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Technical assessment of discarded tires gasification as alternative technology for electricity generation

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ABSTRACT

Concern about contamination associated with the disposal of tires has led to the search for technologies to reuse discarded tires, which include the use of Tire Derived Fuel (TDF) as fuel in advanced thermal-conversion processes, this allows the energy use of these wastes at affordable costs and reduces the environmental impact on scrap tires disposal. A theoretical assessment of the technical viability of TDF gasification for electric and thermal power generation, from the producer gas combustion in an internal combustion engine and in a gas turbine, was performed. The combustion of producer gas derived from the gasification of TDF in an internal combustion engine driving a generator (ICE-G) appears as the more efficient route for electricity generation when compared with the efficiency obtained with the use of gas turbine (GT-G). A higher global efficiency, considering the electric and thermal generation efficiency can be expected with the use of TDF producer gas in GT-G, where is expected an overall efficiency of 77.49%. The assessment shows that is possible produces up to 7.67 MJ and 10.62 MJ of electric and thermal energy per kilogram of TDF gasified using an ICE-G and up to 6.06 MJ and 13.03 MJ of electric and thermal energy respectively per kilogram of gasified TDF using a GT-G.

1. Introduction

Tire disposal is a problem throughout the world that is aggravated as the vehicle fleet grows. The tire must have proper disposal procedure, to reduce their impact on the environment. However, most of the time, incineration becomes the disposal procedure, since it is the fastest and easiest way to discard it. Tire incineration forms hundreds of different combustion products, ranging from simple to complex hydrocarbons and halogechlorinated hydrocarbons (ranging from chlorinated methanes to the ultra-toxic dioxins and polychlorinated biphenyl (PCBs)) (Lew, 1990). Pyrolytic oil, is also produced which contains toxic chemicals and heavy metal compounds, capable to cause adverse health effects.

The estimated number of waste tires generated annually in Brazil rounds between 17 and 20 million units, from which 6 million units are generated in the state of São Paulo. The number of accumulated units in inappropriate deposits is estimated to be at least 100 million units (Andrade, 2007; ABRELPE, 2015).

Concern about contamination associated with the disposal of tires has led to the search for technologies to reuse discarded tires, which include energetic valorization, introduction as raw material in buildings construction, in the processing of asphalt surfacing and in the footwear industry, among others.

Due to its high calorific value, scrap tires are widely used as fuel in thermoelectric generation, in co-combustion coal-fired boilers and in the production of oils. Another major objective for uses of tires as fuel is to decrease the number of scrap tires disposed in landfills or stockpiles.

These applications however, are questioned due the pollutant emissions levels. According to United States Environmental Protection Agency (Marchiori, 2007), tire combustion emits approximately 6% of the burned fuel mass as solid particles and volatiles.

The use of Tire Derived Fuel (TDF) as fuel in advanced thermal-conversion processes with low contaminants emissions is a promising alternative in the market today, which allows the energy use of these wastes at affordable costs and reduces the environmental impact on the scrap tires disposal. Some experimental and theoretical studies on waste tires gasification at laboratory scale has been performed, mainly using plasma and steam gasification (Choi et al., 2016; Portofino et al., 2013; Galvagno et al., 2009; Xiao et al., 2008; Wang et al., 2016; Janajreh and Raza, 2014a), but with little information about the applicability of this route for electricity and heat production.

On this background, the main objective of this work is to perform a theoretical assessment of the technical viability of TDF

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Nomenclature

$\dot{m}_x$	mass flux of element x [kg/s]	LHW_x	lower heating value of element x [MJ/kg_{fuel}]
h_{fg}	water vaporization enthalpy [MJ/kg]	TDF	Tire Derived Fuel
Δh_x	enthalpy change of the element x [MJ/kg]	ICE-G	internal combustion engine driving an electric generator
Q_G	heat lost in the reactor [MW]	GT-G	gas turbine driving an electric generator
$\eta_{gasifier}$	reactor cold gas efficiency [%]	BFBG	Bubbling Fluidized Bed Gasifier
HHW_x	higher heating value of element x [MJ/kg_{fuel}]		

gasification for electric and thermal power generation, from the producer gas combustion in an internal combustion engine driving an electric generator (ICE-G) and in a gas turbine driving an electric generator (GT-G). This study provides a support for decision makers in order to select the correct technology for the desired applications from the energetic valorization of this waste.

2. Methodology for the technical analysis

The study evaluated the implementation of waste tires gasification for electricity generation using two different technology. In both cases, are performed the mass and energy balance in all components of the configuration. The generation efficiencies of electricity, heat and the overall efficiency were also determined. In the final stage, a comparison taking into account the thermodynamic efficiency of different cases was performed. Fig. 1 shows the technical analysis methodology for gasification of TDF for electric and thermal energy generation.

3. Waste tire gasification

The tire life cycle consists generally of five main stages, comprising the extraction of raw materials, production, consumption (use), waste tire collection and processing for recycling or disposal, depending on the local conditions of each country or region where they are produced or sold (Van Beukering and Janssen, 2001).

Tires have a mixed composition of carbon black, elastomer compounds, and steel cord, in addition to several other organic and inorganic components. Fig. 2 (ETRMA, 2014) shows a view of the tires average composition.

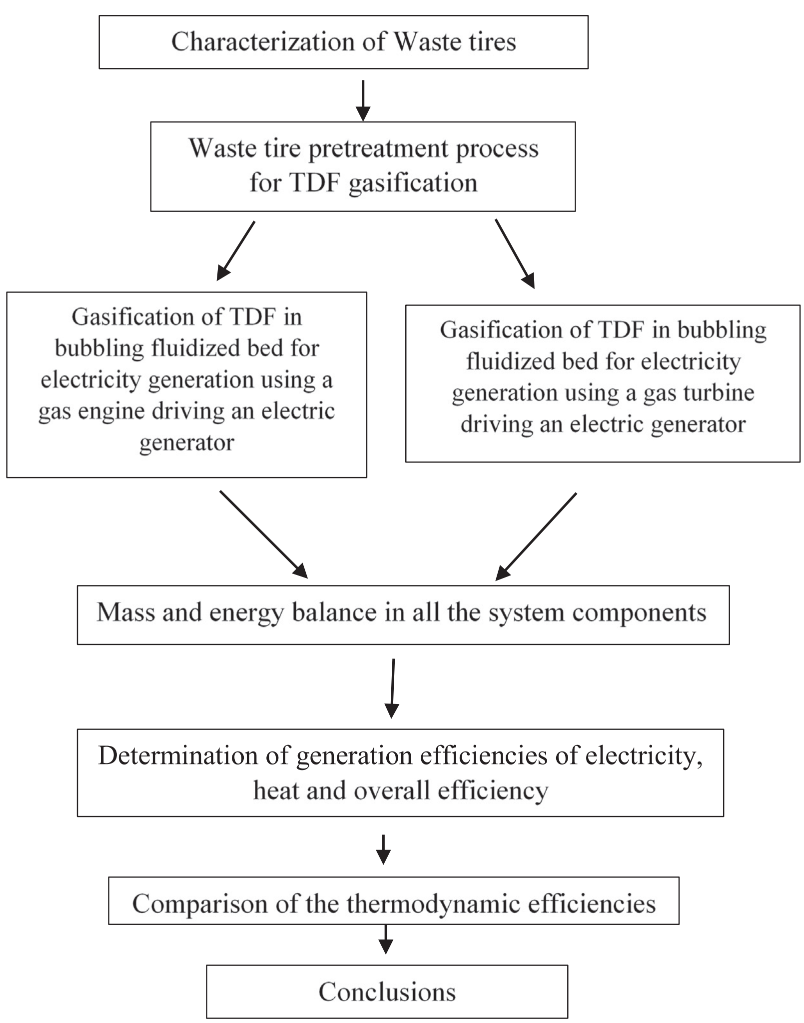

Fig. 1. Technical methodology for gasification of TDF for electric and thermal energy generation.

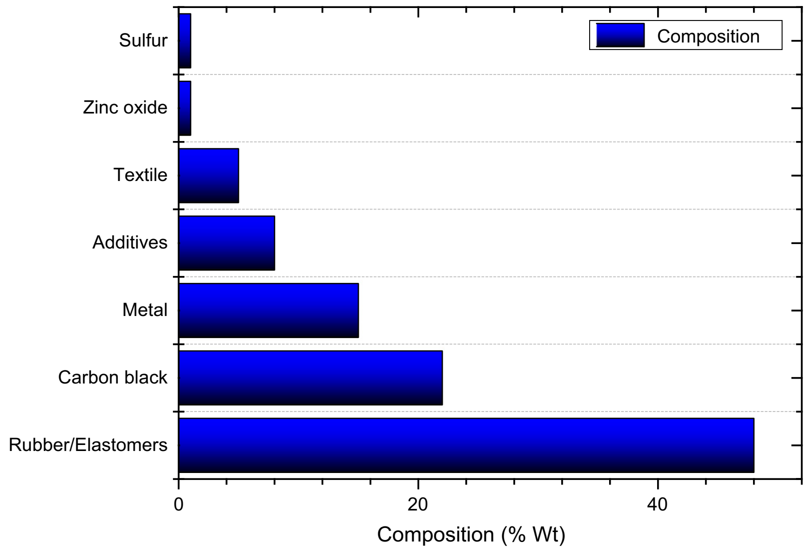

Fig. 2. Average composition of a tire.

The main components of the tires, the rubbery materials, are presented in the form of C_xH_y, with some fibrous materials, and they are considered thermoset polymers (Leung and Wang, 1998). Vehicle tires (both passenger and truck) are mainly a blend of natural (NR) and synthetic rubber (SR), such as butyl rubber (BR) and styrene–butadiene copolymer (SBR) (Martinez et al., 2013). The NR comes from Hevea tree, while the SR is generally derived from petroleum-based products (Shulman, 2004). NR has unique elastic properties and it is an essential element of a tire.

Analyzing different rubber compounds, several authors report different results of proximate and elemental analysis, as shown in Table 1 (Lee et al., 1995; Zhang et al., 2008; Chang, 1996; González et al., 2001; Williams and Richard, 1995; Orr et al., 1996; Cunliffe and Williams, 1998; Lanoir et al., 1998) and Table 2 (Rodríguez et al., 2001; Zhang et al., 2008; Isabel de Marco Rodriguez et al., 2001; Chang, 1996; González et al., 2001; Laresgoiti et al., 2004; Cunliffe and Williams, 1998; Arion et al., 2001; Williams and Richard, 1995; Orr et al., 1996; Lanoir et al., 1998) respectively. For obtaining the average content of elements in tires, each part of tire must be analyzed.

The higher heating value was estimated using the mean elemental compositions reported in Table 2 and the Modified Dulong Eq. (1), generally best for fuel-like, high carbon/hydrogen materials such as Tire Derived Fuels (TDF), on a moisture and ash-free basis (Buckley and Domalski, 1988), where C, H_2, S, O_2, and N_2 stand for the corresponding element mass percentage in the fuel.

$$HHV = \left[78.31C + 359.32\left(H_2 - \frac{O}{8}\right) + 22.12S + 11.87O_2 + 5.78N_2\right]0.0041868\ (\text{MJ/kg}) \qquad (1)$$

The HHV is mathematically related with lower heating values (IPCC Guidelines, 2006) (LHV), by the Eq. (2) in MJ/kg.

$$LHV = HHV - 0.212 * H_2 - 0.0245 * M - 0.008 * O_2\ (\text{MJ/kg}) \qquad (2)$$

where M is the percent moisture in the feedstock.

The TDF fuel is compact, has a consistent composition and low moisture content which are, all benefits to the fuel user in advanced thermal-conversion processes with low contaminant emissions.

3.1. Waste tire processing

While some combustion systems, like cement kilns, can accept whole tires, most of the thermal-conversion systems required that the tires be processed to certain sizes and purity to ensure that the material consistently meets the needs of the particular fuel users. Shredding waste tires to produce TDF uses standard material processing technologies which include shredding, component separation and dirt and other contaminants removal.

Processing waste tires into TDF mainly involves two physical processing stages: chipping/shredding and metal removal. In the

Table 1
Proximate analysis for waste tire rubber by several authors.

Reference	Volatile (wt%)	Fixed carbon (wt%)	Moisture (wt%)	Ash (wt %)
16	67.3	28.5	0.5	3.7
17	61.61	22.66	1.72	14.01
18	62.32	26.26	1.31	10.29
19	61.9	29.2	0.7	8.0
20	66.5	30.3	0.8	2.4
21	68.7	23.3	0.4	7.6
22	62.2	29.4	7.1	1.3
23	64.0	30.7	0.9	4.4

Table 2
Elemental analysis of waste tire rubber by several authors.

Reference	C (wt%)	H (wt%)	N (wt%)	S (wt%)	O (wt%)	Ash (wt%)
24	74.2	5.8	0.3	1.5	4.7	13.5
17[a]	81.24	7.36	0.49	1.99	8.92	–
25	74.2	5.8	0.3	1.5	4.7	13.5
18	74.4	6.94	0.21	1.6	5.02	10.21
19	86.7	8.1	0.4	1.4	1.3	2.1
26	81.16	7.22	0.47	1.64	2.07	7.44
22	74.2	5.8	0.3	1.5	4.7	13.5
16	83.8	7.6	0.4	1.4	3.1	3.7
27	73.8	5.3	0.44	1.71	0.11	17.8
20	85.8	8.0	0.4	1.0	2.3	2.4
21	81.3	7.3	0.3	1.5	–	1.4
23[a]	82.63	7.5	0.36	1.69	–	–
28	86.7	6.9	0.3	1.9	0.9	3.3

[a] Based on free of ash.

first step, whole waste tires are either fed into the shredder or have the beads removed prior to shredding. The processing equipment are typically high-shear, low-torque shredders. Scrap passenger and truck tires up to 1.22 m in outside diameter can be initially reduced in these rotary shear shredders to pieces ranging in size from 2.5 to 10 cm, depending on the end-use. To produce TDF, whole tires are reduced to nominal 5 cm pieces using one shredder or a series of shredders, screening equipment, and magnetic separation equipment (ASTM, 2006). Magnetic separators are required to remove the steel. A screen in the discharge of the shredder controls the shred/chip size where the two-inch sized material falls through the screen openings, while the oversized material is recirculated back to the shredder. Because a significant amount of rubber is entrained and lost in the wire removal stream, downstream shredding and wire removal can be employed to recover additional rubber, make a cleaner steel product for sale as scrap and to avoid landfilling of this wire/rubber material. If smaller-sized TDF is specified, then more size reduction, metal and fiber separation, classifying, screening and cleaning equipment may be required.

In this study, it is considered that waste tires will be processed using an Eldan Tire Recycling Plant model E1500T. This plant needs 200 kW h of electricity to process 1–1.5 t of waste tires per hour to produce TDF with size range of 0–4 mm (Evans). The main objective of scrap tire pretreatment is the steel separation from this waste and the reduction of the fuel particle size before its introduction in the gasification island. The final dimensions of the fuel particles will depend on the gasifier technology.

3.2. TDF gasification

Gasification is a promising technology for waste based power generation (Mendiburu et al., 2014; Mota et al., 2015; Couto et al., 2015). Is a high-temperature process (873–1273 K), that decomposes the waste into gaseous fuel, primarily hydrogen, carbon monoxide, and carbon dioxide. Some tars (PAH- polycyclic aromatic hydrocarbon), char, methane, water, and other constituents also are formed (Reed and Das, 1998; Ismail et al., 2016; van de Beld et al., 2001; Pedroso et al., 2013). Hydrogen and carbon monoxide are the desired product gases, because a mixture of them can be fed directly to ICE-G and GT-G for power generation or can be used for chemicals synthesis. The main gasification reactions of carbonaceous fuels are as follows (Reed and Das, 1998):

$$C + H_2O \leftrightarrow CO + H_2 \qquad \Delta H^0_{298} = 131.5 \text{kJ} \cdot \text{mol}^{-1} \tag{3}$$

$$C + CO_2 \leftrightarrow 2CO \qquad \Delta H^0_{298} = 172 \text{ kJ} \cdot \text{mol}^{-1} \tag{4}$$

$$C + 2H_2 \leftrightarrow CH_4 \qquad \Delta H^0_{298} = -74 \text{ kJ} \cdot \text{mol}^{-1} \tag{5}$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta H^0_{298} = -41 \text{ kJ} \cdot \text{mol}^{-1} \tag{6}$$

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \qquad \Delta H^0_{298} = -206 \text{ kJ} \cdot \text{mol}^{-1} \tag{7}$$

The extent of the above reactions, the products distribution and the producer gas composition are function of gasification conditions, such as gasification agent, gasification temperature, stoichiometric ratio, residences time and fuel composition.

The waste tire gasification for energy generation is a technology that has been mainly carried out with plasma gasifiers due to the complex composition of this feedstock. The waste tire processing for obtaining TDF makes possible the employment of less complex gasification technologies.

The viability of the implementation of Bubbling Fluidized Bed Gasification (BFBG) of TDF, for electricity generation using a gas engine and a gas turbine, will be analyzed.

In BFBG the fuel feeding is typically at the base of the reactor bed. The bed material is fluidized by the gasifying agent (oxygen in our case) entering the gasifier through nozzles distributed along the bottom of the reactor. The fluidization velocity of the gasifying agent is low because there is no significant movement of the solid; the typical superficial velocity ranges 0.8–1.4 m/s. These gasifiers are usually used in plant sizes lower than 10 MW (thermal). The reason for this size limitation is the requirement for good fuel distribution over the bed, which becomes more difficult with increasing diameter of the reactor.

The main advantages of fluidized beds include: better control of the reaction rates and temperatures, high specific capacity, easy adaptation to changes in fuel characteristics and lower efficiency losses caused by unreactive particles. These types of reactors also have low sensitivity to variations in fuel moisture (Zainal, 2010).

The energy balance in a gasifier employing air, oxygen, steam or mixtures as gasification agent is defined by Eq. (Prins et al., 2003; Karamarkovic and Karamarkovic, 2010) (6):

$$\begin{aligned} &\dot{m}_{TDF} LHV_{TDF} + \dot{m}_{air}\Delta h_{air} + \dot{m}_{O_2}\Delta h_{O_2} + \dot{m}_{H_2O}(h_{fg} + \Delta h_{H_2O}) \\ &\quad = \dot{m}_{PGas}(\Delta h_{PGas} + LHV_{PGas}) + \dot{m}_{Char}(\Delta h_{char} + LHV_{char}) \\ &\qquad + \dot{m}_{ashes}\Delta h_{ashes} + Q_G \end{aligned} \tag{8}$$

where: $\dot{m}_x$ is the mass flux of the element x, h_{fg} is the water vaporization enthalpy, Δh_x is the enthalpy change of the element x, Q_G is the heat lost in the reactor, *Pgas* (producer gas) and *LHV* is the lower heating values in MJ/kg.

Fig. 3 shown the main mass and energy fluxes considered in the BFBG for the balance in the studied case.

It was considered in the study that gasification agent was oxygen at standard conditions, and gasification occurs at Carbon Boundary Point, i.e. when it is incorporated into the exact amount the gasification agent, ensuring complete gasification of the fuel with no char formation; the energy balance in the analyzed system (Fig. 3) is defined as follows:

$$\begin{aligned} \dot{m}_{TDF} \cdot LHV_{TDF} + \dot{m}_{O_2}\Delta h_{O_2} &= \dot{m}_{PGas}(\Delta h_{PGas} + LHV_{PGas}) + \dot{m}_{tar}\Delta h_{tar} \\ &\quad + \dot{m}_{ashes}\Delta h_{ashes} + Q_G \end{aligned} \tag{9}$$

Since gasification process intends to produce a clean fuel gas usable at ambient temperature, and considering that the gasification agent (oxygen in our case) is not pre-heated before entering the reactor; the cold gas efficiency ($\eta_{gasifier}$) is defined as the ratio of the heat content of the producer gas generated by the gasification of the TDF to the heat released by TDF when it is totally burnt. The $\eta_{gasifier}$ is given by the Eq. (9):

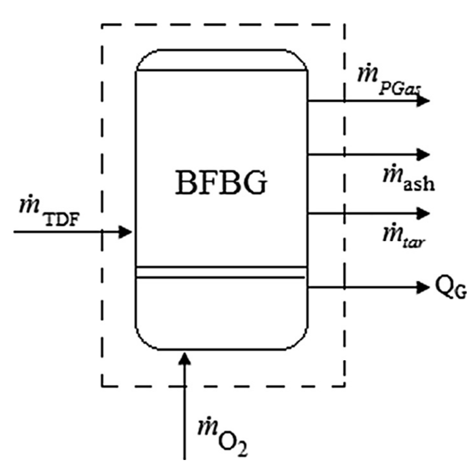

Fig. 3. Main mass and energy fluxes in the BFBG.

$$\eta_{gasifier} = \left(\frac{\dot{m}_{PGas} \cdot LHV_{PGas}}{\dot{m}_{TDF} \cdot LHV_{TDF}}\right) \quad (10)$$

The $\eta_{gasifier}$ of the BFBG in our case was considered 67%, considering the experimental results reported by several authors (Xiao et al., 2008; Karatas et al., 2013, 2012; Leung and Wang, 2003). The gasification process of TDF was modelled considering the theoretical results reported (Mitta et al., 2006) and (Janajreh and Raza, 2014b). For the calculus was also considered a stoichiometric ratio oxygen/TDF of 2.64 according to the composition reported in Table 2 and a gasification temperature of 1223 K.

4. BFBG of TDF for electricity generation using a gas engine driving an electric generator

The development of new engines and gas turbines able to use gas with low heating value as fuel (Barsali et al., 2015; Gobbato et al., 2015; Pérez et al., 2015) and the relatively high heating value of TDF enable the implementation of the gasification of TDF for electric and thermal power generation.

In this configuration, the combustion of the producer gas, derived from the gasification of TDF, in an ICE-G, is proposed. For the study, a Jenbacher gas engines generator, model JMS 620 (Table 3 Jenbacher Gas Engines) was considered.

In the proposed configuration (Fig. 4), after the waste tire pretreatment in the E1500T plant, the TDF is fed to the gasification island composed by a Bubbling Fluidized Bed Gasifier (Carbona® Technology) (E4TECH, 2009), an Air Separation Unit (ASU) and gas cleaning systems.

Using oxygen as gasification agent for gasification of TDF, considering the elemental composition as reported in Table 2 and the equivalent ratio of 0.3, the gasification island yields 1.7 kg of producer gas per kg of TDF fed.

Fig. 5 shows the interconnection between the installations that compose the Gasification Island; which is formed by the ASU, the BFBG and the Cleaning System. The considered technology of BFBG was the RENUGAS, technology commercially available and tested (Pérez et al., 2015).

To determine the mass flow rate of TDF that will be introduced into the gasifier ($\dot{m}_{TDF}$), the fuel fraction contained in the waste tires after steel separation is considered as well as its HHV and LHV are determined, by mean of the equation Eqs. (1) and (2) as discussed in Section 3. The obtained values were 36.80 and

Table 3
GE Jenbacher, model JMS 620 parameters.

Electrical output	kW_{el}	2433
Recoverable thermal output (180 °C)	kW	2743
Energy input	kW_{th}	6205
Fuel consumption based on a LHV of 18 MJ/Nm^3	Nm^3/h	1241
Electrical efficiency	%	39.2
Thermal efficiency	%	44.2
Total efficiency	%	83.4

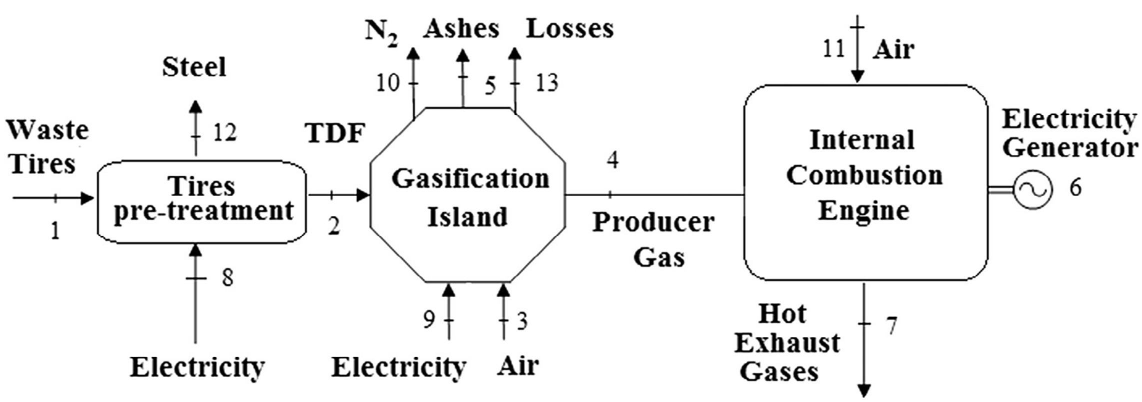

Fig. 4. Gasification of TDF for electricity generation using a gas engine driving an electric generator.

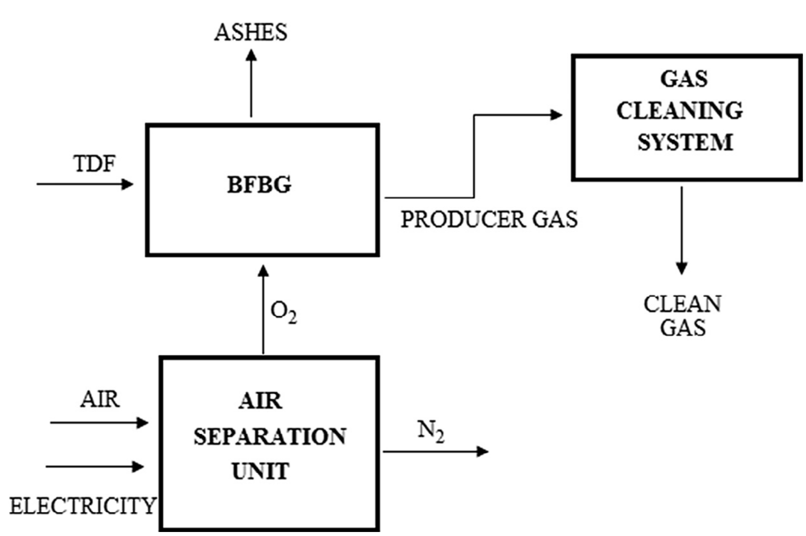

Fig. 5. Interconnection between the installations that compose the Gasification Island.

35.26 MJ/kg respectively, similar to the experimental values reported by other authors (Karatas et al., 2013, 2012; Leung and Wang, 2003; Mitta et al., 2006; Cooper et al., 1999; Clark et al., 1991).

Table 4 shows the results of the mass and energy balance for the implementation of this configuration for the TDF gasification for electricity generation using an ICE-G.

In this configuration, the net electricity generated is 1.49 MWe with electric efficiencies of 21.41%. The thermal power in the exhaust gases is 2.06 MWth. It was considered clean gas exit from the gasification island at standard ambient temperature and pressure (SATP) to feed the ICE-G. Hence, according to Eq. (9), the lost in the gasification island (Point 13) can be considered as:

$$Lost = \dot{m}_{PGas}\Delta h_{PGas} + \dot{m}_{ashes}\Delta h_{ashes} + \dot{m}_{tar}\Delta h_{tar} + Q_G \quad (11)$$

Approximately 75% of the lost in the gasification process correspond to the thermal energy transferred to the producer gas in the form of latent heat (Jankes et al., 2012; Basu, 2006; Higman and van der Burgt, 2008) ($\dot{m}_{PGas}\Delta h_{PGas}$); that can be recovered for downstream applications. More complex is the recuperation of the tar chemical energy and the heats lost in the hot ashes and through the gasifier wall. In the case of the proposed plant the available latent heat in the producer gas at the gasifier exit, reaches 1.69 MWth., The thermal efficiency in the proposed configuration is 53.85%.

Table 4
Results of the mass and energy balance for the implementation of the BFBG of TDF coupled to ICE-G model JMS 620.

Point	Mass flow [kg s^{-1}]	Temperature [K]	Pressure [kPa]	Energy flow [MW]
1	0.292	298	101.3	6.86
2	0.194	298	101.3	6.86
3	0.978	298	101.3	0
4	0.382	298	101.3	4.59
5	0.018	298	101.3	0
6	–	–	–	1.80
7	4.27	740	101.3	2.03
8	–	–	–	0.2
9	–	–	–	0.18
10	0.772	298	101.3	0
11	3.89	298	101.3	0
12	0.097	298	101.3	0
13	–	–	–	2.26

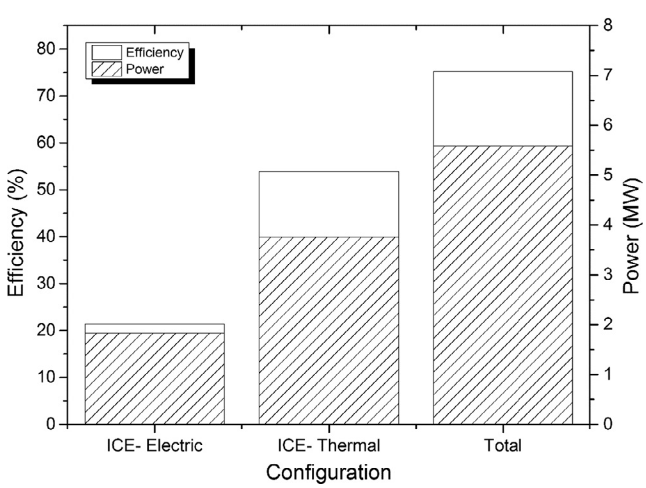

Fig. 6. Electric, thermal and total power and generation efficiencies in the ICE-G.

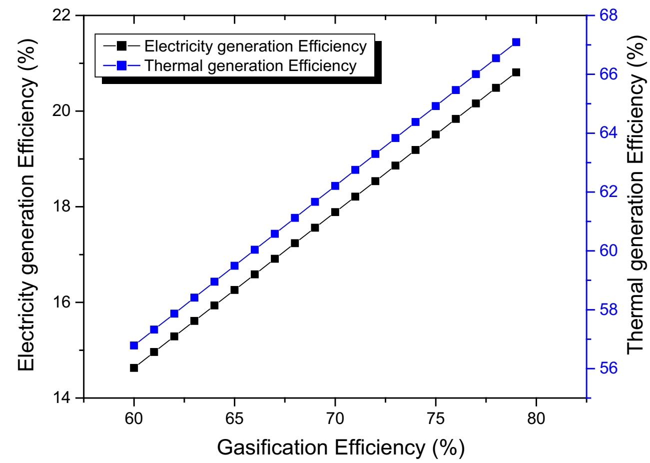

Fig. 7. Effects of gasification efficiency variation of on ICE-G thermal and electricity generation efficiency.

Fig. 6 shows the electric, thermal, total power generated and the generation efficiencies when the TDF derived producer gas is fed into the ICE-G for electricity and thermal power generation.

The thermal energy in the producer gas and engine exhaust gases could be also used for hot water production or refrigeration in absorption chiller (Gobbato et al., 2015; Edera and Kojima, 2002; Jankes et al., 2012). In this configuration the thermal energy represents the 67.2% of the total energy obtained in the TDF gasification. The global efficiency in this configuration could reach 75.25%, and the capacity of processing scrap tires, will be function of the gasifier size or the number of gasifiers in the gasification island.

The gasifier efficiency is shows as a key parameter for the performance for this type of arrangement. Effects of gasification efficiency variation of on thermal and electricity generation efficiency was studied as shows in Fig. 7.

For the range of cold gas efficiencies analyzed, is possible observes the impacts in the electricity and thermal generation efficiencies of the variation in the gasification island performance, showing a low sensibility of the variation of this parameter in the energies generation performances of the studied configuration.

5. BFBG of TDF for electricity generation using a gas turbine driving an electric generator

In the second proposed alternative (Fig. 8), the producer gas will be generated with the same installations employed in the previous analyzed case. The producer gas will be used as feedstock for five Flex Turbine® model GT333S of 333 kW connected in parallel (considering the capacity of the gasifier and the gas turbine nominal capacity). The main characteristics of the Flex Turbine® model GT333S are shown in Table 5 (High Efficiency Gas Turbine Generator with Lowest Emissions, 2017).

Table 6 shows the results of the mass and energy balance for the implementation of this configuration for electricity generation using a GT-G.

In this case, the net electricity generated is 1.518 MWe, with an electric efficiency of 16.91%. The thermal power in the exhaust gases is 2.53 MWth; the, thermal efficiency in this case is 60.58%. Fig. 9 shows the electric, thermal and total power generated and generation efficiencies when the TDF derived producer gas is fed to the GT-G for electricity and thermal energy production.

In this case the thermal energy represents the 73.5% of the total energy obtained in the TDF gasification. The global energy generation efficiency with this configuration is 77.49%.

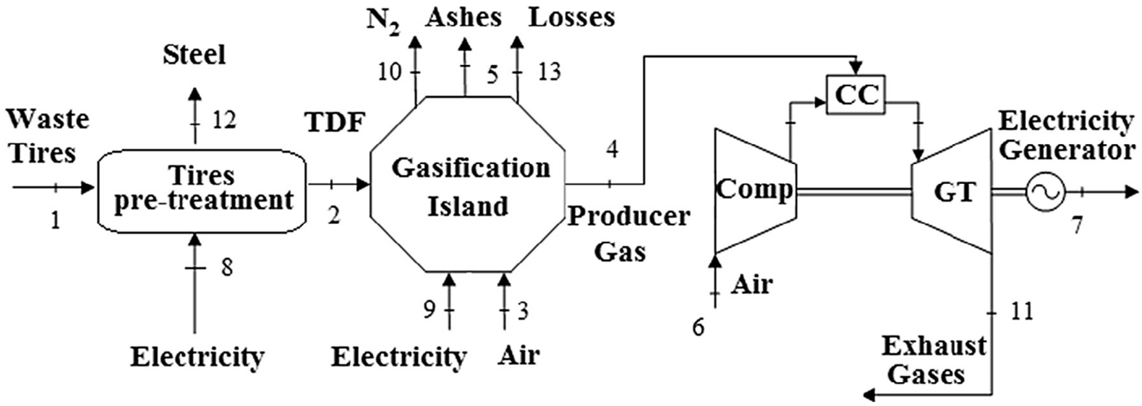

Fig. 8. Gasification of TDF for electricity generation using a gas turbine driving an electric generator.

Table 5
Flex Turbine® model GT333S parameters.

Electrical output	kW_{el}	333
Recoverable thermal output (264 °C)	kW	556
Energy input	kW_{th}	1025
LHV requirement WI*	MJ/Nm^3	12.1–22.3
Producer gas temperature requirements	°C	−1 to 46
Electrical efficiency without gas booster	%	33
Thermal efficiency	%	55
Total efficiency	%	88.4

* Wobbe Index Lower heating value.

Table 6
Results of the mass and energy balance for the implementation of the BFBG of TDF coupled to six GT-G.

Point	Mass flow [$kg\ s^{-1}$]	Temperature [K]	Pressure [kPa]	Energy flow [MW]
1	0.292	298	101.3	6.86
2	0.194	298	101.3	6.86
3	0.978	298	101.3	0
4	0.382	298	101.3	4.59
5	0.018	298	101.3	0
6	10.53	298	101.3	0
7	–	–	–	1.52
8	–	–	–	0.2
9	–	–	–	0.14
10	0.772	298	101.3	0
11	10.86	537	101.3	2.53
12	0.097	298	101.3	0
13	–	–	–	2.262

The effects of gasification efficiency variation of on thermal and electricity generation efficiency was also studied in this configuration as shows in Fig. 10.

Is possible note that the effect in the electricity and thermal generation efficiencies of the gasification island performance variation, in in this configuration is more significative than when ICE-G is implemented, but still with a relatively low impact.

6. Comparative technical analysis of the studied cases

Fig. 11 shows a comparison of results obtained for the electric, thermal and total power generation from the TDF gasification in the studied configurations.

There is a slight difference between the overall generation efficiencies for both configurations. The total power generation in the GT-G is slightly higher (3%) than the total power generated in the ICE-G. Nevertheless the differences in the electric and thermal power generation efficiencies between both configurations are more pronounced, being the electric efficiency 20.4% higher in the ICE-G than in the GT-G, and the thermal generation efficiency 12.5% lower in the ICE-G than in the GT-G, favoring the selection of the technology according to the intended main application (electricity or thermal application).

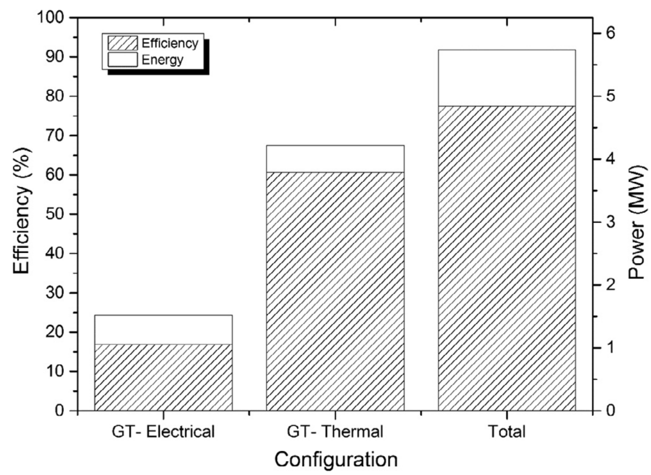

Fig. 9. Electric, thermal and total power and generation efficiencies in the GT-G.

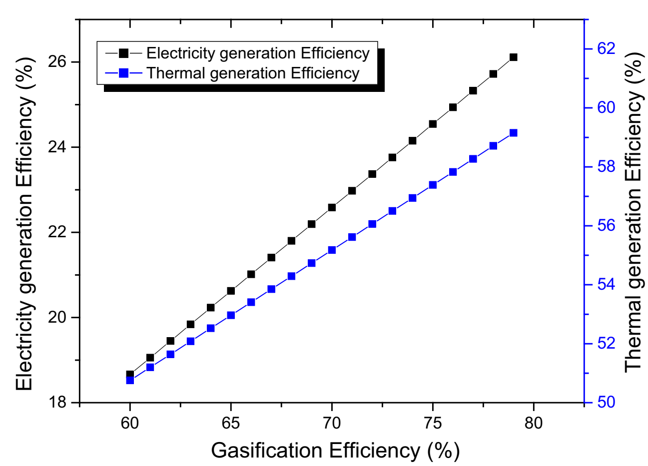

Fig. 10. Effects of gasification efficiency variation of on thermal and electricity generation efficiency.

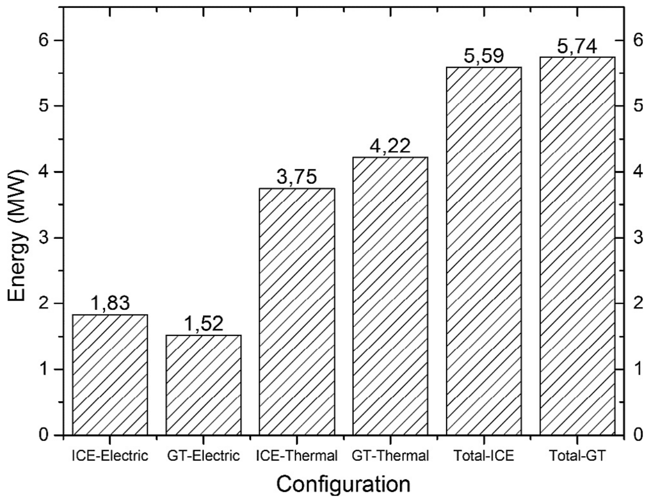

Fig. 11. Electric, thermal and total power generated by combustion of producer gas derived of gasification of TDF in the ICE-G and GT-G.

With the use of the producer gas of TDF to feed an ICE-G, it is possible to produce up to 7.67 MJ and 10.62 MJ of electric and thermal energy, respectively, per kilogram of TDF gasified. In the case that the producer gas is used to feed a GT-G is possible to produce up to 6.06 MJ and 13.03 MJ of electric and thermal energy respectively per kilogram of gasified TDF when a BFBG and oxygen as oxidant is used in the gasification process.

7. Conclusions

An assessment of the technical viability of TDF gasification for electric and thermal power generation, including the producer gas combustion in an internal combustion engine driving an electric generator and the use of the producer gas in a gas turbine, was performed. Despite the efficiency lost in the considered gasification technology, the TDF gasification showed to be a promising route for energetic valorization of waste tires, considering the complexity of this residue. In the routes for electric and thermal energy production evaluated, it was not found a significant difference in the total power generation efficiencies in both configurations. The combustion of producer gas derived from the gasification of TDF, in an ICE-G, appears to be a more efficient route for electricity generation (21.4%) when compared with the efficiency obtained with the use of GT-G (16.91%), in opposition with the results obtained for the efficiencies of thermal energy generation. In the GT-G the thermal efficiency reaches 60.58% while in the ICE-G, this parameter reaches 53.85%. The energy parcel of thermal energy in both studied case was essential for the elevated global efficiency in both cases, representing 67.2 and 73.5% of the total energy available when TDF producer gas is used in ICE-G or in GT-G respectively. When implemented the TDF gasification for energy production with ICE-G it is possible produce up to 7.67 MJ and 10.62 MJ of electric and thermal energy, respectively per kilogram of gasified TDF. The implementation of GT-G favors the thermal energy instead electric energy; producing up to 13.03 MJ of thermal energy and 6.06 MJ of electric energy per kilogram of gasified TDF

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