests and diseases that represent a risk to public health. Therefore, rubber tires used in automobiles are an excellent example of a material that, although historically is not biodegradable, its main components are rubber (a cross-linked styrene-butadiene), steel cords and other organic and inorganic compounds [4].

These represent a material with an important potential for recycling and utilization. Likewise, the conversion of these wastes into energy, value-added products or for the improvement of raw materials, should be a sustainable way that allows the best use of these wastes and thus, they go from being a waste or a problem to a product with a particular interest attached to the regulations in force.

The Colombian state through Resolution No. 1457, issued on July 29, 2010, establishes that some subsectors use used tires as fuel in their production processes, but this inadequately, others burn them in the open air for the extraction of steel, one of the components of tires, this is a polluting source for the atmosphere and also for human health.

In addition to the above, this resolution aims to properly manage the waste from used tires, highlighting the responsibility of manufacturers and producers of these and emphasizing that it is a task that requires awareness campaigns, both manufacturers and people who have a vehicle. If tire demand and production increase, sales increases and, as a consequence, tire waste and its accumulation also increases. According to Castellanos [5], there are three main thermochemical processes: combustion, gasification and pyrolysis. As mentioned by Bolívar and Cuenca [6], combustion can be defined as the total oxidation of a fuel to produce energy; gasification is the total degradation of the carbon substrate to gaseous form; the third of these main processes is pyrolysis and, as mentioned, it is the transformation of biomass into liquid, solid and gaseous fractions generated by heating the biomass, in the absence of oxygen, and with temperatures close to 500 °C.

As mentioned above, pyrolysis consists of heating organic matter in the absence of oxygen at a specified rate or heating rate, up to a maximum temperature known as pyrolysis temperature, and maintaining it there for a specified time [6]. The products of pyrolysis correspond to: liquid, condensable gases and solid char or ash; in turn, the condensable gas can be further decomposed into non-condensable gases (CO, CO₂, H₂ and CH₄), liquid and char [7]. This process is gaining its place as a suitable recycling technique and can be carried out in different ways depending on a combination of the operating conditions, the nature of the reactor employed or even the use or not of a catalyst; it is important to note that this is a process that demands heat energy for the thermal degradation reactions to take place.

The products obtained from the pyrolytic process are three, mainly the solid product (ash or carbon black), the liquid product (oil) and the gaseous product, which contains condensable and non-condensable gases. According to Castells and Velo [8], the pyrolytic product is made up of smaller molecules that are separated from the carbon chains of the biomass, in this particular case rubber; i.e. from one to four carbon compounds such as methane (CH₄), propane (C₃H₈) and butane (C₄H₁₀); in addition to non-pyrolytic gases such as hydrogen (H₂), carbon dioxide (CO₂) and carbon monoxide (CO).

By the end of the 2030s, the weight of scrap tires will be up to 1200 million tons annually [9], [10]. Currently, this particular process proves to be a promising way for the transformation of waste organic matter, such as tires consisting mainly of rubber, into fuel by thermal degradation in the absence of oxygen in a temperature range from 300 to 800 °C.

The present research article will focus on the valorization of tire waste with a circular economy approach, particularly on the design and simulation of the tire pyrolysis gas condensation process to obtain crude oil for liquid fuels. The input variables for the pyrolytic gas condensation process will be identified and the simulation model that allows the condensation of these gases from the pyrolysis reactor will be developed.

1. Materials and Methods

1.1 Description of the process

Scrap tires, which mainly consist of rubber, are an important alternative for obtaining energy, due to their main composition in the form of C_xH_y with a calorific value of 33 MJ/kg [11]. In addition, they are the raw material that constitutes the pyrolysis of tires. This process produces more than 110 products according to experimental results obtained from oil and gas industries, and they can be identified as gas, non-aromatic liquids, aromatic liquids and tar at 530 °C, the process presents three stages of thermal decomposition between 120 and 520 °C, which corresponds to the volatilization of plasticizers and degradation of natural and synthetic rubber [12].

Pyrolysis is an alternative for the conversion of tires into energy; it consists of the thermal decomposition of macromolecules in the absence of oxygen to obtain products such as liquids, gases and residual carbon that can be used as raw materials for other processes or as fuels [13], [14], [15]. Coal can be used as a solid fuel or can be converted into activated carbon. Gas, which mainly consists of butadiene, ethylene and methane, with its high calorific value can be used as an energy source again for the process.

The oil contains high value-added and commercially valuable components such as benzene, toluene, xylenes and limonene. For this process, variables and operating conditions are defined and from this the experimental stage can be developed.

The feed to the ASPEN HYSYS model has been characterized as a mixture of gases coming from the pyrolysis reactor, in its experimental stage, with a composition taken from a gas chromatography carried out previously [6].

1.2 Experimental design

Tires go through a pretreatment where the main objective is the size reduction of the samples into smaller pieces, up to dimensions close to 4 x 4 cm, these are the starting point of the pyrolysis process. Subsequently, the samples enter a reactor that has been adapted with recycled and reused material as illustrated below:



Figure 1 Pyrolysis reactor
Source: Own Elaboration

A burner provides heat to the reactor, which operates at 1 atm pressure, the corresponding temperature measurements are taken and, subsequently, the pyrolysis gas leaves the reactor to enter a shell and tube heat exchanger that has a tube bundle of 21 tubes in a single pass, in a square layout.

This functions as a condenser and employs a countercurrent water flow as the cooling fluid. The water is pumped to the exchanger by a 0.5 hp water pump as shown in figures 2 and 3.

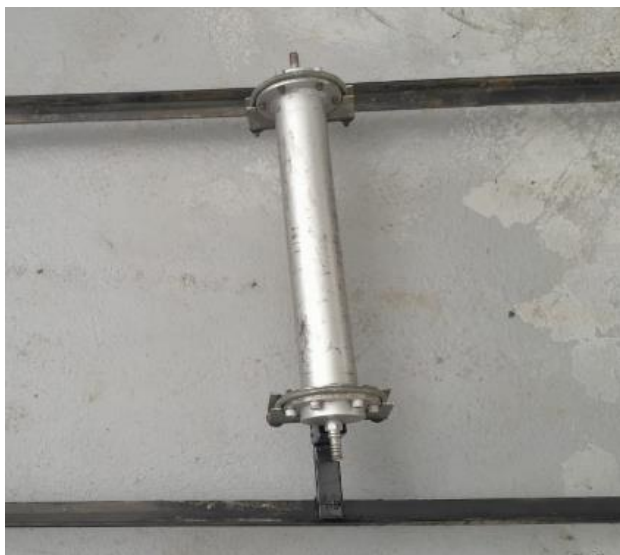


Figure 2 Shell and tube heat exchanger
Source: Own Elaboration



Figure 3 Water pump
Source: Own Elaboration

The water is recirculated back to the water pump, at the outlet of the heat exchanger the condensed gas is obtained. Considering that cooled gas is not completely condensed, the remaining is recirculated to the burner as a power source. The assembly of the equipment is illustrated below:



Figure 4. Rubber pyrolysis equipment
Source: Own Elaboration

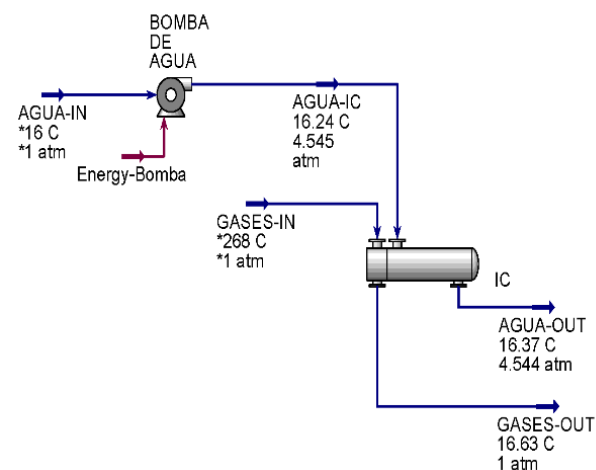


Figure 5 Flow process diagram
Source: Own Elaboration

1.3 Model description

The process flow diagram, elaborated in the ASPEN HYSYS simulation software, corresponds to the cooling cycle with the objective of condensation of the gases coming from the pyrolysis reactor, it consists of a water pump and a shell and tube heat exchanger; the efficiency, power, in the case of the pump, the dimensions of both the tubes and the shell and its length, for the heat exchanger, have been taken from the equipment mentioned in the experimental stage.

According to Acosta and Castro, among the variables that most influence the pyrolysis process are the type of biomass to be fed into the reactor, in this case tires, the time-temperature profile and the atmospheric pressure, the latter two being the most important, together with the particle size and moisture level. As for the time-temperature profile, it refers to the heating rate, the maximum temperature and the residence time [17]. Having said that, by correctly managing the process variables mentioned above, it is possible to optimize or, if necessary, maximize the fraction of the desired product.

1.3.1 Feed gas composition

To determine the composition of feed gas, which is a gaseous mixture, a gas chromatography is used to separate the different volatile compounds of a gaseous sample in this case. This technique achieves the separation of these compounds with the passage of a sample through a stationary phase with help of a mobile phase; in addition, it allows to know both the absence or presence of a compound, as well as the amount of individual components present in a sample through the calibration curves of each standard, likewise it has a great capacity for separation of both thermally stable and volatile organic and inorganic compounds [16].

The composition of the feed gas, the chemical compounds in (% mol) of the synthesis gas from the tire rubber pyrolysis process at different temperatures resulting from the samples selected for chromatographic analysis performed previously [6] are:

Components	Process temperature (°C)		
	400	450	500
H_2	8	9.1	11.6
CH_4	20.3	21.8	27.5
CO	4.5	2.7	3.1
CO_2	5.8	5.2	4.6
C_2H_4	9.2	9.9	9.1
C_2H_6	6.6	8.6	10.6
H_2S	0.9	1.3	1
C_3H_6	6.5	6.3	5.7
C_4H_8	31.8	27.2	19
Others	6.4	7.9	7.8

Table 1 Chemical compounds in (% mol) of the synthesis gas from the tire rubber pyrolysis process at different temperature

Source: LEONARDI, Chiara. *Development of an innovative pyrolysis plant for the production of secondary raw materials. Dottorato di ricerca in chimica. Università di Bologna. 2015 *Diferentes tipos de neumáticos*

These gases together with their corresponding mole fraction are entered as the feed components through the shell and tube heat exchanger tubes. In addition, the cooling liquid of choice is water which enters the shell side of the heat exchanger with a mole fraction of 1. In the ASPEN HYSYS simulator they are categorized at 1 atm pressure as follows:

Formula	Simulation Name	Molar Fraction
H_2	Hydrogen	0.08
CH_4	Methane	0.203
CO	CO	0.045
CO_2	CO_2	0.058
C_2H_4	Ethylene	0.092
C_2H_6	Ethane	0.066
H_2S	H_2S	0.009
C_3H_6	Propene	0.065
C_4H_8	i-Butene	0.318
Others	Others	0.064

Table 2 Chemical compounds present in the feed to the simulation in ASPEN HYSYS

Source: Own Elaboration

Likewise, in the experimental stage, the corresponding temperature gases (hot fluid), as well as for the water (cold fluid) were measured; The mass flow of gas feed and the volume flow of water before entering the pump that feeds the heat exchanger were measured as well; in addition, it is important to highlight the process is carried out at 1 atm of pressure. These conditions are listed below:

Parameters	Fluids	
	Water	Pyrolysis gases
Inlet temperature (°C)	16	268
Mass flow rate ($\frac{kg}{h}$)	-----	1
Flow rate ($\frac{L}{min}$)	16.39	-----

Table 3 Feed parameters to the process at 1 atm pressure obtained from the experimental stage

Source: Own Elaboration

The above mentioned compositions and feed parameters are the starting point of the simulation performed in ASPEN HYSYS and will allow the process to be carried out.

1.3.2 Properties

The equation-of-state models provide an accurate description of the thermodynamic properties of the high temperature conditions for the pyrolysis gases coming from the reactor, for the hot side entering through the heat exchanger tubes.

The Peng-Roninson model was chosen for this application because of the majority of hydrocarbon gas components. For the cold side of the heat exchanger, which enters through the shell of the heat exchanger, the NRTL model was chosen because water is a polar compound and enters at a pressure of less than 10 bar. The normal boiling points ($^{\circ}\text{C}$) of the components are listed below according to the ASPEN HYSYS simulator where the components have been normalized.

Formula	Simulation Name	Molar Fraction	Normal Boiling Pt ($^{\circ}\text{C}$)
H_2	Hydrogen	0.0855	-252.6
CH_4	Methane	0.2169	-161.5
CO	CO	0.0481	-191.5
CO_2	CO_2	0.0620	-78.55
C_2H_4	Ethylene	0.0983	-103.8
C_2H_6	Ethane	0.0705	-88.60
H_2S	H_2S	0.0096	-59.65
C_3H_6	Propene	0.0694	-47.75
C_4H_8	i-Butene	0.3397	-6.851

Table 4. Boiling points of feed components according to ASPEN HYSYS

Source: Own Elaboration

1.3.2 Components of the simulation

The simulation is comprised of two main pieces of equipment, the water pump which will receive a flow rate of 16.39 L/min and, in turn, the output of this equipment will feed the shell and tube heat exchanger.

1.3.2.1 Water Pump

This equipment increases the pressure of a liquid stream; it calculates pressure, temperature or efficiency. It is part of the experimental stage and its main characteristics, which have been entered into the process simulator, are mentioned below:

Water pump	
Parameters	Specifications
Inlet temperature ($^{\circ}\text{C}$)	16
Inlet flow rate ($\frac{\text{L}}{\text{min}}$)	16.39
Adiabatic efficiency (%)	25.90
Duty (hp)	0.5

Table 5 Water pump specifications

Source: Own Elaboration

1.3.2.2 Heat Exchanger

The heat exchanger transfers heat between two streams; the reactor outlet gas is cooled with water coming from the pump entering countercurrent. The hot fluid, the gas, enters this device through the tubes and the cold fluid, the water, through the shell. This heat exchanger has been adapted from another cooling process and its specifications are described:

Type of heat exchanger	AEL
Position	Horizontal
Shell outer Diameter (DO)	0.06604 m
Shell Internal Diameter (DI)	0.05267 m
Number of tubes	21
Length of tubes	0.50 m
Number of passages through tubes	1
Outer diameter of tubes (DO)	0.00793 m
Inner diameter of tubes (DI)	0.00663m
Tube spacing (PT)	0.00992 m
Tube pattern (arrangement)	Cuadrado 90°
Outer diameter (OD) and inner diameter (ID) of nozzle where fluids enter	21.34/16.6 mm

Table 6 Shell and Tube Heat Exchanger Specifications

Source: Own Elaboration

With the specifications mentioned above, the layout of the heat exchanger itself and the pattern of the tubes are constructed in the simulator:

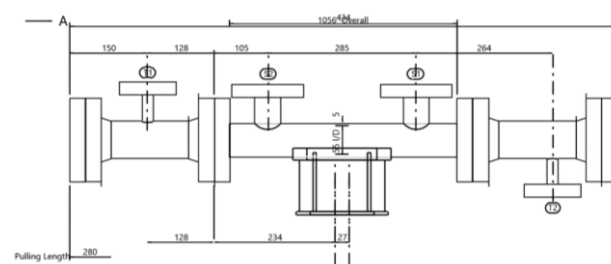


Figure 6 Layout of the heat exchanger

Source: Own Elaboration

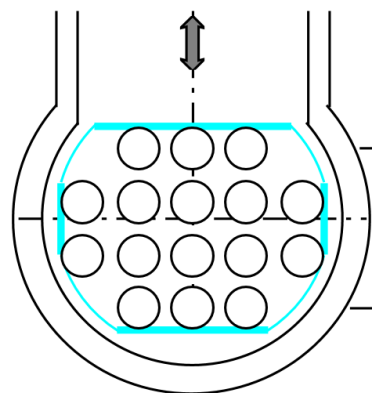


Figure 7 Square arrangement of the tubes

Source: Own Elaboration

Having said that, the above mentioned parameters and operating conditions are entered into the simulation in ASPEN HYSYS and the model is allowed to run. The simulation results will be shown in section 3.

1.4. Use of refrigerant R-717

An alternative in the cooling system is the use of a refrigerant, in this case R-717, the simulation illustrated in Figure 5 is taken up again and the cold fluid feeding the process is varied, replacing in this case water to observe if this favors the condensation of the pyrolysis gases coming from the reactor in the experimental stage.

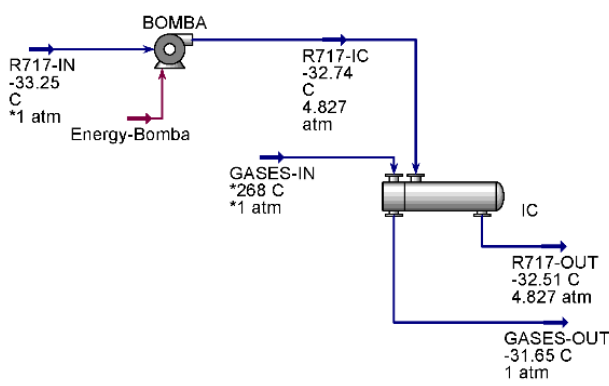


Figure 8 Refrigerant process diagram
Source: Own Elaboration

1.4.1 Characteristics of the refrigerant R-717

The coolant enters in liquid phase and with a mole fraction of 1, the characteristics of the feed at 1 atm of pressure are listed in the following table:

R-717 refrigerant	
Parameters	Especifications
Inlet temperature (°C)	-33.25
Inlet flow rate ($\frac{L}{min}$)	16.39

Table 7 R-717 refrigerant specifications at 1 atm pressure
Source: Own Elaboration

2. Results and discussion

2.1. Simulation results

Based on a pyrolysis gas feed to the process of 1 kg/h, the results obtained in the simulation are listed:

Water pump		
Delta P	3.545	atm
Power	0.5	hp
Efficiency	25.90	%
Inlet pressure	1.000	atm
Outlet Pressure	4.545	atm
Flow rate	16.39	L/min
Inlet Temperature	16	°C
Outlet temperature	16.24	°C

Table 8 Water pump results in ASPEN HYSYS
Source: Own Elaboration

The above describes that the cold fluid, water, enters the shell of the heat exchanger with a pressure of 4.545 atm and a temperature of 16.24 °C; that is, the water pump provides an increase in pressure and a slight increase in temperature to the water. According to the composition of the gas mixture fed to the process and taken from the literature, the pertinent analysis of the heat exchanger is carried out, which provides the following results:

Shell & tube heat exchanger					
Process data	Units	Shell		Tubes	
		Input	Output	Input	Output
Total flow	$\frac{kg}{h}$	981		1	
Steam	$\frac{kg}{h}$	0	0	1	1
Liquid	$\frac{kg}{h}$	981	981	0	0
Temperature	°C	16.24	16.37	268	16.62
Vapor mass fraction		0	0	1	1
Pressure	KPa	460.534	460.387	101.325	101.321
Convection coefficient	$\frac{W}{m^2 \cdot K}$	774.8		16.6	
Duty	kW	0.1381			
Area	m ²	0.2296			
UA	$\frac{kJ}{°C \cdot h}$	11.4			
LMTD	°C	43.62			

Table 9 Heat exchanger results using water provided by ASPEN HYSYS
Source: Own Elaboration

The temperatures of both the hot fluid, in red, and the cold fluid, in blue, along the path through the heat exchanger are illustrated in the graph below. It is possible to observe the cooling that the hot fluid undergoes from a feed temperature of 268 °C to its exit from the heat exchanger at 16.63 °C. In addition to the above, the water undergoes a slight heating from its exit from the pump and entrance to the heat exchanger on the shell side, with a temperature of 16.24 °C until it exits at 16.37 °C.

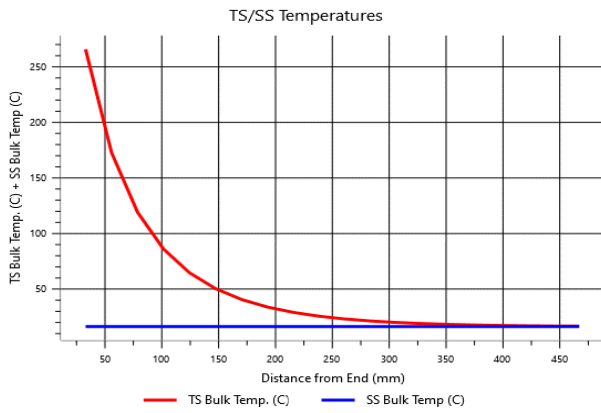


Figure 9 Temperature profile using water
Source: Own Elaboration

It also illustrates the slight pressure drop that occurs on the tube side of the heat exchanger, along the 500 mm distance that the gases have to travel against the flow of water fed to the process by means of the centrifugal pump. The above has been calculated by the simulator itself.



Figure 10 Pipe side pressure drop
Source: Own Elaboration

In addition to the above, the film or convection coefficients for both fluids are presented, in blue the coefficient of the cold fluid, water, and in red the hot fluid, pyrolysis gases, this coefficient quantifies the influence of the properties of the fluid, surface and flow when heat transfer by convection occurs and that, contrasted with Table 9, have a value of 774.8 and 16.6 W/(m²· K), respectively.

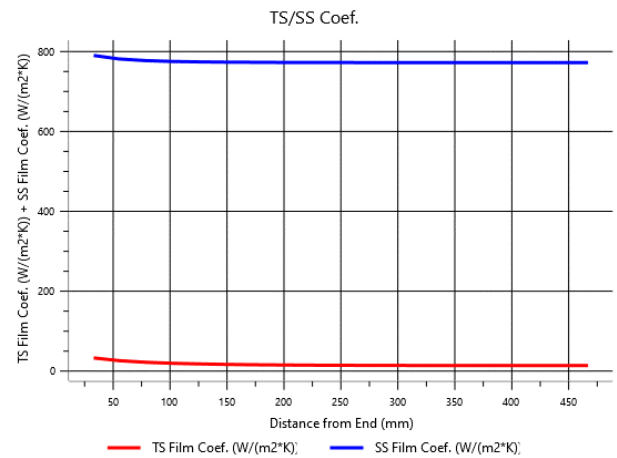


Figure 11 Film coefficients of both fluids
Source: Own Elaboration

Finally, to determine whether the gases that make up the feed have condensed, taking into account that the components of this mixture, as well as their mole fraction composition, have been taken from the literature as mentioned in Table 2, the following graph is observed. It illustrates the mole fraction of the gas mixture against the length of the shell and tube heat exchanger itself.

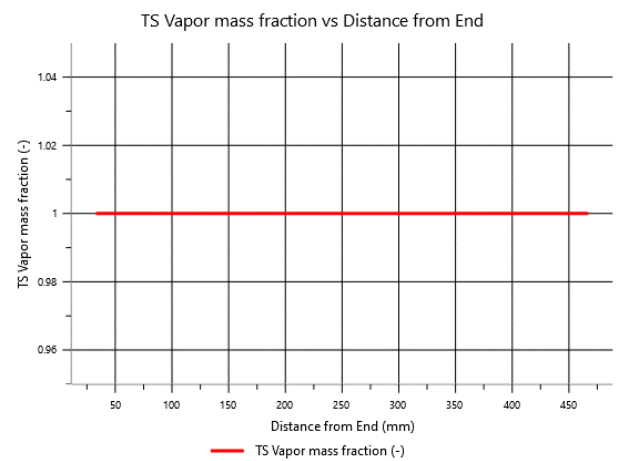


Figure 12 Fraction of steam in the heat exchanger
Source: Own Elaboration

According to the above graph, no condensate formation is observed for this gas mixture mentioned in Table 2 and entered into the ASPEN HYSYS simulator, when water is used as the cooling liquid, this is supported by the phase change temperatures listed in Table 4. For more accurate results for this particular process, it is recommended to perform a gas chromatography on the gas mixture coming directly out of the pyrolysis reactor, which favors the determination of the chemical compounds and their molar compositions present in the gas stream.

With the above, the mole fractions of the components of the hot fluid leaving the heat exchanger are listed, all of them in vapor phase:

Formula	Simulation Name	Molar Fraction
H_2	Hydrogen	0.0855
CH_4	Methane	0.2169
CO	CO	0.0481
CO_2	CO_2	0.0620
C_2H_4	Ethylene	0.0983
C_2H_6	Ethane	0.0705
H_2S	H_2S	0.0096
C_3H_6	Propene	0.0694
C_4H_8	i-Butene	0.3397

Table 10 Mole fractions of the gaseous stream at the heat exchanger outlet

Source: Own Elaboration

2.2. Results of the use of R-717 refrigerant

As mentioned above, the use of R-717 refrigerant is an alternative to favor the condensation of the pyrolysis gases that make up the gaseous mixture at the outlet of the pyrolysis reactor and that enters the heat exchanger on the side of its tubes. The results are listed for the pump that will feed the cooling fluid.

PUMP		
Delta P	3.827	atm
Power	0.5	hp
Efficiency	25.90	%
Inlet pressure	1.000	atm
Outlet pressure	4.827	atm
Flow rate	16.39	L/min
Inlet temperature	-33.25	°C
Outlet temperature	-32.74	°C

Table 11 Pump results in ASPEN HYSYS

Source: Own Elaboration

Again, the heat exchanger operates countercurrent, on the shell side the coolant is fed by the pump and the pyrolysis gas mixture enters through the tubes. Table 12 lists the results of the simulation of this equipment. It is possible to observe that the outlet temperature of the hot stream is -31.65 °C. This, according to the phase change temperatures shown in Table 4, would favor the formation of condensate in this process stream.

In addition to the above, the temperature profile is illustrated when using the coolant, it is possible to observe the decrease in the temperature of the hot stream, in red, and a slight increase for the cold stream, in blue, along the length of the shell and tube heat exchanger.

It is possible to observe the cooling that the pyrolysis gas mixture undergoes from its feed at 268 °C to its exit from the heat exchanger at -31.65 °C. In addition to the above, the water undergoes a slight heating from its exit from the pump and entrance to the heat exchanger on the shell side, with a temperature of -32.74 °C until it exits at -32.51 °C.

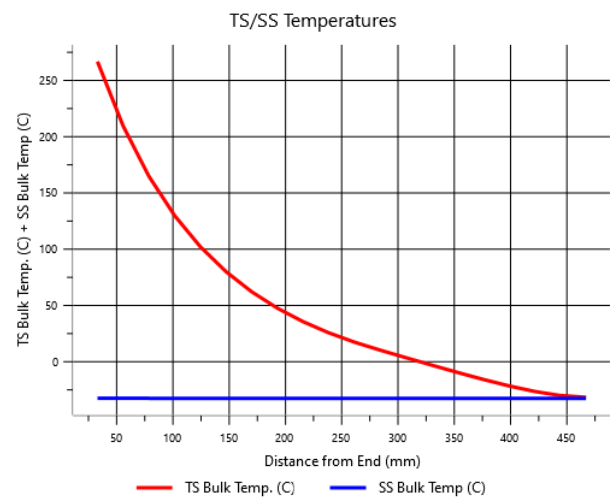


Figure 13 Temperature profile using refrigerant R-717

Source: Own Elaboration

Shell and tube heat exchanger					
Process data	Units	Shell		Tubes	
		Input	Output	Input	Output
Total Flow	kg/h	607		1	
Steam	kg/h	0	0	1	1
Liquid	kg/h	607	607	0	0
Temperature	°C	-32.74	-32.51	268	-31.65
Vapor Mass Fraction		0	0	1	1
Pressure	kPa	489.129	489.054	101.325	101.322
Convection coefficient	$\frac{W}{m^2 \cdot K}$	830.1		33.8	
Duty	kW	0.1620			
Area	m^2	0.2296			
UA	$\frac{kJ}{°C \cdot h}$	11.12			
LMTD	°C	55.22			

Table 12 Heat exchanger results using R-717 refrigerant provided by ASPEN HYSYS

Source: Own Elaboration

In addition, there is a slight pressure drop on the hot fluid side, through the heat exchanger tubes, this along the 500 mm of the length of this equipment. Starting with a pressure of 101.325 kPa and exiting at a pressure of 101.322 kPa. This can be observed graphically as shown below:

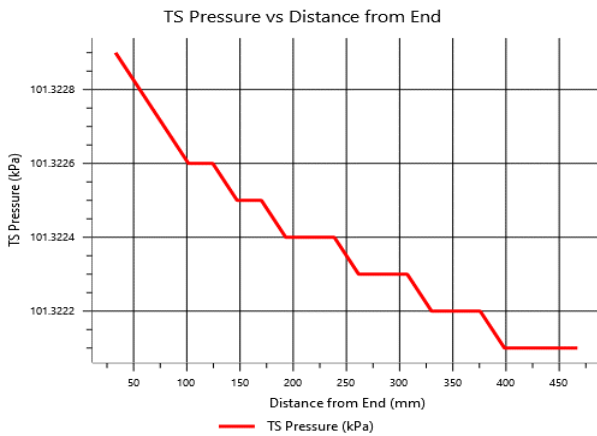


Figure 14 Pressure drop on the pipe side
Source: Own Elaboration

As mentioned above, the film coefficients of both the cold fluid, blue in the graph, and the hot fluid, in red, quantify the influence of fluid, surface and flow properties when convective heat transfer occurs having a value taken from Table 12 of 830.1 and 33.8 $W/(m^2 \cdot K)$, respectively.

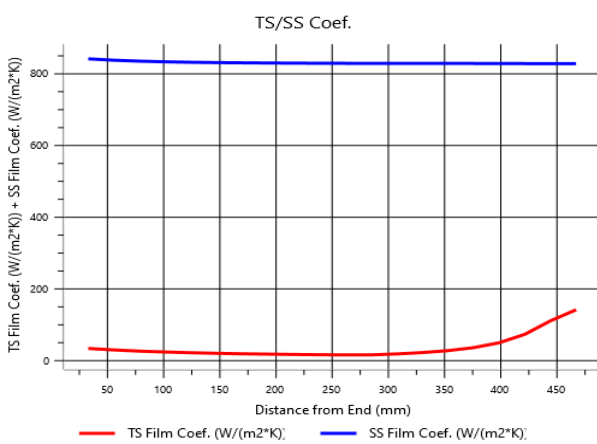


Figure 15 Film coefficients of both fluids
Source: Own Elaboration

On the other hand, to determine the condensate formation, the following graph shows the tube length of 500 mm versus the steam fraction. It is also possible to determine that, at an approximate length of 444 mm there is a decrease in the vapor fraction, i.e., there is condensate formation for this same shell and tube heat exchanger with the use of refrigerant R-717. The above for the composition of the gas mixture taken from the literature and listed in Table 2.

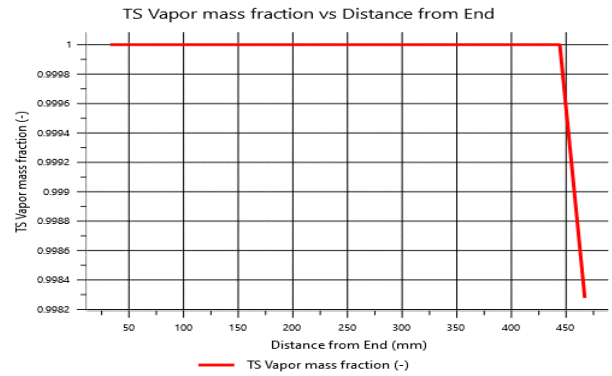


Figure 16 Vapor fraction in the heat exchanger
Source: Own Elaboration

On the other hand, condensate formation is supported by the phase change temperatures of the initial components of the gas phase and presented in Table 4. The following is a list of the components at the exit of the process, for a temperature of $-31.65\text{ }^\circ\text{C}$ on the tube side, and where the formation of certain pyrolysis gases is favored.

Formula	Vapor phase	Liquid phase
H_2	0.0856	0.0000
CH_4	0.2173	0.0020
CO	0.0482	0.0001
CO_2	0.0621	0.0026
C_2H_4	0.0985	0.0061
C_2H_6	0.0706	0.0077
H_2S	0.0096	0.0015
C_3H_6	0.0695	0.0364
C_4H_8	0.3387	0.9436

Table 13. Molar fractions of the exhaust gas stream with the use of refrigerant R-717
Source: Own Elaboration

2.3 Proposal for the condensation cycle design

On the other hand, a new proposal is made for the design of the condensation cycle where the pump and the heat exchanger of the experimental stage simulated in the previous section using water as cooling liquid are reused.

In this particular case, a cooler and a separator are added to the process, as illustrated in the following process diagram:

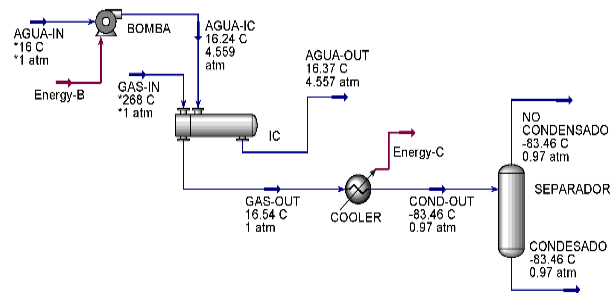


Figure 17 Process diagram for the proposed cooling cycle design

Source: Own Elaboration

Again, the previous conditions of feeding the heat exchanger using water for cooling are resumed. The gases leaving the heat exchanger, which have been cooled to a temperature of 16.54 °C at 1 atm pressure, enter a cooler with the following characteristics:

Cooler		
Parameters	Input	Output
Temperature (°C)	16.54	-83.46
Temperature Delta (°C)		100
Pressure (atm)	1	1
Mass flow (kg/h)	1	1
Duty (kW)		0.1227

Table 14 Cooler specifications

Source: Own Elaboration

The simple cooler is specified through the temperature delta, this specification of a fall of these pyrolysis gases. To observe graphically the condensate formation, a temperature of 100 °C is added to favor the cooling of the gaseous stream and the condensation of the graph corresponding to the vapor fraction as the temperature decreases, i.e., the lower the temperature, the more condensate is obtained.

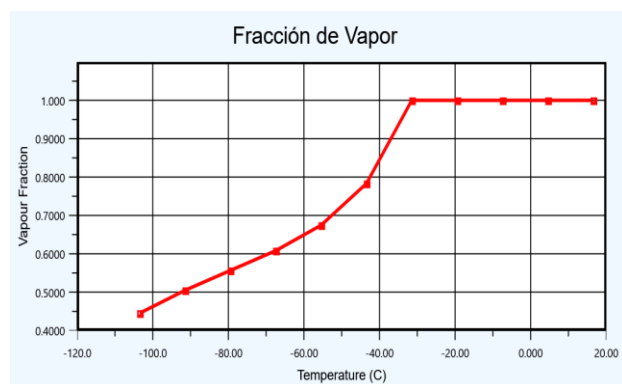


Figure 18 Steam fraction leaving the cooler

Source: Own Elaboration

According to the above, if the vapor fraction graph is observed from left to right, as cooling occurs, the condensation of pyrolysis gases is favored. These results are listed below:

Temperature (°C)	Vapor fraction
16.5428	1.0000
6.5428	1.0000
-3.4571	1.0000
-13.4571	1.0000
-23.4571	1.0000
-33.4571	0.9511
-43.4571	0.7796
-53.4571	0.6861
-63.4571	0.6257
-73.4571	0.5797
-83.4571	0.5379

Table 15 Cooler results

Source: Own Elaboration

The above shows that the use of a cooler favors the phase change and, consequently, the formation of condensate; in addition, it is observed that from a temperature of -33.4571 °C the greatest phase change of the compounds and the formation of liquid phase occurs. Finally, the gases that have condensed the most are listed:

Formula	Vapor phase	Liquid phase
H_2	0.0855	0.0001
CH_4	0.2169	0.0083
CO	0.0481	0.0003
CO_2	0.0620	0.0231
C_2H_4	0.0983	0.0470
C_2H_6	0.0705	0.0585
H_2S	0.0096	0.0105
C_3H_6	0.0694	0.1287
C_4H_8	0.3397	0.7235

Table 16 Molar fractions resulting from condensation with the use of a cooler

Source: Own Elaboration

Finally, the above indicates that at an outlet temperature of -83.46 °C the condensation of gases such as propene and i-butene is favored, with liquid phase mole fractions of 0.1287 and 0.7235, respectively, these gases come from the pyrolytic reactor outlet and compositions taken from the literature as mentioned above.

3. Conclusions

Waste rubber tires have generated a large amount of waste, particularly in Bogota, Colombia. This waste has become an environmental problem due to the agglomerations and the subsequent diseases it can cause.

In this sense, tire pyrolysis is proposed as a viable environmental alternative with a circular economy approach, the products of solid waste pyrolysis can be considered as biofuels with multiple uses. Tests in the experimental stage with scrap rubber tires show that the process works and that the three expected products are obtained and can be separated.

The simulation of the experimental data in the ASPEN HYSYS process simulator allowed corroborating the real operation of the process, taking up compositions from the literature and with operating conditions specific to the experimental stage. In addition, the temperatures of the experimental tests have been compared with those obtained from the simulation, being these similar to those obtained experimentally.

It was found that the use of a refrigerant favors the condensation of pyrolysis gases, allowing a better performance in terms of condensate with a high added value for other processes where its use is required. In addition, if it is desired to use water as cooling liquid, due to its lower utility cost, the use of a cooler is recommended to favor the phase change and the condensation of the gas mixture.

In addition to the above, for further work, it is recommended to perform a gas chromatography of the gas stream leaving the pyrolytic reactor, in order to obtain the precise compositions of the gases and their composition in the gas mixture that enters the heat exchanger for the subsequent condensation stage.

The gases that have not condensed will be re-entered into the pyrolysis reactor as fuels to the burner that feeds energy in the form of heat to the reactor itself. In addition, water that is supplied to the shell and tube heat exchanger as a cooling liquid is recirculated back to the water pump for reuse.

Pyrolysis as an urban solid waste utilization system favors the reduction of tires as waste and provides them with a second use as biofuel or as raw material for other processes, all of this is favorable with the circular economy approach of the project, thus showing a good profitability for the process.

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