Exercise 2 (Regenerative Rankine Cycle)

A regenerative Rankine cycle consists of three expansion stages (17000 kPa, 10000 kPa, 2000 kPa, 11 kPa). The gaseous fuel consists of a volumetric mixture of methane (92%) and ethane (8%). Air and fuel enter at 100 kPa and 25ºC. The excess air is 160%. The flue-gas leaves the chimney at 427ºC and 100 kPa. The relative humidity of the air is 70%.

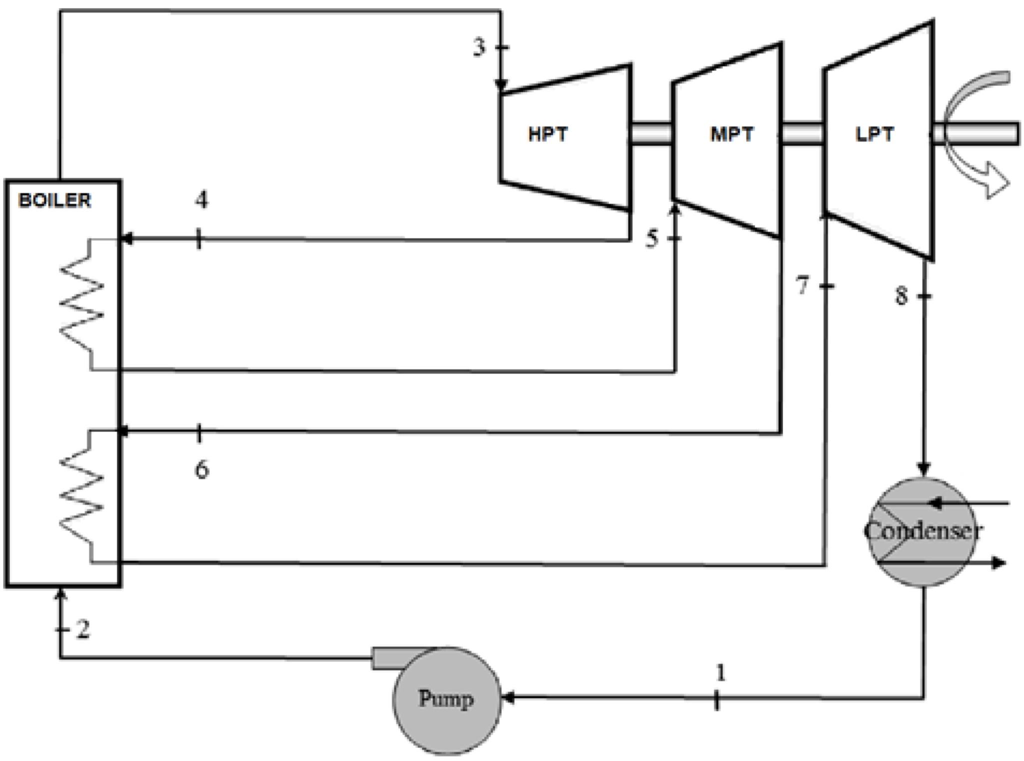
Get:

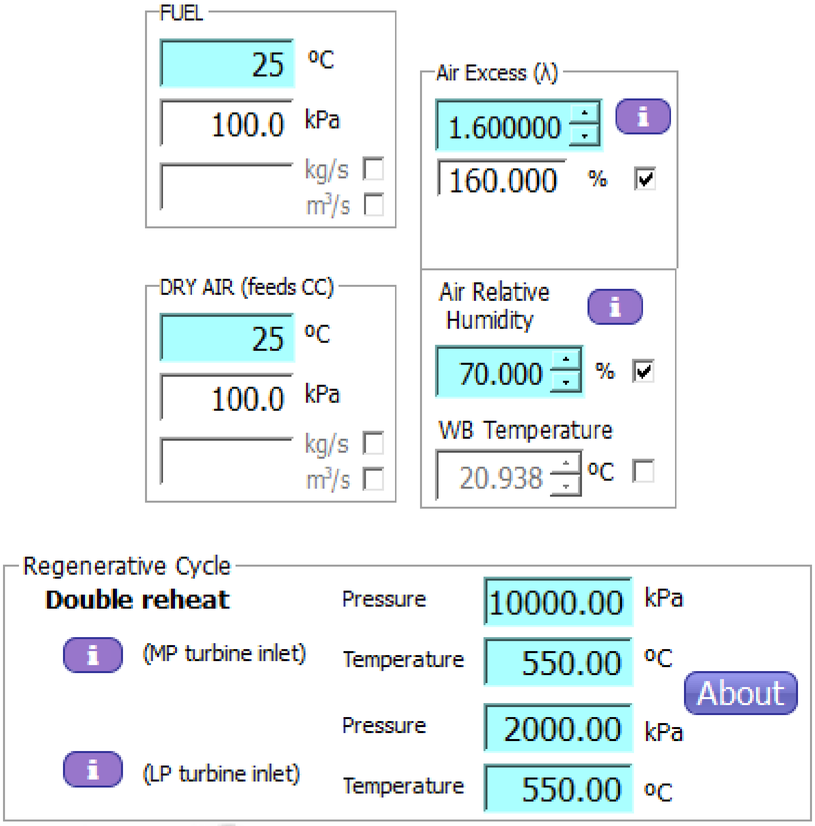
a) Mass balance

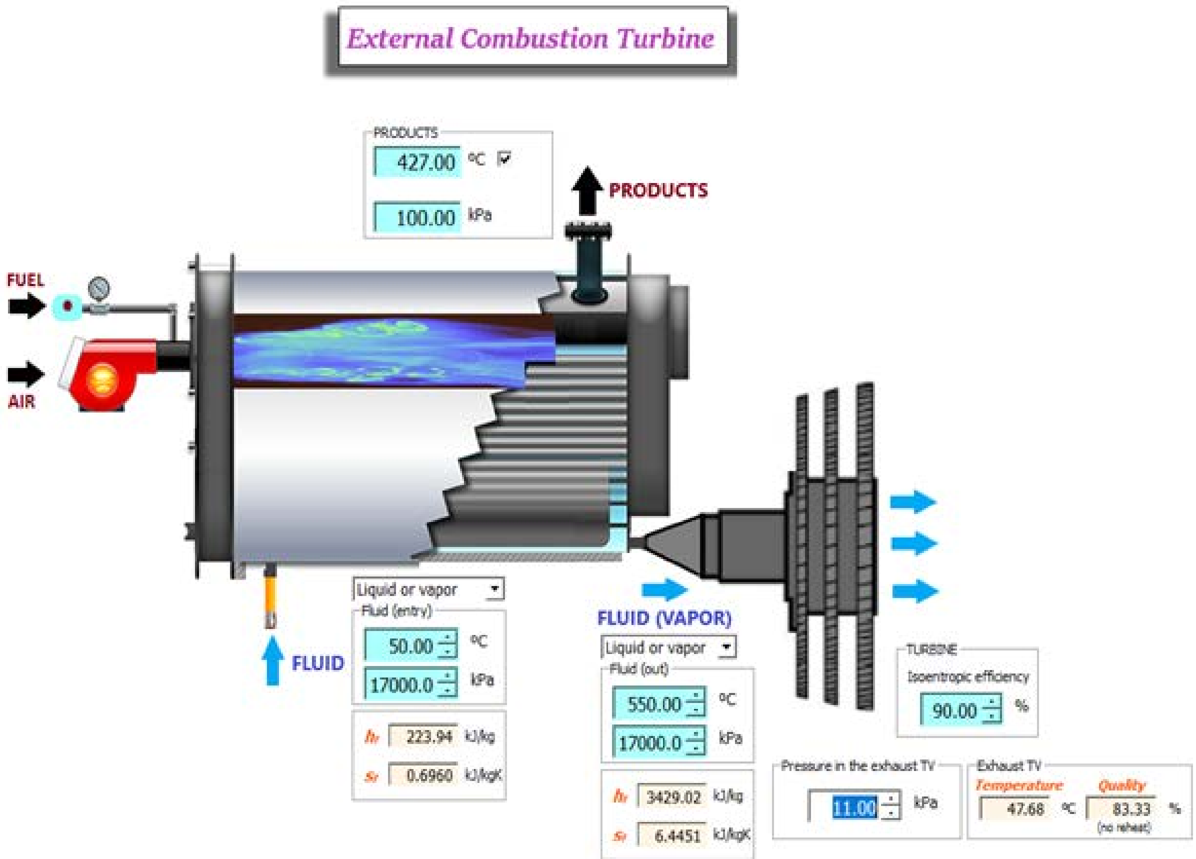
b) Energy balance

c) Exergy balance

The installation scheme is:




FUEL
25 ºC
100.0 kPa
kg/s
m³/s
Air Excess (λ)
1.600000
160.000 %
DRY AIR (feeds CC)
25 ºC
100.0 kPa
kg/s
m³/s
Air Relative Humidity
70.000 %
WB Temperature
20.938 ºC
Regenerative Cycle
Double reheat
(MP turbine inlet)
(LP turbine inlet)
Pressure 10000.00 kPa
Temperature 550.00 ºC
Pressure 2000.00 kPa
Temperature 550.00 ºC
About


External Combustion Turbine
PRODUCTS
427.00 ºC
100.00 kPa
PRODUCTS
FUEL
AIR
FLUID
Liquid or vapor
Fluid (entry)
50.00 ºC
17000.0 kPa
223.94 kJ/kg
0.6960 kJ/kgK
FLUID (VAPOR)
Liquid or vapor
Fluid (out)
550.00 ºC
17000.0 kPa
3429.02 kJ/kg
6.4451 kJ/kgK
TURBINE
Isentropic efficiency
90.00 %
Pressure in the exhaust TV
11.00 kPa
Exhaust TV
Temperature
Quality
47.68 ºC
83.33 %
(no reheat)

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	P_{vapor}(T^a fuel) kPa	Molar ratio %		
Gas T>Tc		92.0000	CH_4	Methane
Gas T<Tc	4190.33	8.0000	C_2H_6	Ethane

Inerts: %

FUEL 2

Total: 100.0000

	Lower Heating, LHV		Higher Heating, HHV
NET	852.35	kJ/mol fuel	943.89
	49656.61	kJ/kg fuel	54989.64

GROSS

kJ/mol & kJ/kg

Fuel Properties

Enthalpy of formation	-75.636	kJ/mol fuel
Absolute entropy (1 atm & 25ºC)	189.6352	J/mol fuel K
Standard chemical exergy	886.44	kJ/mol fuel
Standard Gibbs Free Energy of Formation	-49.36	kJ/mol fuel

☑ Experimental correlation
Kotas (1995)
☑ Thermocombustion database

Moisture in Air — Air

0.02269	mol water / mol dry air
0.00041	kg water / mol dry air
0.78657	mol water / kg dry air

Absolute humidity

0.01417	kg water / kg dry air

Vapor pressure: 2.21895 kPa — Dew Point Tª: 18.87 ºC

Air/fuel ratio

16.51893	mol/mol fuel
27.53358	kg/kg fuel

Moisture in Air — Fuel

0.36655	mol water / mol fuel
0.00660	kg water / mol fuel
21.35462	mol water / kg fuel
0.38471	kg water / kg fuel

Vapor pressure: 2.21895 kPa — Dew Point Tª: 18.87 ºC

Air/fuel ratio

16.51893	mol/mol fuel
27.53358	kg/kg fuel

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Air/Fuel ratio (dry air)

AIR

Theoretical	*Actual*	
10.09524	16.15238	☐ mol/mol fuel
16.96804	27.14887	☐ kg/kg fuel

Reactants (fuel + dry air)

17.15238 mol/mol fuel

(Assume 1 mol fuel is being combusted)

FLUE GAS (Combustion Products) ☑ On wet basis ☐ On dry basis

	☑ mol/mol fuel	☐ kg/kg fuel	Mole %	Mass %
CO_2	1.080000	2.769057	6.2156	9.8222
CO				
H_2O	2.446547	2.567756	14.0803	9.1082
N_2	12.760381	20.825228	73.4381	73.8701
O_2	1.088722	2.029672	6.2658	7.1995
SO_2				
H_2				
Ar				
unburned				
TOTAL	17.3757	28.1917	100.00 %	100.00 %

Dew Point (and P_{sat})

52.66 ºC H_2O (liquid) ☐ 100% mol/mol fuel

% kg/kg fuel

14.08 kPa

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Heat (Released or Absorbed)

i

Exothermic
Exo = release

ENERGY

632.561 kJ/mol fuel

☐ Reactants

☐ Products

$$Q_f = \sum_{\text{Products}} n_{out}\, h_{out}(T_{out}) - \sum_{\text{Reactants}} n_{in}\, h_{in}(T_{in})$$

-796.836 kJ/mol fuel -164.275

$Q_f = H_P(T_{out},P) - H_R(T_{in},P) = H_P(T_{out},P) - H_P(T_{ad},P)$

☑ kJ/mol fuel ☐ kJ/kg fuel ☐ kW

$H = H_{form} + H(T,P) - H(25^oC, 1\ atm)$

Products Temperature

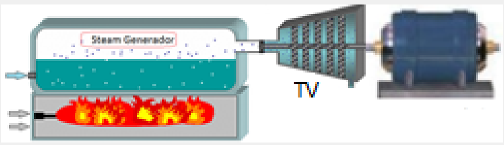
427.00 ºC

Adiabatic Flame Temperature

For λ = 1.6000 **(Actual)** 1426.90 ºC

For λ = 1.0 (max) **(Theoretical)** 2017.90 ºC (25ºC, 1atm)

Boiler/Furnace Efficiency



74.21 %

i

◉ LHV

○ HHV

Stack heat losses i

219.79 kJ/mol fuel

25.79 % (of the calorific value of the fuel)

Results of the Energy Analysis

i

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STEAM GENERATOR

Useful heat	632.56	kJ/mol fuel
Thermal efficiency	74.21	%
Exhaust products loss	219.79	kJ/mol fuel

Mass ratio

5.0668	Mol fuel/kg fluid	0.0870	kg fuel/kg fluid

Thermal efficiency (Plant)

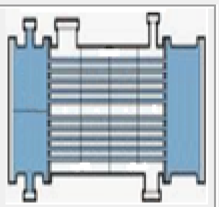
30.79 %

Net work

262.47 kJ/mol fuel

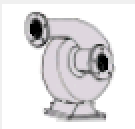
CONDENSER

Released heat 364.94 kJ/mol fuel



ADIABATIC PUMP

Waste work	5.15	kJ/mol fuel
Isoentropic efficiency ?	53.23	%



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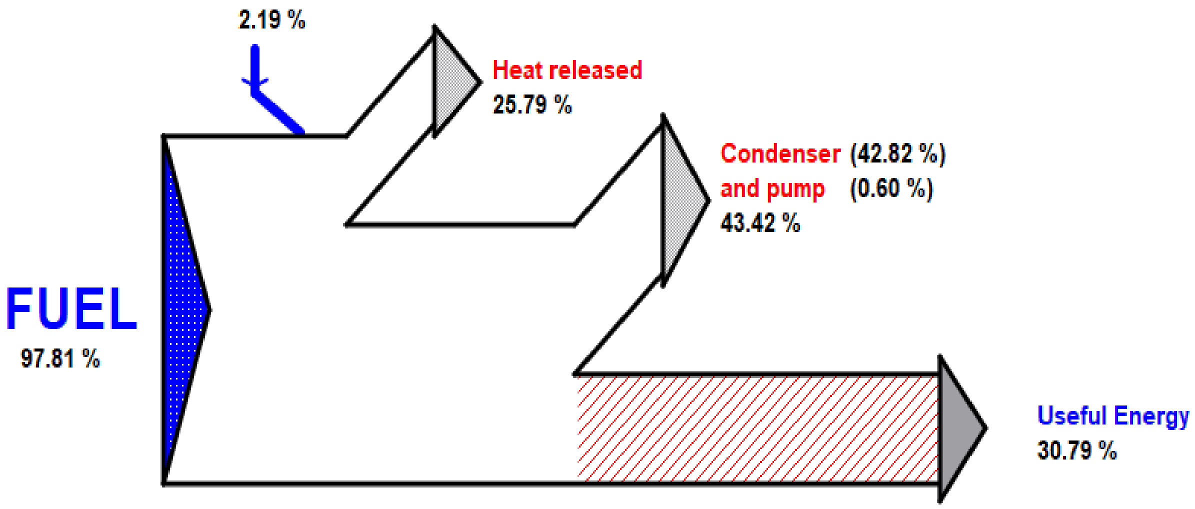
ADIABATIC TURBINE

	STAGE, HP		STAGE, MP (Alternativel Exchanger)		STAGE, LP	
Enthalpy at the entrance	549.09	kJ/mol fuel	560.77	kJ/mol fuel	573.10	kJ/mol fuel
Specific work	24.47	kJ/mol fuel	70.84	kJ/mol fuel	172.31	kJ/mol fuel
Stack discharge	524.62	kJ/mol fuel	489.93	kJ/mol fuel	400.79	kJ/mol fuel
Stack losses temperature	462.44	ºC	315.36	ºC	45.81	ºC
Isoentropic efficiency	? 90.00	%	? 90.00	%	90.00	%
Isoentropic stack losses temperature	873.69	ºC	550.00	ºC	45.81	ºC



Method Exergy Applied to Chemically Reactive Systems

Exergy balances, which allow exergy destruction rates and exergy efficiencies to be determined, for the main components of the installation, that is, the boiler (differentiating between the combustion chamber and heat exchanger), turbine stages, condenser, and circulating pump.

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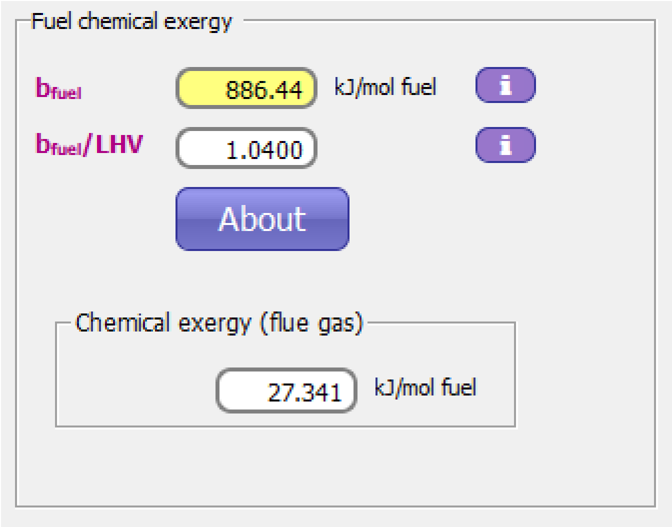

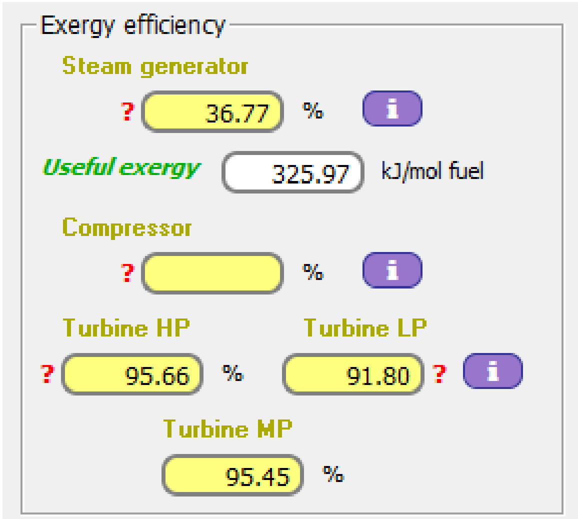

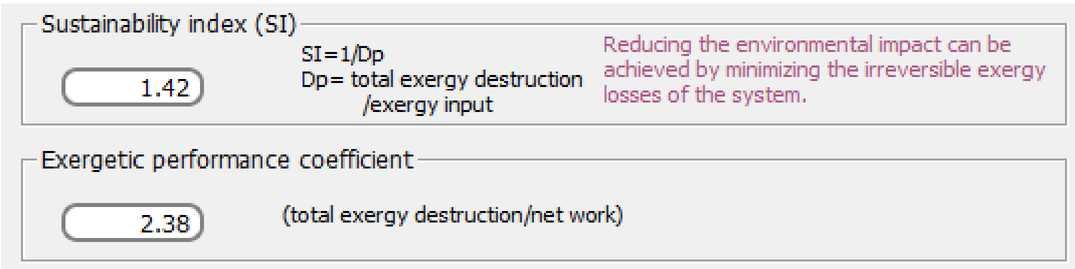

ThermoCombustion Hidrocarbon Fuels

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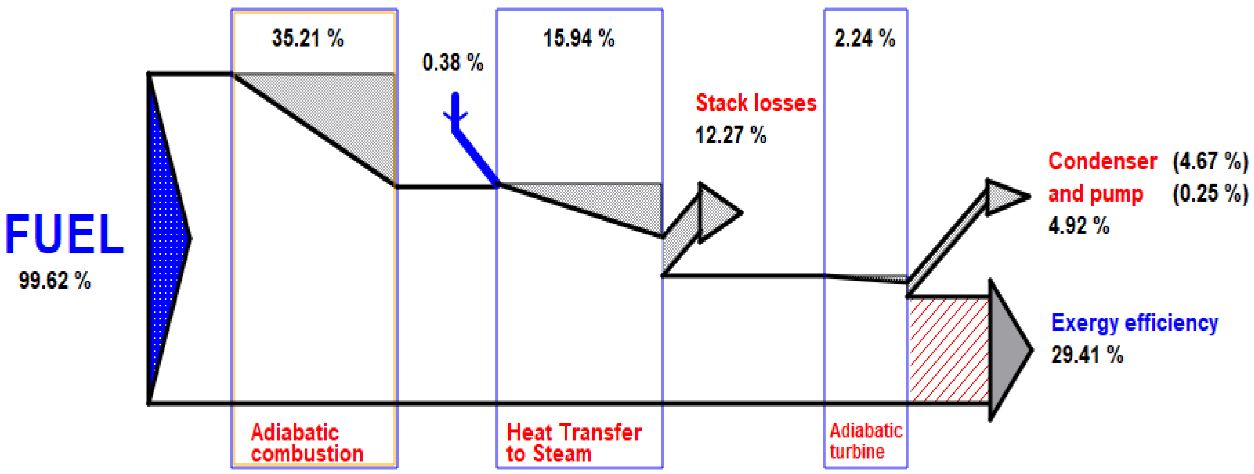
Irreversibilities

Combustion Chamber: 312.15 kJ/mol fuel	Compressor: kJ/mol fuel	Turbine (HP): 1.11 kJ/mol fuel
Heat Exchanger: 141.27 kJ/mol fuel	Condenser: 41.38 kJ/mol fuel	Turbine (MP): 3.38 kJ/mol fuel
Stack losses: 108.80 kJ/mol fuel	Pump: 2.23 kJ/mol fuel	Turbine (LP): 15.40 kJ/mol fuel
Regenerative Heat Exchanger: kJ/mol fuel	Exergy Destroyed (total)	625.72 kJ/mol fuel



Si resolvemos el ciclo no regenerativo:

Results of the Energy Analysis

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STEAM GENERATOR

Useful heat	632.56	kJ/mol fuel
Thermal efficiency	74.21	%
Exhaust products loss	219.79	kJ/mol fuel

Mass ratio

5.0668	Mol fuel/kg fluid	0.0870	kg fuel/kg fluid

Thermal efficiency (Plant)

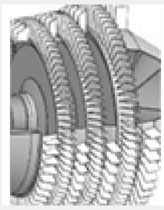
28.19 %

Net work

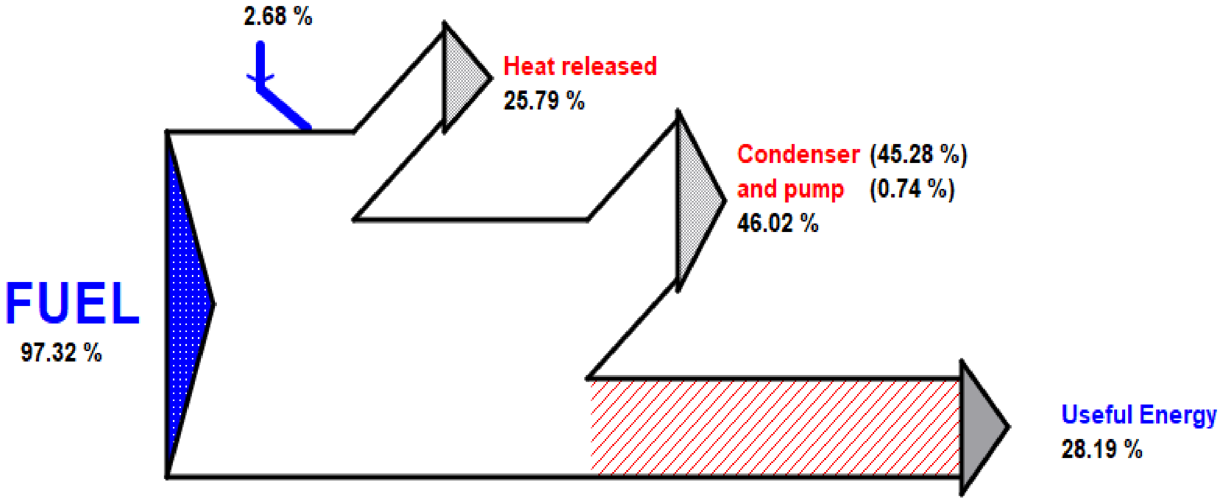
240.31 kJ/mol fuel

ADIABATIC TURBINE

STAGE, HP



Enthalpy at the entrance	676.76	kJ/mol fuel
Specific work	246.65	kJ/mol fuel
Stack discharge	430.11	kJ/mol fuel
Stack losses temperature	462.44	ºC
Isoentropic efficiency ?	90.00	%
Isoentropic stack losses temperature	873.69	ºC



Method Exergy Applied to Chemically Reactive Systems

Irreversibilities

Combustion Chamber: 312.15 kJ/mol fuel	Compressor: kJ/mol fuel	Turbine (HP): 25.62 kJ/mol fuel
Heat Exchanger: 172.98 kJ/mol fuel	Condenser: 25.58 kJ/mol fuel	Turbine (MP): kJ/mol fuel
Stack losses: 108.80 kJ/mol fuel	Pump: 2.75 kJ/mol fuel	Turbine (LP): kJ/mol fuel
Regenerative Heat Exchanger: kJ/mol fuel	Exergy Destroyed (total)	647.88 kJ/mol fuel

Sustainability index (SI)

1.37

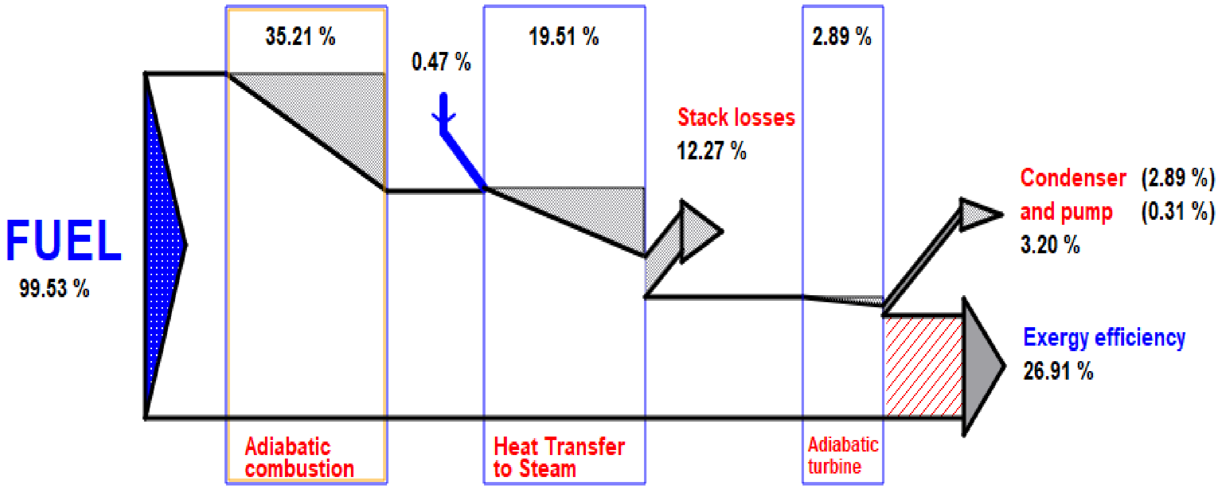
SI=1/Dp
Dp= total exergy destruction /exergy input

Reducing the environmental impact can be achieved by minimizing the irreversible exergy losses of the system.

Exergetic performance coefficient

2.70

(total exergy destruction/net work)


35.21 %
0.47 %
19.51 %
2.89 %
Stack losses
12.27 %
Condenser (2.89 %)
and pump (0.31 %)
3.20 %
FUEL
99.53 %
Exergy efficiency
26.91 %
Adiabatic combustion
Heat Transfer to Steam
Adiabatic turbine