TECHNICAL EVALUATION AND DESIGN PROPOSAL OF A POWER ENERGY SYSTEM BASED ON SYNGAS FROM THE GASIFICATION OF END-OF-LIFE TIRES

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ABSTRACT

The technologies for solid waste-to-energy are numerous and are continuously studied in the literature. One of the most reliable and used of these technologies is the gasification process, which is a thermochemical decomposition process that generates something called syngas, that is then used to generate energy. On the other hand, End-of-Life Tires are a non-biodegradable Municipal Solid Waste that continues to be a problem for a lot of cities around the world despite the recycling efforts. In this sense, this paper aims to make a technical evaluation and general design proposal of a power energy system based on the syngas generated by the gasification of End-of-Life Tires. First, a procedure is proposed to determine the approximate quantity of tires out of use generated by a city. Then, an exhaustive review was done to estimate the low heating value of the tires, the air volumetric flow needed for the gasification process and the estimated syngas mass flow generated. Subsequently, a general procedure to design the gasifier was proposed, including the drying zone, pyrolysis zone, combustion zone, reduction zone, and the ash pit. Finally, the additional equipment needed in this whole process is mentioned. Additionally, the proposed procedure is used to design a power energy system based on the syngas from the gasification of End-of-Life Tires in Cochabamba-Bolivia.

1 INTRODUCTION

Over the past two decades, Bolivia has heavily relied its economy on natural gas exports, with Brazil and Argentina standing as its primary trading partners. However, its once prominent position in the global natural gas market has witnessed a decline since 2013, marked by a substantial depletion of the natural gas reserves in the country. By 2018, Bolivia's gas reserves decreased to 8.79 TCF representing a significant decline [1]. Concurrently, the nation's reliance on imported liquid fuels, such as diesel and gasoline, climbed reaching a notable sum of US$ 2,999 million in 2022 [1]. In response to this economic shift, the Bolivian government has initiated strategic measures including the construction of a Biodiesel Plant with a production capacity of up to 1,500 barrels per day [2]. Furthermore, the government is encouraging the scientific research and exploration of alternative opportunities such as gasification or pyrolysis to obtain fuel from agricultural waste, forest residues, industrial waste and municipal solid waste.

One of the non-biodegradable Municipal Solid Waste (MSW) are the End-of-Life Tires (ELTs). Globally, about 3 billion tires are sold per year, with an equivalent amount of tires being discarded. Furthermore, it is estimated that the number of ELTs will increase to approximately 5 billion per year according to [3]. Nowadays, around 41% of all of these ELTs produced worldwide are disposed of in landfills or dumps without any material recuperation or any kind of conversion. This happens most likely because of the relatively low cost of the tires and especially because of the complexity of recycling them.

It is important to mention that in many countries, there has been some efforts and strategies in order to reduce the percentage of the ELTs simple disposal, however, there are still huge amounts of material

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that are not recovered and simply accumulate in illegal stockpiles around the world. In the European Union (EU), due to strict legislation on waste treatment, a high recovery rate (around 92%) of ELTs is observed but, regardless of this, a significant amount (8%) ends up in landfills [3]. In Latin America (LA), in spite of landfill disposal being totally prohibited in some countries (such as Argentina, Brazil, Colombia, Chile, Mexico and Uruguay), a large part of the generated ELTs ends up in illegal sites either way endangering the environment and public health [4].

The chemical composition of the ELTs makes them extremely resistant to degradation with a potential long-term perpetuity in the environment, which is why they require special processes for their final disposal or recycling. On the other hand, they have the particularity of storing large amounts of methane in their interior and have a high heating value (HV), which causes fires of a magnitude that is difficult to control. When ELTs are disposed of in urban areas, they became a danger to the population due to the proliferation of fauna harmful to public health, such as mosquitoes and rats. For this reason, studies are needed to help find a way to reuse them, in addition to controlling the problems caused by their accumulation [4].

The main methods of solid waste revalorization in general are: regeneration, incineration, pyrolysis and gasification [5]. The processes of ELTs revalorization by regeneration are not recommended due to their high costs, in addition to producing a large amount of secondary pollution. On the other hand, ELTs revalorization process by incineration, which is generally used within the industry, waste up to 2/3 of the energy contained in the ELTs, making it a very inefficient process [6]. Fuels derived from ELTs, composed of whole or shredded tires, are mainly used in furnaces (51%), where energy recovery from the combustion of ELTs allows the reduction of CO2 emissions with respect to commercial fuels due to the higher heating value (32 MJ/kg). Also, it should be considered that only a small part (about 15%) of the energy used in the tire production process (200 MJ/kg) can be recovered [3].

The other technologies for the revalorization of the ELTs for energy purposes are pyrolysis and gasification. Pyrolysis is a thermal decomposition of organic materials in the absence of oxygen at temperatures between 300 up to 800 °C and often at slow heating rates to break down the organic materials into the basic components of the organic chain. On the other hand, gasification is a thermochemical conversion technology that uses sub-stoichiometric air (or oxygen), steam, heat and pressure to convert organic substances into synthesis gas (a mixture of carbon monoxide and hydrogen) [7].

The revalorization process of ELTs by pyrolysis focus on producing mainly pyrolytic oils, and the energy contained in the gaseous phase is wasted in the same way that is wasted with the incineration process. So, pyrolysis is actually not a very energy efficient process [7]. On the other hand, the gasification process is considered one of the most efficient and suitable means to adequately exploit the properties of ELTs, not only because of its capacity to recover and take advantage the gaseous phase produced, but also because it is a process that can be suitable to operate with considerable amounts of material, as gasification allows the recovery of a solid phase (carbonized material) and a liquid phase (pyrolytic oils).

The process of pyrolysis and gasification of ELTs has been largely investigated and there are some plants around the world working now-a-days, but also some challenges (see [8] for more details). For instance, Gokalp et al. [9] analyze the techno-economic feasibility for the gasification process of ELTs for energy generation in Turkey. The authors used a mixture of pre-heated air and steam as the gasification agent and a circulating fluidized bed gasifier. The authors proved that the 10 MWe capacity power gasification plant, fed by about 30,000 tons of granulated ELTs per year has a return on investment of 3.2 years.

In this context, this work proposes a detailed procedure for the design of a gasification system from ELTs, determining the appropriate parameters of the system, focusing especially on the production of the synthesis gas or SYNGAS, considering that this gas can be used within different energy production systems such as engines, heating networks or electric power systems. Additionally, the proposed

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procedure will be applied to design a gasifier for the revalorization of ELTs in Cochabamba-Bolivia. It is worth mentioning that this work deepens the work done by [5], in which the feasibility of a gasification system for solid waste generated by the city was analyzed.

2 GASIFICATION PROCESS

2.1 Gasifiers

Gasification is a thermochemical process of decomposition; this process needs a controlled gasification medium in order to avoid complete combustion. This process produces mainly SYNGAS that can be used within different energy systems [10]. The gasifiers are divided into two types: fixed bed or fluidized bed. Tables 1 and 2 show the main characteristics of both types.

Table 1: Fixed bed gasifiers [15]

Properties	*Direct flow*	*Inverted flow*	*Cross flow*
Temperature (°C)	1000	900-1000	800-900
Gasification agent entrance	Upper reactor zone	Lower reactor zone	Medium reactor zone
Particle production	Moderate	High	High
Tar production	High	Low	High
Heating Value of *SYNGAS*	High	Low	High

Based on the characteristics described on Table 1 and 2, this study focuses on fixed bed gasifiers because they can be operated to produce energy at low and medium scale. On the other hand, [11] [12] and [13] recommend their use, especially the inverted draft gasifier, because of its low tar production. Additionally, it was identified that there is a gasification equipment that improves the properties of inverted draft gasifiers by reducing the reaction zone, this equipment is known as Inverted Draft Gasifier Imbert or Inverted Draft Gasifier with Throat. This technology reduces significantly the amount of tars within the produced SYNGAS, in addition to causing a reduction in ash production, having a simple operation and simple construction [14].

Table 2: Fluidized bed gasifier [16]

Properties	*Circulating fluidized bed*	*Bubbling fluidized bed*
Temperature (°C)	900	700-900
Slag production	High	High
Tar production	High	High
Heating Value of *SYNGAS*	Moderate	High
Heat transfer	Moderate	High
Pressure	High	High

2.2 Feeding system

After collecting the ELTs from various sources, they will be sorted based on size, type and condition. Then, the ELTs will undergo some preparation such as removing metal components and cleaning. After this process of preparation, the ELTs are fed into a shredding machine in order to be triturated and reduced into smaller pieces. The product of this trituration process is the feedstock that will be transformed to syngas.

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The feedstock of the ELTs must comply with two fundamental parameters to ensure satisfactory gasification:

- Feedstock size: there are two criteria to determine the feedstock size, the first one indicates that it should be between 20 and 80 mm, the second one indicates that the feedstock size should range between 10 and 20% of the unit reactor diameter [15].
- Low humidity: The recommended relative humidity is between 15 and 20%, as these values contribute to reduce the tar content [11]. ELTs in chunks have a relative humidity close to 4% [17], therefore, they are viable as feedstock for the gasifiers.

2.3 Gasification agent

The gasification agent is the element that allows the process to work correctly. With the gasification agent is possible to control the amount of tars generated during the process, as well as its efficiency. The gasification agent can be: air, water steam or oxygen, however, the most used agent is air due to its availability and low cost.

2.4 SYNGAS

The composition of SYNGAS produced from the gasification of ELTs can vary depending on several factors such as the type of the gasifier, the operating conditions and the composition of the tires themselves. However, typical syngas composition from the gasification of tires (carbonaceous materials) usually includes a mixture of carbon monoxide and hydrogen as primary products, but also it could have presence of carbon dioxide, methane (depending the use of a catalyst), nitrogen and water vapor.

The SYNGAS requires 2 filtration stages in order to guarantee the use of this gas in internal combustion equipment:

- First filtration stage: It is related to the production of pyrolytic oils in the form of tiny droplets during the gasification process. These oils are removed during this first stage because they interfere with the second filtration stage, reducing the heating value of the SYNGAS and can cause damage to the internal combustion equipment [18].
- Second filtration stage: It deals with the solid particles, which, like tars, are dispersed within the SYNGAS itself and are composed of ash and carbon [18].

2.5 Additional processes

Finally, all the auxiliary and secondary processes that will be part of the gasification process must be identified. There are 6 processes necessary for its correct operation: feed shredding, air compression, gasification, filtering/conditioning of the SYNGAS and the electricity generation system.

The sequence of all the above processes are shown in Figure 1.

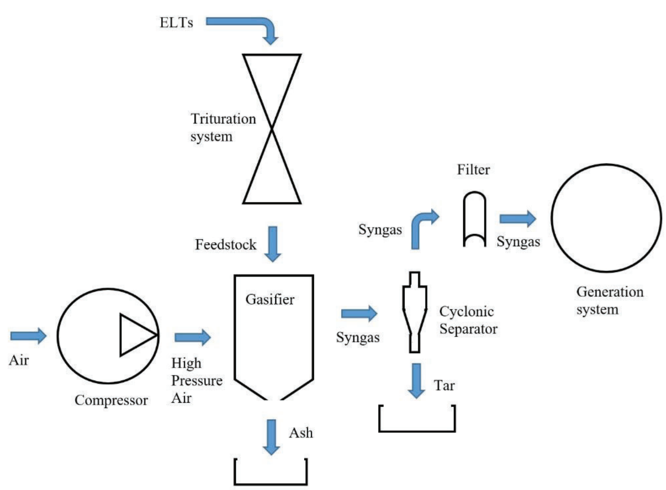

Figure 1: Additional processes for the gasification process

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3 METHODOLOGY

For the design of a gasification process, it is important to determine different parameters and properties first.

3.1 Heating value of the ELTs

The typical chemical composition of the ELTs is shown in Table 3.

Table 3: Typical chemical composition of the ELTs [19].

Element	Composition ($\%_{mass}$)			
	ELT Totally dry and ash-free	***ELT Totally dry***	***ELT with intrinsic humidity***	***ELT with surface humidity***
Carbon (C)	90.42	85.9	82.464	82.464
Hydrogen (H_2)	8.21	7.8	7.488	7.488
Nitrogen (N_2)	0.42	0.4	0.384	0.384
Sulfur (S)	0.53	0.5	0.48	0.48
Oxygen (O_2)	0.42	0.4	0.384	0.384
ash	0	5	4.8	4.8
Intrinsic humidity	0	0	4	4
Surface humidity	0	0	0	0
Total	**100**	**100**	**100**	**100**

Equation (1) gives the approximation of the higher heating value (HHV) for the selected gasifier feed as recommended by [13], which uses a semi-empirical correlation.

$$HHV_x = 349.1 * C + 1178.3 * H + 100.5 * S - 103.4 * O - 15.1 * N - 21.1 * Ash \tag{1}$$

Using the chemical composition information of the fully dried ELTs from Table 3 in Equation (1), the HHV of the ELTs was approximated as 39.07 MJ/kg.

The lower heating value (LHV), which is a function of the HHV and the latent heat of vaporization of the water, h_{fg} [20], was also estimated as:

$$LHV_x = HHV_x - h_g * \left(\frac{9 * H}{100} + \frac{Humidity_i}{100}\right) \tag{2}$$

From this equation, the LHV was estimated as 37.5 MJ/kg.

3.2 Stoichiometric air flow

It is important to determine the air-fuel ratio necessary for the ELTs to achieve complete combustion. First, in order to complete the stoichiometric combustion reaction, we need the molar composition of the ELTS, which is shown in Table 4.

Table 4: Molar composition off the ELTs.

Element	ELTs totally dry ($\%_{mass}$)	ELTs totally dry ($\%_{mol}$)
C	85.9	7.15833
H_2	7.8	3.9
N_2	0.4	0.01428
S	0.5	0.01562
O_2	0.4	0.01250
Ash	5.0	0

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Once we have the molar composition of the ELTs, and considering that the air is approximately 21% Oxygen and 79% Nitrogen, the stoichiometric combustion reaction ends up being the following:

$$7.1583\ C + 3.9\ H_2 + 0.01429\ N_2 + 0.01562\ S + 0.0125\ O_2 + a_{teo}\left(O_2 + \frac{79}{21}\ N_2\right) \rightarrow x\ CO_2 + y\ \ H_2O + z\ \ SO_2 + w\ \ N_2 \quad (3)$$

Through a molar balance in the reaction, the values obtained for the combustion gases (products) and theoretical air (reactive) are: 7.1583 mol CO_2, 3.9 mol H_2O, 0.01429 mol SO_2, 34.29 mol N_2 and 9.11 mol of air. Subsequently, the air-fuel ratio required for the ELTs to achieve complete combustion can be obtained with the following equation:

$$m_{th} = \frac{9.11 * \left(1 + \frac{79}{21}\right) * 28.96}{100} \left(\frac{kg_{air}}{kg_{fueldry}}\right) \quad (4)$$

3.3 Gasification agent volumetric flow

Gasification is a process that operates under incomplete combustion conditions, so the stoichiometric or ideal air-fuel ratio is not the required ratio, therefore, it is necessary to apply a correction factor called equivalence ratio (ER). The equivalence ratio can vary from 0.2 to 0.4, which is why this ratio has been extensively studied to determine the optimum value, since this variable can have a considerable influence on the production of tars and carbonized material [13]. An exhaustive analysis by [21] [22] [23] [24] and [25] concludes that the most recommended equivalence ratio is 0.3 because the gas produced has a lower amount of tars and the calorific value of SYNGAS is higher.

Thus, under the criteria described above, the actual air-fuel ratio for the gasification feed is obtained:

$$m_{real} = m_{th} * ER\left(\frac{kg_{aire}}{kg_{combseco}}\right) \quad (5)$$

After this, the mass air flow must be estimated. First, we need to define the mass flow of feedstock to be processed in a day of operation, so that the amount of feedstock per working hour (FCR_T) can be determined. In order to determine the amount of feedstock available, the first thing to do is to select a location for the gasifier to determine the quantity and quality of the feedstock, in addition to delimit the amount of feedstock to be processed in a working day and finally, to know the environmental conditions under which the system will operate. Therefore, to determine the mass air flow rate of the gasifier, we multiply the amount of feedstock to be processed per hour, FCR_T, and the actual air-fuel ratio, m_{real}:

$$\dot{m}_a = m_{real} * FCR_T\left(\frac{\mathrm{kg_{aire}}}{\mathrm{h}}\right) \quad (6)$$

Then, the ideal gas equation of state was used to calculate the volumetric flow of air for gasification, according to this equation:

$$Q_a = \frac{\dot{m}_a * R * T_L}{P_L}\left(\frac{m^3}{h}\right) \quad (7)$$

Where TL is the temperature of the operating location and PL the average pressure of the determined location.

3.4 Design of the gasifier system

Fig. 2 shows the design sequence of an Imbert type Inverted Draft Gasifier (with throat).

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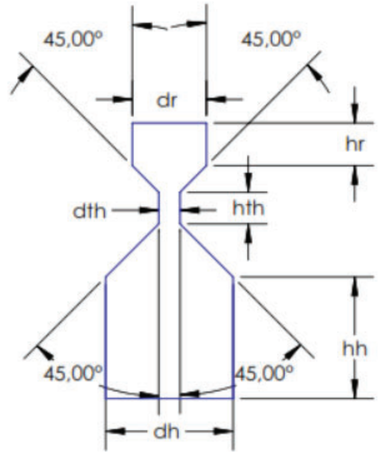

Figure 2. Gasifier design

As shown in Fig. 2, the gasifier has 3 zones: throat zone, reactor zone and ash collection zone. The three zones will be circular because they allow a better heat exchange and therefore allow the production of a SYNGAS with a higher heating value. Also, it is important to define the material with which the gasifier equipment will be made. The desirable alloy steel is the AISI 310, since this steel is used for high temperature processes.

For the geometrical design of the gasifier, first two basic parameters of the gasification unit were determined: i) the thermal power of the gasifier, which can be calculated using the mass flow of processed feedstock per hour (FCR_T), the lower heating value of the feedstock (LHV) and ii) the gasifier efficiency (ηgef), which is usually between 60% and 80% [12]. Therefore, it is advised to assume that the gasifier has an efficiency of 60% because within this equation it is a critical point of analysis [16].

$$E_T = FCR_T * LHV_x * \eta_{gef} \ (\frac{MJ}{s}) \tag{8}$$

Additionally, the thermal energy produced by the designed unit must be evaluated, since inverted draft gasifiers must have a thermal power between 1 kW and 2 MW [26].

Also, one parameter that must be defined is the SYNGAS production, and to determine it, it is necessary to have previously obtained the thermal energy (E_T), in addition to knowing the lower heating value (LHVg) and the density of the SYNGAS (ρ_g) [12].

$$SG = \frac{E_T}{LHV_g * \rho_g} \ (\frac{m^3}{h}) \tag{9}$$

Once both basic parameters were defined, the gasification unit is designed zone by zone.

3.5 Design od the throat zone

Starting with the sizing of the throat zone (d_{th}), it should be clarified that the first variable to be determined is the area of this zone (A_{th}), so it is necessary to know the specific gasification rate (SGR) and the SYNGAS flow produced by the main equipment [11]. The SGR has typical values between 1.92 and 2.64 $m^3/(m^2*h)$, it is recommended to use the lower value according to [26].

$$A_{th} = \frac{SG}{SGR} \tag{10}$$

So, the diameter of this zone can be determined by:

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$$d_{th}^2 = A_{th} * \frac{4}{\pi} \tag{11}$$

As a final dimension, the height of this zone (h_{th}) is calculated using the following correlation:

$$h_{th} = d_{th} * 1{,}5 \tag{12}$$

3.6 Design of the reactor zone

The reactor zone is directly dependent on the throat diameter, so the following correlation is used in order to determine the diameter of this zone (d_r) [12]:

$$\frac{d_r}{d_{th}} = 3.5 \tag{13}$$

Then, the height of this zone (h_r) is obtained through the following equation:

$$\frac{h_r}{d_{th}} = 2.0 \tag{14}$$

On the other hand, as mentioned in the introduction, the size of the feedstock material is important and it is recommended to be between 10 and 20% of the reactor diameter. So, using the critical point of this range, the diameter of the feedstock should be:

$$d_{Feedstock} = d_r * 0.10\ (mm) \tag{15}$$

Likewise, it should be verified that these dimensions are between 20 and 80 mm. It is worth to mention that using the diameter of the feedstock, the design and implementation of a grill should be carried out, which will be mounted between the reactor zone and the ash collection zone, this grill allows the large fragments of feed to remain in the reactor zone, thus allowing the gasification process to function correctly.

3.7 Design of the ash recollection zone

The sizing of the ash collection area first requires obtaining the diameter of this area (d_h), so it is necessary to know the total amount of feed that will be stored during an operation cycle (FCR_p) and it is also necessary to know the relative capacity tube (RCT), whose value can range between 250 and 300 kg/(m^2*h). According to [26], it is recommended to use the lower value.

$$d_h^2 = \frac{FCR_P}{RCT} * \frac{4}{\pi} \tag{16}$$

It is required to obtain the volume to be stored by this zone (V_o), therefore, it is necessary to know the amount of feedstock processed per hour (FCR_T), the total working time of the equipment (t_T) and the density of the feedstock material (ρ_x).

$$V_o = \frac{FCR_T * t_T}{\rho_x} \tag{17}$$

Finally, the height of the ass recollection zone is estimated according to the following correlation [12]:

$$h_h = \frac{V_o}{A_h}\ (cm) \tag{18}$$

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4 RESULTS

This section presents the sizing of a gasification unit using the equations presented in section 2. The first step for the sizing of this equipment was the estimation of the amount of feedstock to be processed in the study area, which will be the city of Cochabamba, Bolivia, equal to 609 of ELTs per day, a value obtained based on several surveys to tire suppliers, assuming that for each tire purchased by the population, one ELT is generated. As a result of these surveys to 58 tire importers and considering that each ELT has an average mass of 7.26 kg, 4,422.86 kg of ELTs are generated per day.

For sizing purposes, it was assumed that only 25% of the daily generation of ELTs in the city will be processed, so 1120 kg/day of ELTs will be subjected to gasification per day, and taking into account that one day of operation is equivalent to 8 h, the mass of ELTs to be processed will be 140 kg/hr.

Subsequently, equation (8) was used to calculate the thermal energy of this ELT flow:

$$E_T = 140\left(\frac{kg}{h}\right) * 37{,}5\left(\frac{MJ}{kg}\right) * 0{,}6 * (\frac{1\ h}{3600\ s}) *= 0{,}875\ (\frac{MJ}{s}) \tag{19}$$

Then, the SYNGAS production was calculated using equation (9), considering a LHV of 45.5 MJ/kg [15] and a gas density of 1.09 kg/m3 [9], then it is obtained:

$$SG = \frac{0{,}875\ \left(\frac{MJ}{s}\right) * \left(\frac{3600\ s}{h}\right)}{45{,}5\frac{MJ}{kg} * 1{,}09\frac{kg}{m^3}} = 63{,}51(\frac{m^3}{h}) \tag{20}$$

Finally, following the guide for the design of the different zones of the gasifier equipment described in section 3, the dimensions are estimated. These dimensions are shown in Table 5.

Table 5: Dimension of the gasifier equipment.

Zone	Parameter		Value
Throat Zone	Area (cm^2)	A_{th}	330.78
	Diameter (cm)	d_{th}	20.52
	Height (cm)	h_{th}	30.78
Reactor Zone	Diameter (cm)	d_r	71.82
	Height (cm)	h_r	41.04
	Feedstock diameter (mm)	$d_{Alimento}$	71.80
Ash Recollection Zone	Diameter (cm)	d_h	168.88
	Volume (m^3)	V_o	2.09
	Height (cm)	h_h	93.5

As a result of the sizing of the gasification unit applied to ELT, the equipment shown in Fig. 3 is obtained.

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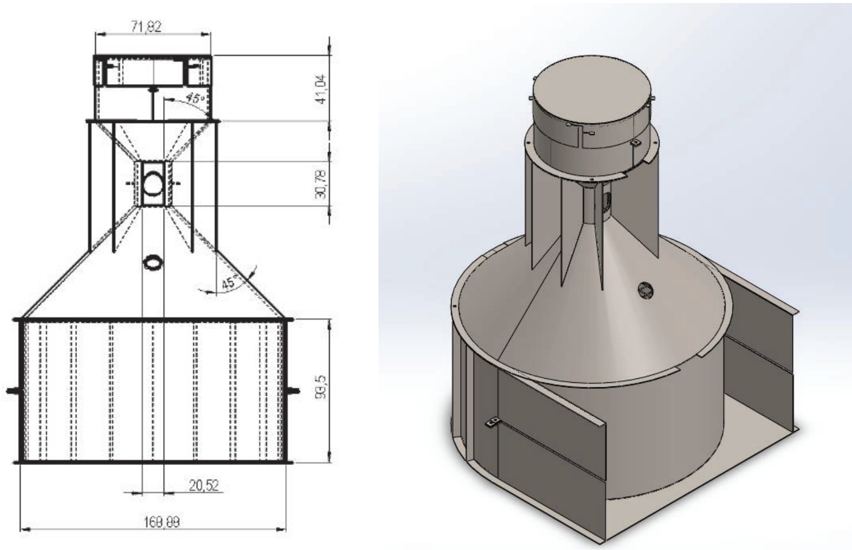

Figure 3. Gasifier equipment.

5 CONCLUSIONS

Although the gasification process was born with coal, a non-renewable energy source, it was later applied to biomass processing, and in the present work it is presented as a solution to the excessive accumulation of ELTs.

The research provided valuable information about the revaluation of ELTs, resulting in an in-depth study of the gasification process, as well as the correct sizing of the main unit for the process, and it also allowed to identify each of the elements, required auxiliary and secondary processes. It was also possible to gather important information about the conditioning of the gas produced in order to implement it as fuel in internal combustion equipment. Finally, it was possible to identify the different conditions under which an electric generation equipment can be selected to use the produced gas. The result is a complete guide for the correct sizing of a gasification unit applied to ELTs.

It is also important to mention that, in order to validate the composite procedure, the present work should be complemented with the construction of a prototype, in which the operating parameters can be verified and corrections to the guide can be made.

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