EXERGETIC ANALYSIS OF A STEAM MICROTURBINE INTEGRATED TO A SOLID WASTE INCINERATOR

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Abstract. *The solid waste incineration processes should happen in high temperatures, associating exergetic to the combustion gases, in order to guarantee the elimination of dangerous organic compositions. In a usual incineration process, this exergy is destroyed after accomplishing their objectives, as the case of the solid wasted incinerator, located in the biotery at the State University of Maringá. However, it is possible to take advantage from the hot gases as input in a power cycle. For that, it is necessary, not only the level of exergetic associated to the temperature, but also the enough amount for the available commercial equipments. In the present work, it was developed a computer program to determine the exergetic destruction in the incineration processes and constructed a Grassmann diagram. It was verified that the combustion gases' exergy at the existent equipment has temperature level and enough amount to feed a Rankine cycle using a 125 kW steam micro turbine.*

Keywords*: Incineration, Microturbine, Exergy, Grassmann Diagram*

1. INTRODUCTION

Solid waste incineration must reduce hazardous constituents in the resulting ashes allowing them to be disposed in proper landfills (Dempsey and Oppelt, 1993). Besides controlling the ashes' contents, the gaseous emissions should not affect negatively the environment. In order for doing so, it is required to control the incineration process, improving the equipment performance. As the main factors that influence an incinerator efficiency are the temperature, residence time, turbulence and the oxygen content in the chamber. Temperature, residence time and turbulence are commonly referred as the reactor 3Ts (Moura and Bufo, 1997). However, not only these factors contribute in the estimating of incinerator efficiency. Other factors such as thermal efficiency, pollutant emissions and controlling devices, feeding procedure and ashes characteristic must be accounted.

The incinerator of the biotery at the State University of Maringa comprises 2 chambers. In the chamber 1 (primary) occurs the pyrolysis and in the chamber 2 (secondary) occurs the complete combustion, where the gaseous temperatures must be around 1200 C. The minimum residence time according to *CONAMA* 316/2002 standard must be 2s, for assuring adequate waste destruction.

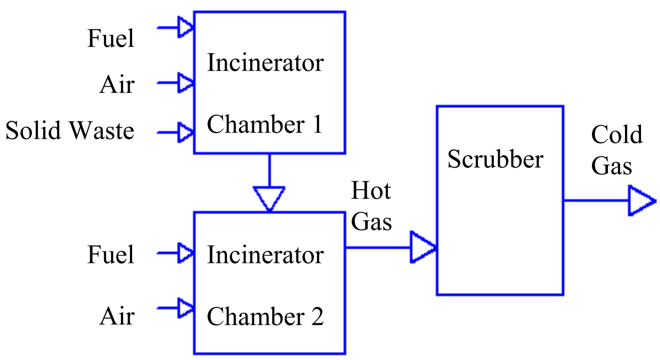
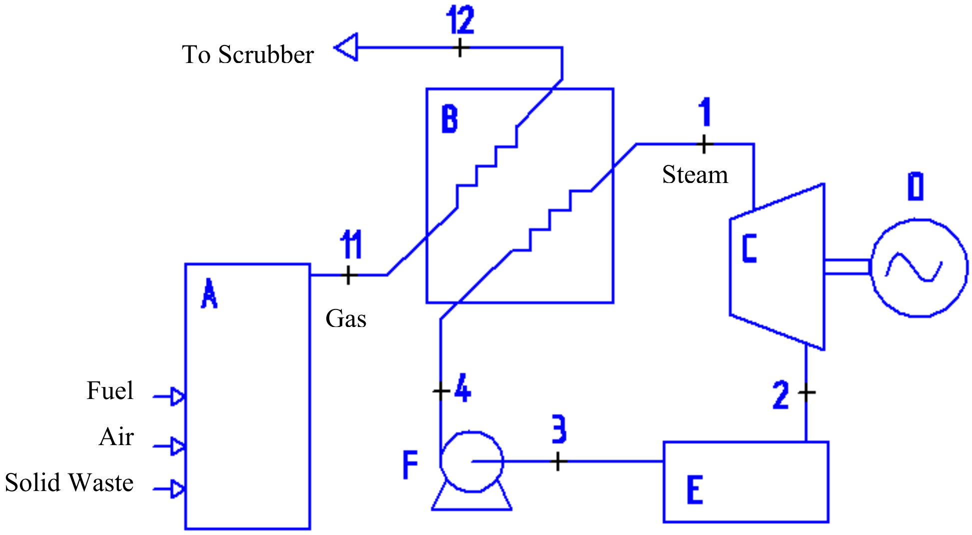


Figure 1. Current incinerator configuration

It is well known the increase in thermomechanical exergy with the temperature for a fluid (Kotas, 1985). For a common incineration process, this exergy is destroyed and not taken account its availability. This is the case of the solids waste incinerator of the biotery in the State University of Maringa. However, as the combustion gases still contain the most part of the available energy after incineration, could be feasible to use the hot gases in a power generation cycle (Carvalho *et al*, 2003), or simply to generate steam or hot water (Autret *et al*, 2007). In order to obtain this, it is necessary not only the exergy level related to the temperature, but an enough amount that makes possible the use of available commercial equipments. The alternative study in the present work was employing the hot gases in an indirect way for generating steam in a heat recovery steam generator (*HRSG*). In this way, the steam can be used for power generation in a *Rankine* cycle (Fig.2)



A: Incinerator	D: Electric Generator
B: Heat Recovery Steam Generator (HRSG)	E: Condenser
C: Turbine	F: Water Pump

Figure 2. Proposed configuration of power system integrated to incinerator

2. METHODOLOGY

The most useful definition for system exergy is related to the maximum capacity of work generation when the system interacts with the environment. Whereas the energy is conserved, the exergy can be destroyed by irreversibilities that can be quantified by the exergetic analysis, as in a heat transfer process. The exergetic analysis methodology is well known and has examples in various fields as described in Kotas (1985). Nowadays, the exergetic analysis is greatly applied in thermoeconomics and environmental issues. As pointed by Çengel (2007), exergy destruction associated with energy transfer and conversion, and adverse effect on human health and the environment are a measure of deviation from thermodynamics greenness. In other words, in advanced exergy analysis, the exergy destruction within a component and energy conversion system can be split into avoidable/unavoidable exergy destruction (Tsatsaronis, 2008).

The exergetic analysis is based on the 1st and 2nd Laws of Thermodynamics, which are applied for each case. Next, is presented the analysis for *Rankine* power cycle integrated to the solids waste incinerator.

2.1. Mathematical equations

From the fuel consumption rates ($\dot{m}_{fuel}$) and their heat values (LHV) is determined the heat ($\dot{Q}_{fuel}$) of the incineration process that is available for power generation (Eq. 1). Besides the fuel, it is possible to include in the heat accounting the energy release from the waste fed in the incinerator.

$$\dot{Q}_{fuel} = \sum \left(\dot{m}_{fuel}\, LHV \right) \quad \text{[kW]} \tag{1}$$

According to Kotas (1985), the ratio (γ) of the chemical exergy to the lower heating value for a solid fuel, in which *o/c* > 0,66 is obtained using Eq. (2), with the knowledge of fuel chemical composition (*h*, *c*, *n*, *o*):

$$\gamma = \frac{1{,}0438 + 0{,}1882\frac{h}{c} - 0{,}2509.(1 + 0{,}7256\frac{h}{c}) + 0{,}0383\frac{n}{c}}{1 - 0{,}3035\frac{o}{c}} \tag{2}$$

Furthermore, according to Kotas (1985), knowing the fuel moisture (w) and its vaporization enthalpy (h_{fg}), it is possible to calculate the chemical exergy ($e_{x.wood}$) using the ratio γ (Eq. 2). The relation is given in Eq. (3), where the water chemical exergy was neglected. The last assumption proceeds from the exergy balance from combustion reactants and products, where the water is unchanged during the reaction.

$$e_{x.wood} = \gamma(LHV + h_{fg}w) \quad \text{[kJ/kg]} \tag{3}$$

For gaseous fuels, as the Liquefied Petroleum Gas (*LPG*), the chemical exergies of their elementary components are known and the specific values (e_x) are determined according to the molar fraction of their components. Therefore, the exergy rates ($\dot{E}_x$) of the fuel are given by Eq. (4).

$$\dot{E}_x = \sum\left(\dot{m}.e_x\right) \quad \text{[kW]} \tag{4}$$

Although the chemical exergy rates are determined by Eq. (3), the specific thermomechanical exergies from the combustion gases and steam are determined by Eq. (5).

$$e_x(T) = h(T) - h_0 - T_0[s(T) - s_0] \quad \text{[kJ//kg]} \tag{5}$$

where, h is enthalpy, T is temperature, s is entropy and *0* refers to environment conditions.

For the integrated power system, the availability for steam generation can be determined from the mass flow rate and gas temperature in the *HRSG* exit (Eq. 6). From this equation, it is possible to observe the increasing in availability with the lowering of the exit gas temperature. However, the temperature should not be decreased up to the dew point in order to prevent condensation and equipment damage.

$$\dot{Q}_{avail} = \dot{m}_{gas}\int_{T_{in}}^{T_{out}} c_{gas}dT \quad \text{[kW]} \tag{6}$$

where, c_{gas} is the gas specific heat ($c_{gas}/R = A + BT + CT^2 + DT^{-2}$), R is constant for a particular gas according to its molecular weight (M) and A, B, C and D are constants given for each chemical specie (Smith *et al*, 2007).

So, the steam generation capacity is obtained matching Eqs. (6) and (7).

$$\dot{Q}_{in} = \dot{m}_{steam}(h_{out} - h_{in}) \quad \text{[kW]} \tag{7}$$

Equation (7) applied to the *HRSG* and condenser, as well as Eq. (8) applied to the turbine and pump, are simplifications of the 1st Law of Thermodynamics for control volume in the steady state, where the kinetic and potential energy are neglected.

$$\dot{W}_{out} = \dot{m}_{steam}(h_{in} - h_{out}) \quad \text{[kW]} \tag{8}$$

The thermal efficiency from the 1st (η) and 2nd (ε) Laws of Thermodynamics are given in Eqs. (9) and (10), respectively:

$$\eta = \frac{\dot{W}_{net}}{\dot{Q}_{fuel}} \tag{9}$$

Equation (10) is based on the exergy balance (2 nd Law of Thermodynamics) for a global control volume including the power system and the incinerator (Eq. 11), and considering the steady state ($\frac{dE_x}{dt} = \frac{dV_{cv}}{dt} = 0$) and adiabatic processes ($\dot{Q}$ = 0). It must be pointed that the exergetic efficiency increases when the rate of exergy destruction ($\dot{E}_d$) is decreased.

$$\varepsilon = \frac{\dot{W}_{net}}{\dot{E}x_{fuel}} \tag{10}$$

$$\frac{dE_x}{dt} = \sum\left(1 - \frac{T_0}{T}\right)\dot{Q} - \left(\dot{W}_{cv} - p_0\frac{dV_{cv}}{dt}\right) + \sum(\dot{m}e_x)_{in} - \sum(\dot{m}e_x)_{out} - \dot{E}_d \tag{11}$$

For equipment involving heat transfer, as the steam generator, the three last terms in the right hand side of Eq. (11) refer to the inlet and outlet exergy flows and the rate of exergy destruction. These values are used in the Grassmann diagram, inserting Eq. (10) in Eq. (12).

$$\varepsilon = \frac{\sum(\dot{m}e_x)_{out} - \sum(\dot{m}e_x)_{in}}{\dot{E}x_{fuel}} \tag{12}$$

3. RESULTS

3.1. Program development

Using the previous assumptions and equations, it was developed a computational program that performs an exergetic analysis of the power system integrated to the incinerator (Fig 3).

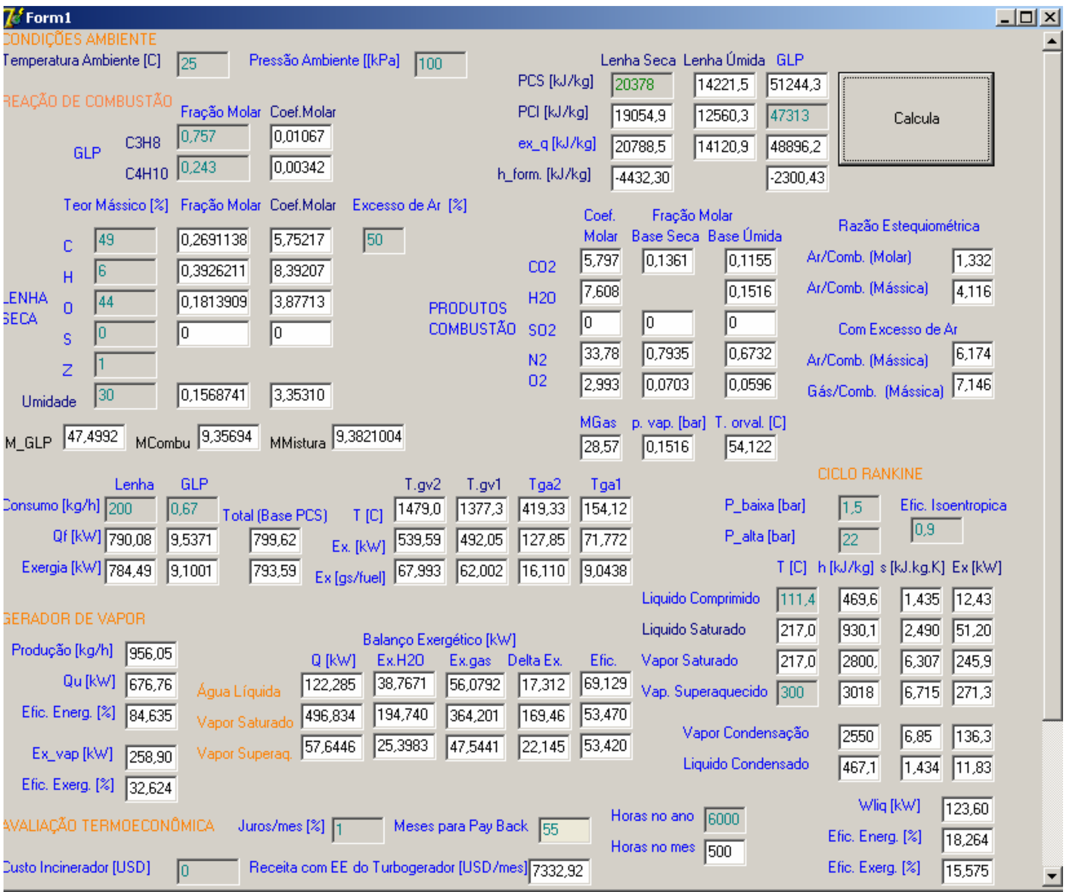


Figure 3. Computational program for exergetic analysis

The program performs the combustion, mass, energy and exergy balance for the proposed system. Using this tool is possible to change the fuel composition, consumption rate, the air excess, and other variables allowing that estimates be made to determine the potential of steam generation and power. Also, calculates the process irreversibilities, energy and exergy efficiency.

If some adaptations were accomplished to allow the insertion of other fuels, it is possible to use this program to compare the emissions or temperatures in other thermal systems involving combustion. Regarding the *Rankine* cycle, the potential and thermal efficiency can be determined according to the pressure and temperature levels, as in the generation, as in the steam condensation. Besides, according to the investment, operation and maintenance costs and of the income proceeding from the power generation, the payback of the necessary investments can be verified for the integration of the proposed power cycle. The complete thermoeconomic analysis has been accomplished in order to verify the real viability of the power cycle integration.

3.2. Exergy analysis

As previously mentioned, the studies were based on the current fuel consumption from the incinerator (Eq. 1). These data were obtained from an incinerator emission report (Barros, 2007). Although the initial setup of the incinerator was to burn *LPG* as the main fuel, mostly of the used fuel is wood in order to reduce costs (Tab. 1).

Table 1. Current consumption in incinerator

Fuel	$\dot{m}_{fuel}$ [kg/h]	*LHV* [kJ/kg]	$\dot{Q}_{fuel}$ [kW]	e_x [kJ/kg]	$\dot{E}_x$ [kW]
LPG	0.67	47313	8.8	48997	9.1
woody (30% moisture)	200	12560	697.8	14502	805.7

Basically, the solid waste employed in the incinerator are rat labs, which can perform as fuel, because their heat value is comparable to the bovine meat (*LHV* = 16180 kJ/kg, McDonell *et al*, 2001). For the present study, the fuel potential of the solid waste was neglected, mainly due to the composition variation. It is expected that, the fuel potential of the solid waste would affect positively the proposed power system.

For calculating the wood chemical exergy, the composition (Tab. 2) was approximated according to the presented by Bazzo (1995). This assumption is justified once the exact composition of the wood is unknown.

Table 2. Wood chemical composition

Element	*C*	*H*	*O*	*z*
[%] mass	0.49	0.06	0.44	0.01

The ratio between chemical exergy and the lower heating value for the solid fuel (γ = 1,091: Eq. 2) is calculated using the data from Tab. 2. Next, employing the water vaporization enthalpy (h_{fg} = 2.442 kJ/kg) in Eq. (3), the wood chemical exergy is determined.

Using the *LPG* chemical composition (Tab. 3) and corresponding chemical exergies (Tab. 4) was determined the chemical exergy of *LGP* (Tab. 5).

Table 3. *LPG* composition

Component	Propane (C_3H_8)	Butane (C_4H_{10})
[%] vol.	75.7	24.3

Source: Vlassov, 2001

Table 4. Chemical exergies of propane and butane

$e_{x.C3H8}$ [kJ/kmol]	$e_{x.C4H10}$ [kJ/kmol]
2163190	2818930

Source: Kotas, 1985

Table 5. Chemical exergies of *LPG* and wood

$E_{x.LPG}$ [kJ/kmol]	$e_{x.LPG}$ [kJ/kg]	$e_{x.wood}$ [kJ/kg]
2322534	48896	14502

For calculating the thermomechanical exergies (Eq. 5), the reference temperature and pressure, T_0= 25º C (298 K) and P_0= 100 kPa were assumed. The steam properties were obtained from Moran and Shapiro (2002). For using Eq. (5) and (6), as the incinerator works at high temperatures, the specific heat changes. So, the relations available from Smith *et al* (2007) were employed for accounting for these changes with temperature

The chosen data from the *Rankine* cycle are in Tab. 6. The gas mass flow, gas composition and the dew point were determined using chemical reaction, while the adiabatic flame temperature was determined using energy balances for reacting systems (Tab. 7). The exit *HRSG* temperature was 100 C above the dew point for preventing gaseous condensation.

Table 6. Operational condition of *Rankine* cycle

Point	P [kPa]	T [^{o}C]
1	2.200	300
2	150	217
3	150	217
4	2.200	111,4

Table 7. Results based in combustion reaction

$\dot{m}_{gas}$ [kg/h]	1434
T_{11} [^{o}C]	1480
$T_{dew\text{-}point}$ [^{o}C]	54
T_{12} [^{o}C]	154
$\dot{m}_{steam}$ [kg/h]	956

The main results for the *Rankine* cycle are presented in Tab. 8. The values were obtained considering isoentropic efficiencies of 90 % for the turbine and pump.

Table 8. Results of *Rankine* cycle

$\dot{W}_{turb}$ [kW]	124.3
$\dot{W}_{net}$ [kW]	123.6
η [%]	18.3
ε [%]	15.6

Using the Eq. (4), (11) and (12), it is possible to determine exergy transfer and exergy destruction in each process (Tab. 9) to construct *Grassmann* Diagram (Fig. 4).

Table 9. Exergies of fuel, gas combustion and steam

(Point) Flow	$\dot{E}_X$ [kW]	T [^{o}C]
Fuel	785	25
(11) Gas	540	1479
(12) Gas	72	154
(1) Steam	271	300
(2) Steam	136	111
(3) Water	11,8	111
(4) Water	12,4	112

From the results in Tab. 9 and Fig. 4, it is possible to verify the exergy of gaseous products after incineration. In numeric terms, 540 kW of gas exergy at 1479 C are destroyed in the gas cleaning system. For the incinerator, the temperature level is high, once most of the thermal systems operate above 1000 C. Regarding to the amount (540 kW), the available level is more usual in internal combustion engines (*Diesel* or *Otto* cycles), but it would not be applicable to this incinerator. Then, it was studied the possibility to recovery the hot gas in order to generate steam in a usual level for other applications (22 bar and 300 C). However in this power range the use of steam turbine is not so usual, the micro-turbine model *TG 320*, developed by *TGM*^{R}, it looked favorable to the proposed system and was used in this work.

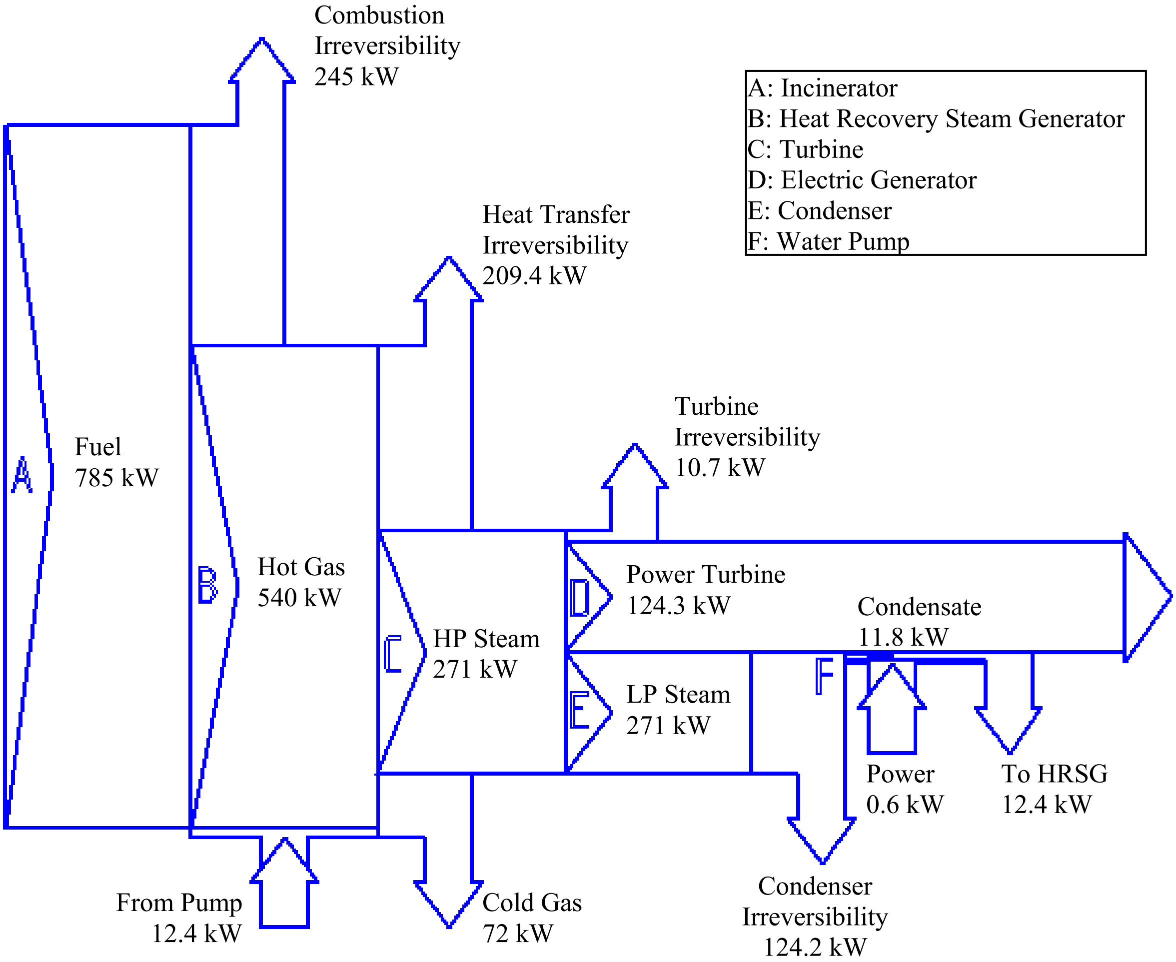


Figure 4. Grassmann diagram of power system integrated to incinerator

4. CONCLUSIONS

In order to assure the elimination of hazardous organic constituents, the temperatures of the residues incineration should be accomplished above 1200 C. The gases in high temperatures are associated to the level of exergy that is destroyed for a usual incineration process. This is the case of the solid waste incinerator, located in biotery at the State University of Maringá.

In the present work, it was determined the exergy destruction that occurs in the incineration process and was verified the possibility to integrate a power system to this equipment. For the implementation of this system be possible is necessary that there is not only the exergy associated to the temperature level, but also the enough amount for the available equipments commercially. It must emphasized that both aspects, high temperature and gas quantity, are relevant to make feasible the exergy recovery. If the quantity is low, it is possible that recovering would not be feasible by an unfavorable ratio cost to available power. Also, if the quantity is considerable, but the temperature is low, the exergy transfer to another fluid can require large heat transfer area.

For the proposed incinerator, it was verified that the combustion gases exergy has a temperature level and enough quantity to work out a *Rankine* cycle using a steam microturbine of 125 kW.

Regarding the losses in the integrated power system, it is verified by *Grassmannn* diagram that the most irreversibility is associated to the combustion and heat transfer. The combustion loss is practically irreversible for this kind of system, once the combustion is unavoidable for the incineration. On the other side, the loss in the heat transfer is associated to the temperature difference between gas and steam and can be improved if the steam pressure is increased. At the *HRSG* exit, the gases are at 154 C, assumed as 100 C above the dew point. Although the last value could be decreased, resulting in an exergy increase of *HP* steam, the impact would not be so relevant for the present study.

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