Energetic evaluation of different alternatives of energy recovery from municipal solid waste

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Abstract:

Brazil has a large population with a high waste generation, the waste generated in the country is deposited mainly in landfills, and however, there is still a considerable fraction of the Brazilian waste, which is allocate improperly. In order to overcome this inadequate deposition is necessary to seek for alternatives routes. Between these alternatives, it is possible to quote gasification and incineration, which are going to be the focus on this paper. Waste incineration is the oxidation using excess of stoichiometric air and gasification is the partial oxidation of the waste with a smaller amount of air than the stoichiometric. The primary difference between these technologies is that, in the case of incineration, waste is directly use as fuel for steam generation while in gasification the waste is used to generate a fuel gas, which can be used in various applications besides boiler. Simulations were performed using the same amount of waste, in mass, on the boiler and on the gasifier entrance. Owing to the high moisture content of Brazilian waste part of the produced syngas is used for drying the waste to acceptable values for the gasification. Because of this synthesis gas consumption there was obtained an efficiency 10.74% lower than efficiency obtained in incineration case, as future work, the study of gasification technology out of incineration operating parameters and cost analysis of both technologies should be done.

Keywords:

Waste-to-Energy; Municipal solid waste; energy recovery

1. Introduction

The municipal solid waste (MSW) generation in Brazil has been rising over the years. Between the years 2012 and 2013, there was a rise of 4.1% in MSW generation, which resulted in a value of 1.4 kg/hab/day in 2013 [1]. In Brazil, the MSW is allocated in landfills, controlled landfills (an intermediate option between landfills and open dumps) and open dumps. From these options, only landfills are considered appropriate for this purpose. In Brazil only 58.3% of the waste has adequate destination [1]. In this context, in 2010, Brazil enacted a law stablishing its National Solid Waste Policy, which aims to decrease the total volume of waste produced nationally and increase the sustainability of solid waste management from the local level to the national level [2].

In this scenario, thermal treatments with energy recovery appear as an interesting alternative to be deployed by the country taking into account the fact that this type of treatment reduces significantly the volume of residue with the advantage of electricity sales to the grid.

Waste to Energy (WTE) plants based on Mass Burning incineration are widely used in Europe and United States. It is a mature and commercial technology used to treat residues in large scale. Gasification of waste is another type of thermal treatment based on the partial oxidation of the waste in order to transform it in a combustible gas (syngas), which increases the plant versatile. Hence, the aim of this study is to compare from energetic point of view two technologies of thermal treatment: the Mass Burning incineration and the Waste Gasification both of them with power generation in a steam cycle.

2. Alternatives of energy recovery from MSW

2.1 Incineration plants

Incineration with energy recovery consists in the use of waste in boilers, as received in the case of Mass Burning, or in the form of refuse-derived fuel (RDF). This fuel will react with the oxygen of the combustion air. In this case, the waste is fully oxidized in a single step. The heat released in the combustion process is then transferred to the water in order to produce steam to the subsequent generation of mechanical and / or electrical energy in a steam power cycle. According to Kaplan et al. (2009) [3] incineration is shown as an attractive alternative in relation to landfill by having a bigger energy potential with smaller emissions. In the author analysis, the only emission that got higher levels in the incineration process was the HCl emissions.

The study by Leme at al. (2014) [4] using LCA methodology also showed that incineration presents as a superior alternative to landfilling. The author also indicates the economic dependence of landfills remuneration on the clean development mechanism and the economic dependence of incineration on the waste tax indicating that, with increasing restrictions and regulations, the incineration process tends to become more viable.

About the advantages and disadvantages of incineration is important to quote, as advantages of the process, the immediate reduction of the volume and weight of the waste without long periods of residence, the smaller area required when compared with the landfill destination, among others. Between the disadvantages is the most relevant is the high capital cost of the plant. [5] Fig. 1 shows the basic outline of an incineration process, according to [6].

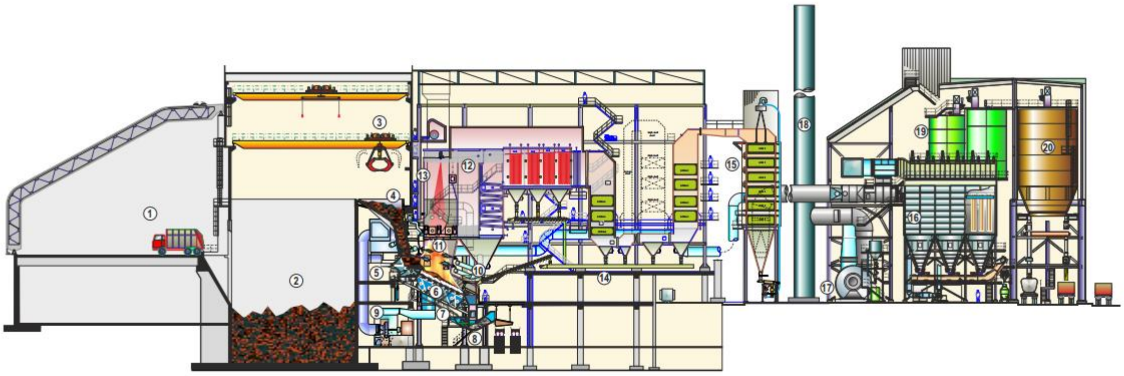

Figure 1. Incineration plant diagram (ASM – Brescia – Italy). (Source: [6])

In the diagram shown in Fig 1 the waste is deposited in the pit (point 2) by the collection trucks. The deposited waste is removed using a claw (3) remotely controlled by an operator and inserted into the furnace feed system (4) where the waste will gradually be driven to the grate (6) where they pass through the combustion process (11). Combustion gases produced along with the fly ash are directed to the heat recovery equipment (12) while the bottom ash is recovered at the bottom of the grate (8). The flue gases, after passing through the heat recovery equipment, are directed to the gas cleaning process where the particulate matter (fly ash) and pollutants are collected (14) and neutralized resulting in atmosphere exhaust gases within the specified limits.

2.2 Gasification plants

The term ‘‘gasification plant’’ is generally used to name the whole system that converts the primary feedstock into useful energy carriers [7]. Gasification is a process in which the biomass is heated at higher temperature with controlled oxygen to produce a fuel gas with minimum amounts of liquid and solid products. Due to the variety of fuels that can be gasified (coal, oil , biomass) seems impossible to have a valid theory for all, in the development of the theory of gasification is possible to focus on the case of pure coal gasification , and discuss causing influences the characteristics of other fuels in the process [7, 8, 9].

Liu and Liu, [10], conducted a study where the process of drying, pyrolysis, gasification, incineration and vitrification of the ashes of MSW is performed by the same equipment. This equipment consists of two chambers, in the first one gasification and vitrification process takes place while the combustion process was mainly completed in the secondary chamber. Experiments were carried out to examine its characteristics in an industrial MSW incineration plant, located in Taiyuan, with a capability of 100 tons per day.

Kwak et al. [11] accomplished experiences in a pilot plant for gasification of 3 ton/day to produce synthesis gas with the following composition 27 – 40% CO, 36 – 40% H_2 and 24 – 30% CO_2 with high heating value 8.0 – 10.2 MJ/Nm^3. According to the authors this process was completely environment friendly owing to the concentrations of toxic heavy metals in melted slag, fly ash, treated water and other pollutants in exhaust gas were found to be much below the Korean regulatory limits.

Arena et al. [12] used five types of fuels derived from waste from municipal solid waste and post-consumer packaging (RDF) to feed a bubbling fluidized bed gasifier, in pilot scale, with capacity of 100 kg/h. The results obtained with these five different fuels confirmed the technical feasibility of gasification process and the good quality of the syngas produced in terms of high calorific value and high concentration of hydrogen.

3. Methods

Two configurations of plant were evaluated in this study.

i) Case I – Incineration.

This configuration considers an incineration plant with energy recovery type *Mass Burning* where waste is used as fuel in boiler as received. The heat released in the waste combustion is then transferred to the water in order to produce steam to the subsequent generation of mechanical and / or electrical energy in a steam power cycle.

ii) Case II – Gasification

This configuration considers the waste gasification and the subsequent combustion of syngas in a boiler to steam production and generation of mechanical and /or electrical energy in a steam power cycle.

Figs 2 to 3 show the respective flow sheet for the Case I and II. Simulations were performed using the Thermoflex ® software [12]. To the assessment of the proposed cycles, several hypotheses were assumed. The amount of municipal solid waste (MSW) for both cases was 9.33 kg/s (33.6 t/h) with moisture content of 41.3% (wet basis). It was assumed the composition of the MSW of Santo André city in Brazil. The simplified gravimetric composition of the Santo Andre MSW is presented in Table 1.

Table 1. Simplified gravimetric analysis of Santo Andre MSW [14]

Gravimetric analysis (%weight)	
Metal	1.98
Plastic	18.65
Paper	12.73
Glass	1.07
Wood	0.89
Organic matter	56.46

From data presented in Table 1 and ultimate composition of each fraction of literature [15, 16] the ultimate composition of MSW can be estimated. Table 2 shows the average ultimate composition of MSW generated in Santo Andre city.

Table 2. Average ultimate and proximate composition of MSW generated in Santo Andre

Ultimate analysis and proximate analysis	(%wet basis)
Carbon	26.7
Hydrogen	3.37
Oxygen	16.14
Nitrogen	0.52
Sulfur	0.11
Ash	11.87
Moisture	41.3
Volatile	41.86

For the incineration plant (Case I - Incineration) the fuel is used in boiler as received (with the reported moisture content of 41.3%), however for the gasification plant (Case II – Gasification) it was necessary to dry up it until a moisture content of 15.7%. The necessary energy to dry process was obtained from the use of 1.467 kg/s of syngas produced by the gasifier.

3.1 Mass burning incineration

According to Fig. 1, the waste is fed into a Grate Boiler (Device 1) that, according to Themelis [17], is the most common technology to MSW incineration. Preheated air also enters in the Grate Boiler; it is heated using the energy content of exhaust gases. Air temperature at the outlet of the Air Heater (Device 8) is determined by heat balance. The exhaust gas temperature at Air-Heater outlet (outlet 10) was set at 199°C according to Chang and Huang [18], the proportion of primary and secondary air was selected according to these authors. The excess air ratio adopted was 100% [18, 19]. The Grate Boiler produces saturated steam, which goes to the superheater (Device 7) where it is heated until 420°C at 40 bar [20]. The pressure and temperature of super-heated steam are limited to these values owing to the possibility of corrosion caused by the chlorine content of some materials found in the MSW. This limitation is the main cause of the low efficiency in electricity generation cycle.
Before entering the Grate Boiler, the water is pre-heated at the Economizer (Device 3) with a temperature increase of 100°C.

3.2 Gasification

The model used to gasification process was chemical equilibrium model. The syngas composition was determined at constant temperature by the equilibrium reactions using the principles of mass conservation and the free Gibbs energy minimization. The chemical kinetic models consist of a mechanism of heat and mass transfer that, through velocity of chemical reactions, determine the syngas composition in time function. However, given the complexity of reaction, number of components and phase inside of the reactor, those models become very expensive to perform the analysis of the main parameters involved. Thus, according to Li et al [21] chemical equilibrium models are a cheaper alternative than other models, thus it was used in this assessment. It is possible using empirical correlations to correct the results of chemical equilibrium and approximate them to experimental results. This approach was adopted in this study. The approach used to model the gasification process was developed through the chemical equilibrium concept, described by Smith et al [22]. The main hypotheses consist of:

- The system is in equilibrium.
- Uniform pressure and temperature.
- N phases with uniform compositions.
- System reversible heat exchange with the environment.

Basu [23] highlights that “at low reaction temperatures, the reaction rate is very slow, so the residence time required for complete conversion is long. Therefore, kinetic modeling is more suitable and accurate at relatively low operating temperatures (< 800 °C) and for higher temperatures, where the reaction rate is faster, the equilibrium model may be of greater use”. Thus, the temperature of gasification operation for this model was chosen in 900ºC. The syngas properties as well as other parameters of gasification process are presented in Table 3.

Table 3. Results of gasification process: temperature of gasification 900ºC.

Gasifier Temperature (ºC)		900
Gasifier Pressure (kPa)		100
Equivalence ratio		0.5
Carbon conversion efficiency (%)		95
Molar fraction of gases		
	CO_2	0.1447
	CO	0.0623
	CH_4	0.0470
	H_2O	0.1530
	H_2	0.0266
	N_2	0.5658
	SO_2	0.0006
LHVs (kJ/kg)		3,668
LHV (kJ/Nm^3)		2,997
Cold Efficiency (%)		89.1

3.3 Rankine cycle

After the waste boiler (Case I - Incinerator) or Gasifier (Case II – Gasification) the steam cycles were configured to operate at the same levels of pressure and temperature as can be observed in tables 4 to 5. These tables show the operation conditions of the steam cycle referent to the figs 2 to 3. Both of systems were simulated using the Thermoflex ® software [13]. Fig. 2 shows the waste boiler (Case I) which is composed by the grate, superheater, air heater and the economizer (water heater) as explained in section 3.1.

On the other hand, Fig. 3 shows the system with the gasifier (Case II). It was assumed that part of the waste is dried up with exhaust gases (Device 1) while the other part is dried up using part of the produced syngas in gasifier (Device 7). Regarding the steam cycle both of the figures show the same configuration. For instance in Fig. 2 the super-heated steam goes to the high-pressure steam turbine (Device 2) where it undergoes an expansion until 1.6 bar. Part of the exhaust steam (outlet of turbine at 1.6 bar) is sent to the deaerator while the remaining flow is directed to the low-pressure turbine (Device 12). For both turbines, a dry step isentropic efficiency of 85% was adopted.

After the low-pressure steam turbine, the saturated steam-liquid mixture is sent to the condenser (Device 14), which operates at 6 kPa. After that, the liquid is pumped (Device 15) to the deareator (Device 9). The operation pressure of deaerator was set at 1.6 bar. It was adopted that water goes out from deaerator as saturated liquid. Finally the, saturated liquid is pumped until the operation pressure of the boiler (Device 13).

For all devices, the properties of inlet and outlet streams were determined. The mass and energy balance as well as the thermal efficiency were evaluated according to Moran and Shapiro [24].

$$\sum \dot{m}_s = \sum \dot{m}_e \tag{1}$$

$$0 = \dot{Q}_{VC} - \dot{W}_{VC} + \sum\left(\dot{m}_e . h_e\right) - \sum\left(\dot{m}_s . h_s\right) \tag{2}$$

$$0 = \sum_j \frac{\dot{Q}_j}{T_j} + \sum\left(\dot{m}_e . s_e\right) - \sum\left(\dot{m}_s . s_s\right) + \dot{\sigma}_{VC} \tag{3}$$

$$\eta = \frac{\dot{W}_{liq}}{\dot{m}_{comb} \times LHV_{comb}} \tag{4}$$

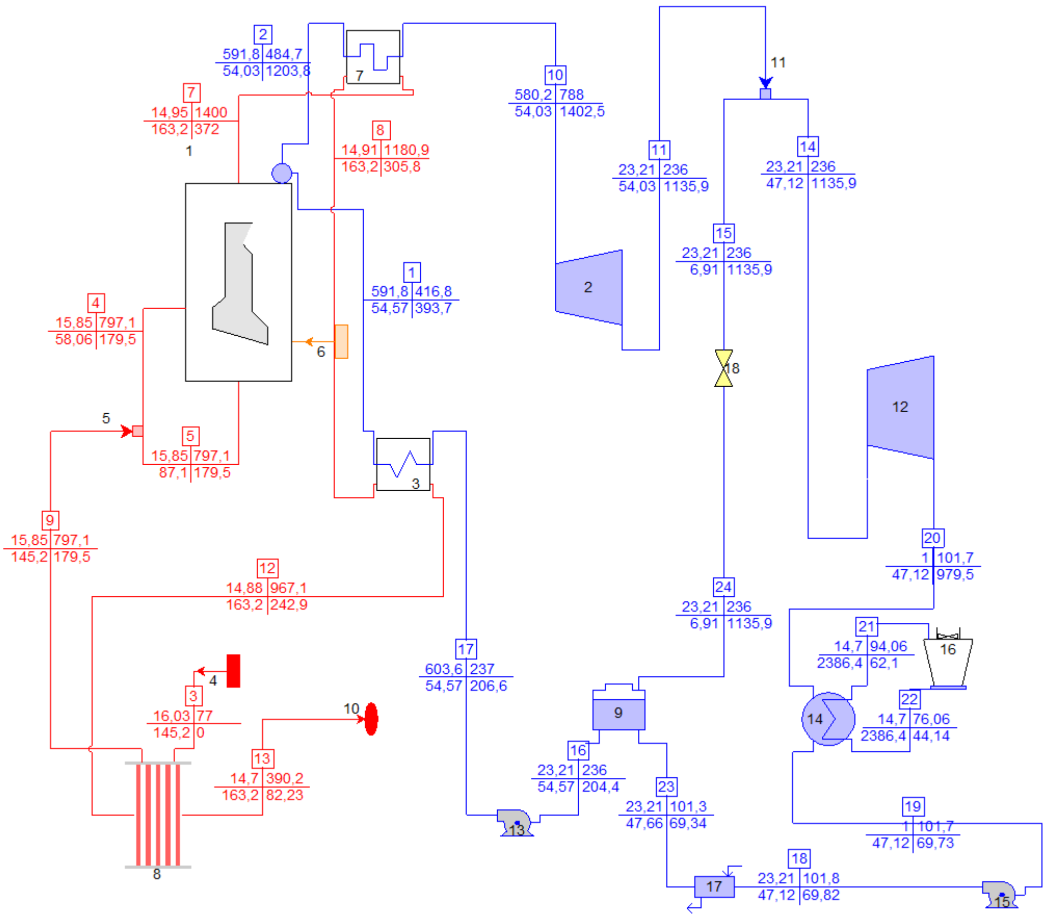

Figure 2. Flow sheet of steam cycle with Incineration Boiler (Case I - Incineration).

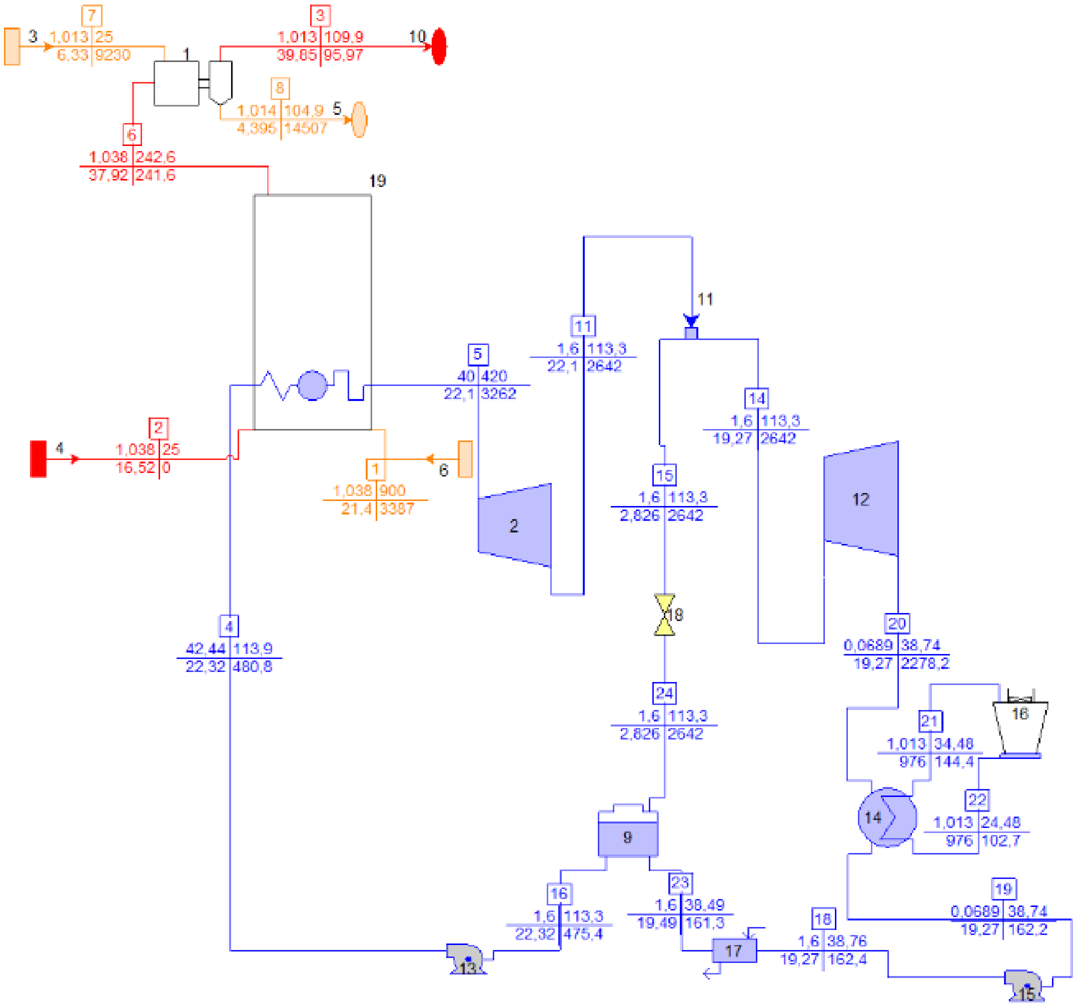

Figure 3. Flow sheet of steam cycle with Gasifier (Case II – Gasification).

Table 4. Operation conditions in each point of the steam cycle–Incineration Boiler (Case I)

Flow	*P(bar)*	*T(C)*	*h (kJ/kg)*	*m (kg/s)*
1 - Feedwater of Furnace w/Grate	40.8	213.8	915.72	24.75
2 - Saturated steam outlet of Furnace w/Grate	40.8	251.51	2799.8	24.51
10 - Steam outlet of Superheater	40	420.00	3262.07	24.51
11 - Outlet Turbine group 2	1.6	113.32	2642.03	24.51
14 - Outlet 1 of Splitter	1.6	113.32	2642.03	21.38
15 - Outlet 3 of Splitter	1.6	113.32	2642.03	3.134
16 - Feedwater outlet of Deaerator	1.6	113.32	475.36	24.75
17 - Water inlet of Economiser	41.62	113.89	480.63	24.75
18 - Inlet of Makeup	1.6	38.76	162.39	21.38
19 - Condensate outlet of Water-cooled Condenser	0.0689	38.74	162.19	21.38
20 - Outlet Turbine group 12	0.0689	38.74	2278.15	21.38
21 - Coolant outlet of Water-cooled Condenser	1.0132	34.48	144.45	1082.4
22 - Coolant inlet of Water-cooled Condenser	1.0132	24.48	102.66	1082.4
23 - Outlet of Make-up	1.6	38.49	161.27	21.62
24 - Heating steam inlet of Deaerator	1.6	113.32	2642.03	3.134

Table 5. Operation conditions in each point of the steam cycle – Gasifier (Case II)

Flow	*P(bar)*	*T(C)*	*h (kJ/kg)*	*m (kg/s)*
4 - Feedwater of Thermo Boiler	42.44	113.9	480.75	22.32
5 - Steam outlet of Thermo Boiler	40	420	3262.07	22.1
11 - Outlet of Turbine group 2	1.6	113.32	2642.03	22.1
14 - Outlet 1 of Splitter	1.6	113.32	2642.03	19.27
15 - Outlet 3 of Splitter	1.6	113.32	2642.03	2.826
16 - Feedwater outlet of Deaerator	1.6	113.33	475.37	22.32
18- Inlet of Makeup	1.6	38.76	162.39	19.27
19- Condensate outlet of Water-cooled Condenser	0.0689	38.74	162.19	19.27
20- Outlet Turbine group 12	0.0689	38.74	2278.15	19.27
21- Coolant outlet of Water-cooled Condenser	1.0132	34.48	144.45	976
22- Coolant inlet of Water-cooled Condenser	1.0132	24.48	102.66	976
23- Outlet of Make-up	1.6	38.49	161.27	19.49
24- Heating steam inlet of Deaerator	1.6	113.32	2642.03	2.826

4. Results and discussion

The main results of simulation are presented in Table 6 where the following quantities are highlighted: mass flow of MSW, lower heating value of MSW, mass flow of syngas produced in gasifier, steam generated at boiler, net power of the cycle, specific power produced and thermal efficiency of the systems.

Table 6. Main results of simulation

	Case I Incineration	*Case II Gasification*
Mass flow of MSW, (kg/s)	9.33	9.33
MSW LHV, (kJ/Kg)	9,230	9,230
Mass flow of syngas (kg/s)	--	22.847
Steam generated at boiler, (kg/s)	24.51	22.1
Net power of the cycle, (kW)	21,654	19,332
Specific power, (kWh/t of MSW)	644.69	575.56
Thermal efficiency of the cycle, (%)	25.15	22.45

Analyzing the Table 6 is possible to highlight that steam produced in the plant with waste incinerator (Case I) is higher than steam produced in the syngas boiler of the gasifier plant (Case II). One reason for this difference was the need of drying the municipal solid waste until values of moisture that enables gasification technology that, in the incinerator, is not necessary. Thus, there was reduced availability of energy for steam generation in the syngas boiler. The production of a smaller amount of steam impacted the power generation availability (there is a lower net power), which consequently led to a lower efficiency.

But it should be noted that gasification of municipal solid waste permit the production of a synthesis gas (syngas) that can be used directly in combustion processes in the boiler, without any prior cleaning. It allows to the system to operate the steam cycle at temperatures higher than 420°C, which is the limit temperature in incinerators operating with municipal solid waste owing to the slagging formation and fouling, which is accompanied by corrosion (mainly due to the presence of chlorine) and accelerated wear of the heat exchange surfaces. The restrictions for the combustion of fuels such as municipal solid waste are related to the presence of certain elements in its composition being the main: potassium, chlorine, sulfur and silica. Thus, an analysis of the cycle with Gasifier (Case II) assuming operation conditions of pressure and temperature higher than assumed in this study is necessary in order to identify potential of power generation for the gasification system coupled to the boiler.

5. Conclusions

This work shows a comparative analysis of two types of technologies for thermal waste treatment. Each technology evaluated has its own particularities. From the hypotheses adopted, the results showed that incineration plant has a slightly higher efficiency in comparison to gasification plant. However, gasification plant coupled to gas boiler has several operational advantages related to the use of MSW as fuel, for instance: lower size of devices, possibility of operation with higher parameters of pressure and temperature in the steam cycle and avoid the formation of slagging and fouling.

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