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Investigation and Evaluation Steam Generator Performance of the Steam Power Plant, Tello Makassar with Energy and Exergy Analysis

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ABSTRACT: This study was conducted at the unit steam power plant, Regional VIII of The State Electricity Enterprice (PLN), located in Tello village, Panakukang subdistrict, city of Makassar, province of South Sulawesi. The analysis was carried out to calculate the energy and axergy in steam generator which are consisted of: furnace, economizer, evaporator, three superheaters, and two air heaters. The calculations are based on the all data recorded during the operation of steam power plant at the maximum electricity load of 10.3 MW. Based on exergy analysis, four components in steam generator ie: economizer, superheater IA, superheater II, and air heater I, give efficiency below 50%, and steam generator's overall efficiency is only 25.01 %, but the overall efficiency calculated by energy method gives 58.04 %.

Keywords: steam generator, energy, exergy

NOMENCLATURE

Ex	- exergy [kJ]
h	- enthalphy [kJ/kg]
P	- pressure [bar]
Q	- heat loss [kJ]
R	- gas costant [kJ/kg.K]
s	- entropy [kJ/kg.K]
T	- absolute temperature [K]
y	- mole fraction [-]

Subscripts

b	- base
dest	- destroy
f.r	- formation for reactan
f.p	- formation for product
in	- inlet
i	- fraction
in	- inlet
m	- total
0	- reference
out	- outlet

1. INTRODUCTION

Exergy analysis is a method that uses the conservation of mass and conservation of energy principles together with the second law of thermodynamics (SLT), design and improvement of energy and other systems. The exergy is defined as the maximum reversible work that can be done by the composite of the system and a specified reference environment. The entropy of systems always increase during a process because of heat transfer, mass flow and irreversibility, while the entropy can not be destroyed, then some of the exergy of the system will be lost. The exergy destroyed is proportional to the entropy generated.

The first law of thermodynamics makes only an energy balance of a system or a control volume, and it does not make any distinction of different forms of energy, particularly between heat and work, or heat available at different temperature. Energies of two systems may be quantitatively equal, but qualitatively they may be different. Thus the exergy method becomes a useful tool for indicating the locations of energy degradation in a process and can therefore lead to improved operation of a system, by reducing the losses. The higher the value of exergy, the more obtainable from the system.

This study is to analyze the exergy on the performance of boiler in steam power plant, Tello Makassar, Indonesia. The power plant has been operated for 40 years since 1970, so that it is necessary to evaluate the existing plant due to decline in various equipment performance and energy losses. Because of the large problems in power plant, the analysis has been carried out by energy and exergy methods only on steam generator. The combustion chamber of the boiler is fueled with marine fuel oil (MFO), HHV 41,012 kJ/kg. The analysis of 1 kg of the fuel in percent weight is: C = 84.91, H_2 = 10.89, S = 3.32, N_2 = 0.246, O_2 = 0.464, H_2O = 0.1. The percentage of O_2 in combustion gas 1.7%, thus it will be considered in combustion reaction and calculations. The operational conditions and parameters used in this study are given on Table 1.

2. SCHEMATIC DIAGRAM OF THE STEAM GENERATOR

The schematic diagram of the steam generator is shown in Fig.1. and it consists of: furnace, economizer, evaporator, three superheaters. The working fluid (water – steam) is heated by combustion gas from water in economizer to saturated steam in evaporator, and to superheated steam in three sperheaters. The condition conversion order of working fluid is shown in Fig. 3. The air is pumped by fresh air fan (FAF) with capacity of 165 kW and heated by flue gas in air heater 1 and air heater 2 before mixing with the fuel in combustion camber. The high temperature flue gas from combustion chamber is sucked by flue gas fan (FGF) with capacity of 48 kW, see Fig. 2, and circulated through the working fluid equipments and air equipments with the sequence as shown in Fig.4.

3. ANALYSIS

The exergy of the system is maximum work obtainable as the system comes to equilibrium with the surroundings. Based on Chengel, et.al [2] and Bejan [3], there are two sources of entropy generation in steam generator in power plant, which are entropy generation due to irreversibility in chemical reaction in combustion chamber and friction and temperature change of the fluid flow, thermal heat transfer in all the components of steam generator. We did the energy and exergy analysis by considering the following assumptions:
- the process is steady-state and steady flow

- the potential and kinetic energies are negligible
- air and flue gas are ideal gas, so its specific heat is constant
- dead state: T_o = 298 K, P_o = 1.1035 bar

In this analysis the kinetic and the potential exergy are assumingly negligible, so that the calculations of exergy only be performed in chemical exergy of a fuel consisting of a known mixture of fuel and air, and in physical exergy of water, steam and flue gasses.

The governing equations are applied to calculate the energy, exergy and efficiency of furnace and all components in steam generator are based on Cengel [2] and Ahern [4],

Energy balance:
In furnace,

$$\sum \left(N_r \overline{h}^o_{f.r} - N_p \overline{h}^o_{f.p}\right) + \sum N_r \left(\overline{h} - \overline{h}_o\right) = \sum N_p \left(\overline{h} - \overline{h}_o\right) + Q_{out} \quad (1a)$$

1st term = lower heating value of fuel
2nd term = sensible heat of reactant
3rd term = sensible heating of product
4th term = heat transfer from combustion chamber

In economizer, evaporator, superheater and air heater are treated as heat exchanger,

$$h_{in} = h_{out} + Q_{out} \quad (1b)$$

Mass balance,

$$m_{in} = m_{out} \quad (1c)$$

Exergy balance:
In furnace,

$$\sum \left(1 - \frac{T_o}{T_b}\right)\dot{Q}_{out} + \sum \left(N_r \overline{h}^o_{f.r} - N_p \overline{h}^o_{f.p}\right) + \sum N_r \left[\left(\overline{h} - \overline{h}_o\right) - T_o\left(\overline{s} - \overline{s}_o\right)\right]$$

$$= \sum N_p \left[\left(\overline{h} - \overline{h}_o\right) - T_o\left(\overline{s} - \overline{s}_o\right)\right] + Ex_{dest} \ \text{kJ} \quad (2a)$$

In economizer, evaporator, superheater and air heater are treated as heat exchanger,

$$\left(h_{in} - h_o\right) - T_o\left(s - s_o\right)_{in} = \left(h_{out} - h_o\right) - T_o\left(s - s_o\right)_{out} + \left(1 - \frac{T_o}{T_b}\right)Q_{out} + Ex_{dest} \ \text{kJ/kg} \quad (2b)$$

Entropy equation for air and flue gasses is treated as ideal gasses and can be calculated from:

$$s = \sum N_i \left[\overline{s}\left(T, P_o\right) - \left(s_{298} - R \ln yiP_m\right)\right] \quad (3)$$

Efficiencies:
The first law efficiency can be calculated by the effectiveness of the fluid stream,

$$\varepsilon = \frac{\text{Temperature change of fluid stream}}{\text{Maximum possible temperature change of stream}} \quad (4)$$

The second law efficiency can be calculated from:

$$\eta_{2nd} = \frac{\text{Exergy rate output}}{\text{Exergy rate input}} = \frac{\text{Exergy released}}{\text{Exergy absorbed}} \quad (5)$$

4. RESUTS AND DISCUSSION

The data recording of operation conditions are used for the analysis as shown on Table 1. Based on this data, we make calculations on energy and exergy by using equations 1 to 5, and the results are tabulated as shown on Table 2. If we compare between the efficiency of FLT and SLT, the results show that furnace is not very efficient from an exergy point of view. According to Ahern [4], exergy loss could be achieved, by reducing the combustion temperature. It can be done by replacing the burner that gives lowering the combustion temperature. For the steam generator components such as economizer until air heater, the efficiencies of FLT are lower compared to the SLT. The SLT efficiency shows the value below 50 % for the economizer, superheater II and air heater I especially for superheater II. Based on Ahern [4], the improvement of the exergy can be done by decreasing the temperature difference in heat exchanger, this means that decreasing the mass flow rate of the water in economizer - then decreasing the flow rate of steam in superheater II, and also decreasing the mass flow rate of the air in air heater I. Another method of reducing the temperature difference can be done by adding extended surface fins to the primary surface. This method will result in increased first cost of the unit that must be considered in a trade-off for the most effective life-cycle cost and use of available energy source. From Table 4, it was found that maximum loss was in furnace (35.51 %), and then in evaporator, superheater II. These conditions have been agree with the above discussions. Based on rate of energy and of exergy losses on Table 3 and Table 4, it has been drawn the Sankey and Grassman diagrams as shown on Fig. 5 and Fig. 6 respectively. The rate of energy and rate of energy to turbine are 58.04 % and 25.01 % respectively. Although the value is larger for energy rate compared to exergy rate, but the definition of real losses in the system are given by exergy method.

5. CONCLUSIONS

According to analysis, it was found that maximum exergy loss was found in furnace (35.51 %), then followed by evaporator (17.78 %) and superheater II (9.12 %). The improvement of the exergy can be done by reducing combustion temperature in furnace, and decreasing the flow rate of working fluid that works at lower stream side. It has been found that the rate of energy and rate of exergy to turbine are 58.04 % and 25.01 % respectively, however the definition of real losses in the system are given by exergy method.

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Table 1: Operation Conditions at Load 10.3 MW

No	*Component*	$\dot{m}$ *(kg/s)*	P_{in} *(bar)*	P_{out} *(bar)*	T_{in} *(°C)*	$\boldsymbol{T_{out}}$ **(°C)**
	Water/Steam Flow					
1	Economizer	14.72	56.88	38.25	162	182
2	Boiler	13.06	–	38.25	182	247.7
3	Superheater IA				283	320
4	Superheater IB				295	395
5	Superheater II		–		363	440
	Flue Gas Flow					
6	Furnace		–98E-05			1867
7	Superheater II		–2.94E-04	–4.91E-04	1000	672
8	Superheater IB			–7.85E-04		529
9	Superheater IA			–1.668E-03		465
10	Airheater IIA			–2.2452E-03		312
11	Economizer			–3.63E-03		220
12	Airheater I			–4.905E-03		140
	Air					
13	Air Heater 1	18.49		0.0412		125
14	Air Heater 2			0.03728		300

Table 2: Energy and exergy balance calculations of each component in the steam generator

Component	*Subtance*	*Energy in* h_{in} *[kW]*	Q_{out} *[kW]*	*Energy out* h_{out} [*[kW]*	*Exergy in* X_{in} *[kW]*	*Exergy out* X_{out} *[kW]*	*Exergy Destroy [kW]*	*Efficiency of FLT[%]*	**Efficiency of SLT[%]**
Furnace	Fuel	51,264.88	10,243.2	51,748.93	49,955.22	33,198.33	18,280.42	83.48	64.49
	Air	10,727.26			1,523.53				
Economizer	Water	10,074	712.21	11,366.86	1,531.86	1,963.08	460.64	37.97	48.35
	Gas	12,064.77		10,059.70	3,148.66	2256.80			
Evaporator	Steam	11,366.86	510.78	34,029.64	1,963.06	11859.75	9152.36	59.24	51.95
	Gas	51,748.93		28,575.37	33,198.33	14149.30			
Superheater IA	Steam	38,070.40	146.27	39,409.28	8,182.82	14,265.39	534.90	23.97	68.68
	Gas	16,997.30		15,512.15	13,891.25	5,035.34			
Superheater IB	Steam	38,536.49	99.04	41,838.52	13,915.29	15,537.74	615.99	38.58	72.48
	Gas	20,398.38		16,997.30	8,182.82	5,944.38			
Superheater II	Steam	40,839.85	5,807.67	43,209.17	15,037.40	16,307.30	4,696.58	16.38	21.28
	Gas	28,575.37		20,398.38	14,149.30	8,182.80			
Air heater II	Udara	7,396.35	116.47	10,727.26	258.22	1,523.53	621.37	52.72	67.07
	Gas	15,512.15		12,064.76	5,035.34	3,148.66			
Air heater I	Udara	5,714.43	24.46	7,396.35	3,41	258,22	324.88	48.93	43.21
	Gas	10,059.70		8,353.31	2,256.80	1,677.11			
To Stack	Gas						1,677.11		
To Turbine	Steam					16,307.30			

FLT = First Law of Themodynamics, *SLT* = Second Law of Themodynamics,

Table 3: Energy balance of each component in the steam generator (adapted from Table 2)

Component	*Energy balance (kW)*			**Rate of Energy**	**%**
	Input (kW)	Output (kW)	Loss (kW)		
Fuel	61,992.14			E_1	100
Furnace			10,243.2	E_2	16.52
Economizer			712.21	E_3	1.15
Evaporator			510.78	E_4	0.82
Superheater IA			146.27	E_5	0.24
Superheater IB			99.05	E_6	0.16
Superheater II			5807.67	E_7	9.37
Air heater II			116.48	E_8	0.19
Air heater I			24.47	E_9	0.04
To Stack			8353.31	E_{10}	13.47
Sub-Total			26,013.44		41.96
To turbine		35,978.70		E_{11}	58.04
Total		61,992.14			100

Table 4: Exergy balance of each component in the steam generator (adapted from Table 2)

Component	*Exergy balance (kW)*			Rate of Exergy	%
	Input (kW)	Output (kW)	Loss (kW)		
Fuel	51,478.75			Ex_1	100
Furnace			18,280.42	Ex_2	35.51
Economizer			460.48	Ex_3	0.89
Evaporator			9,152.34	Ex_4	17.78
Superheater IA			2,773.34	Ex_5	5.39
Superheater IB			615.99	Ex_6	1.20
Superheater II			4,696.60	Ex_7	9.12
Air heater II			621.37	Ex_8	1.21
Air heater I			333.88	Ex_9	0.65
To Stack			1,667.11	Ex_{10}	3.24
Sub-Total			38,601.53		74.99
To turbine		12,877.22		Ex_{11}	25.01
Total		51,478.75			100

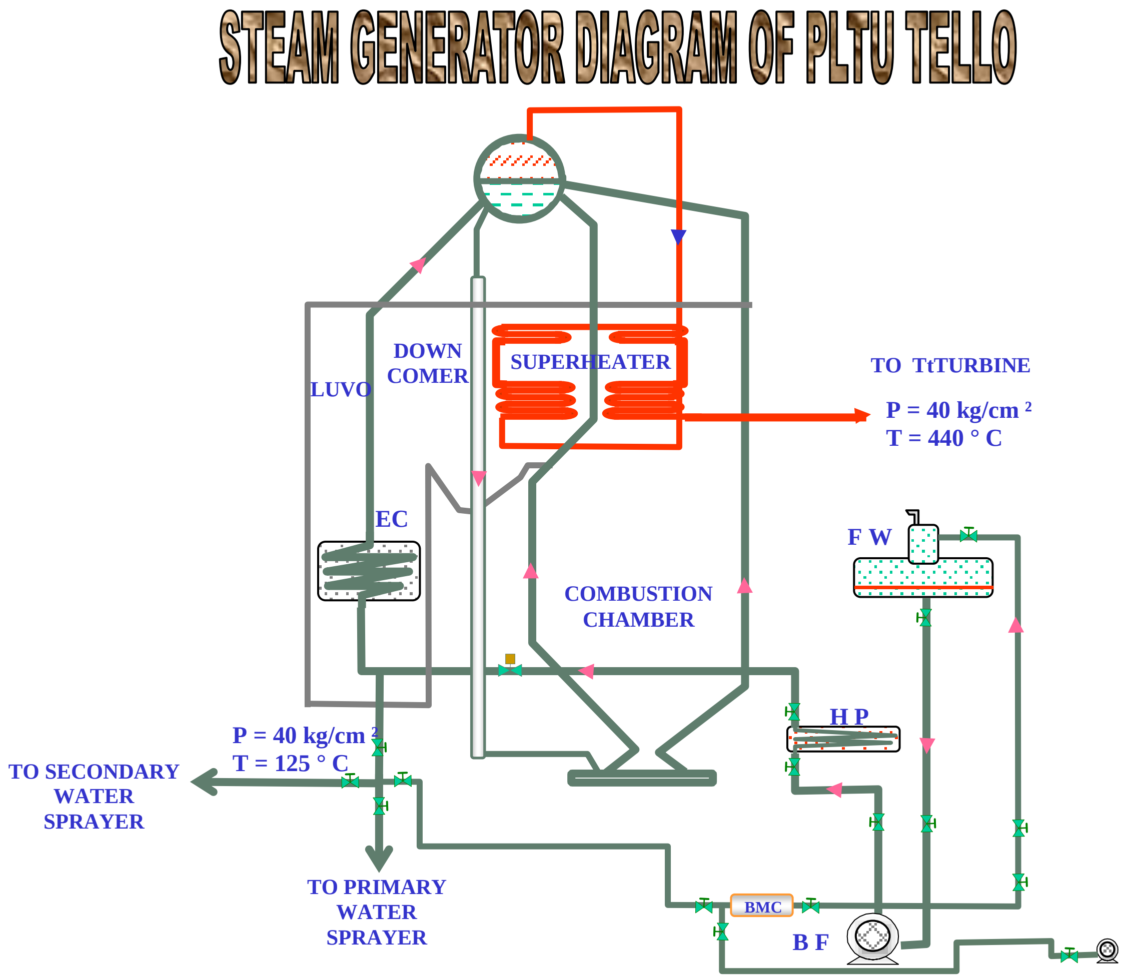

Figure 1 Schematic diagram of steam generator

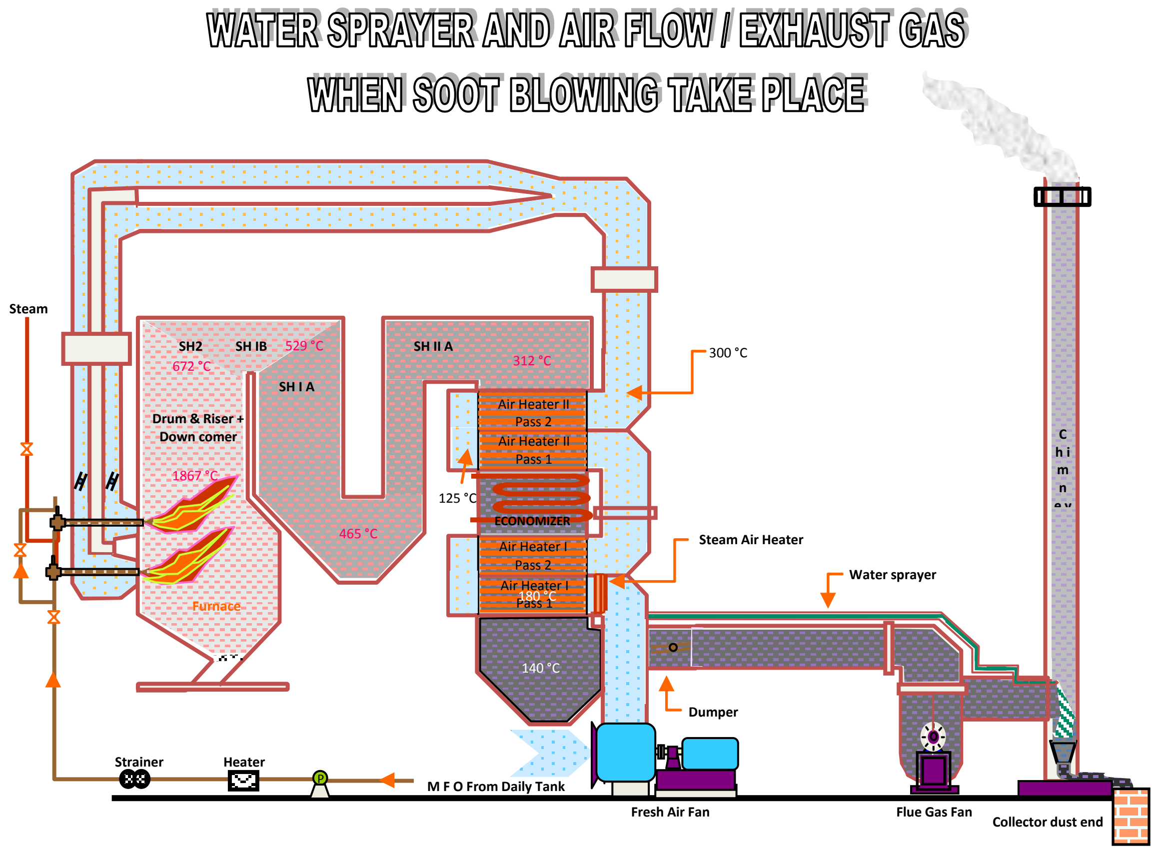

Figure 2 Schematic diagram of steam generator

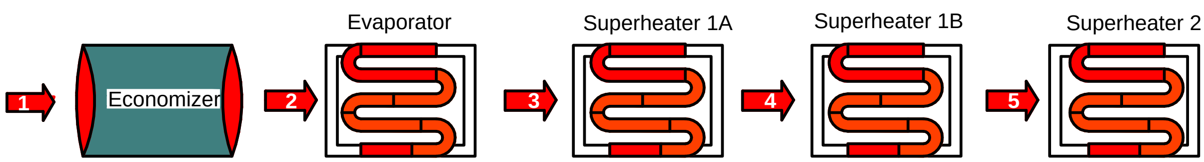

Fig 3 Schematic diagram of working fluid flow in steam generator components

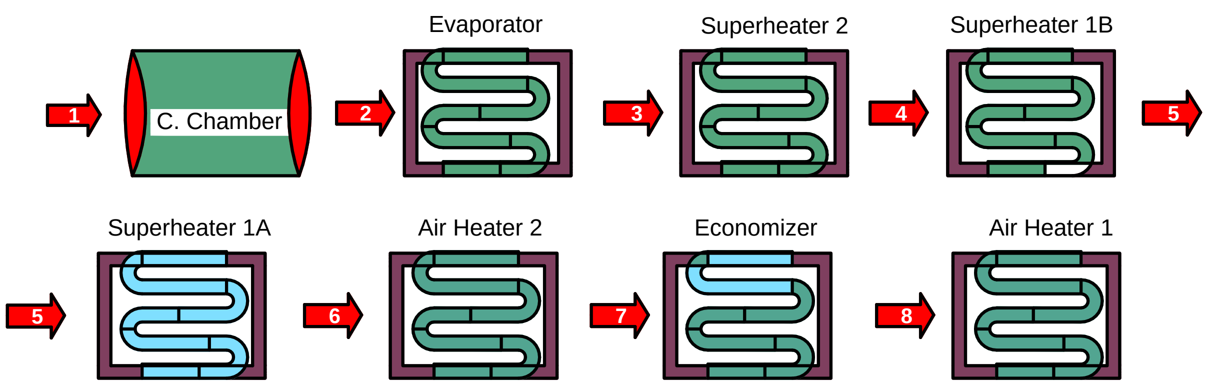

Fig 4 Schematic diagram of the flue gas flow in steam generator components

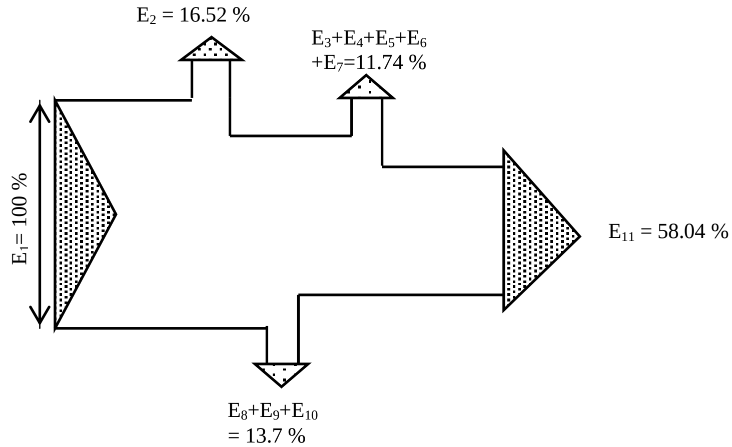

Figure 5 Sankey diagram of steam generator in energy evaluation (adapted from Table 2)

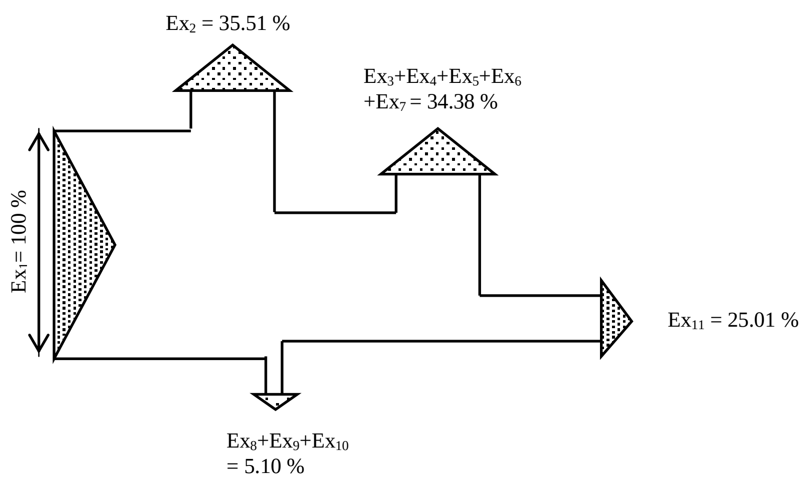

Figure 6 Grassmann diagram of steam generator in exergy evaluation (adapted from Table 3)