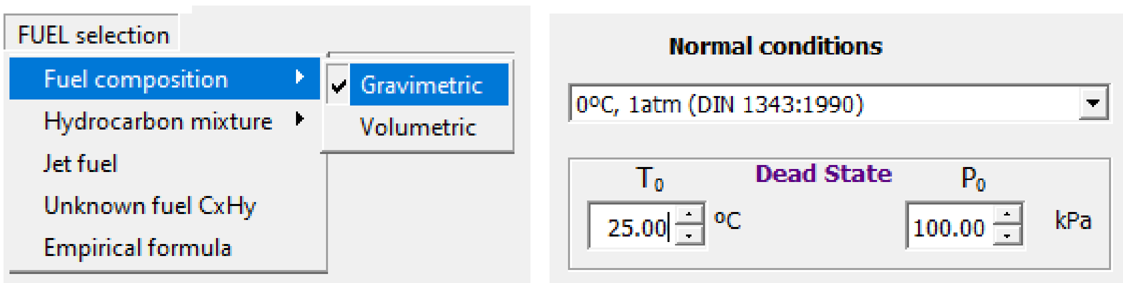
Exercise 6 (Steam Generator Boiler)

From a steam generator (boiler) the following composition of combustion products is obtained on a wet basis:

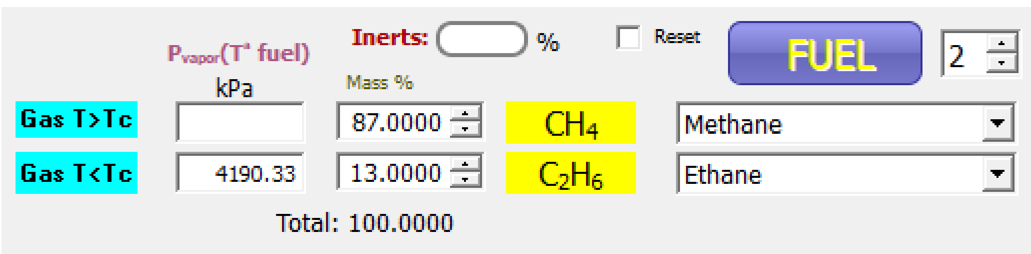
CO_2	5.50 %
CO	2.70 %
O_2, N_2, H_2O y H_2	other

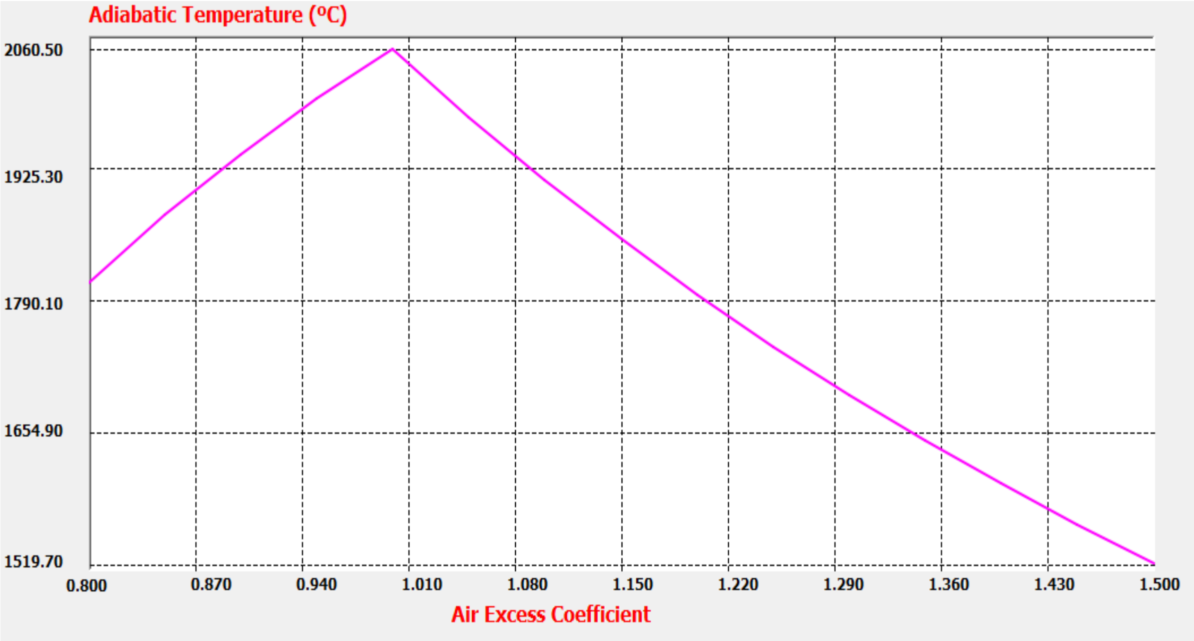
Knowing that the fuel is (mass composition) methane (87%) and ethane (13%) and that the combustion products at its outlet are at 600ºC.
The water enters at 25ºC and 11.00 MPa, leaving at 490ºC and 10.88 MPa

Get:
a) Influence of the coefficient of excess air on the adiabatic temperature of the flame
b) The air / combustion products molar ratio
c) The mass ratio of air / combustion products
d) Excess air coefficient
e) Energy balance
f) Exergy balance
g) Propose actions to improve the process

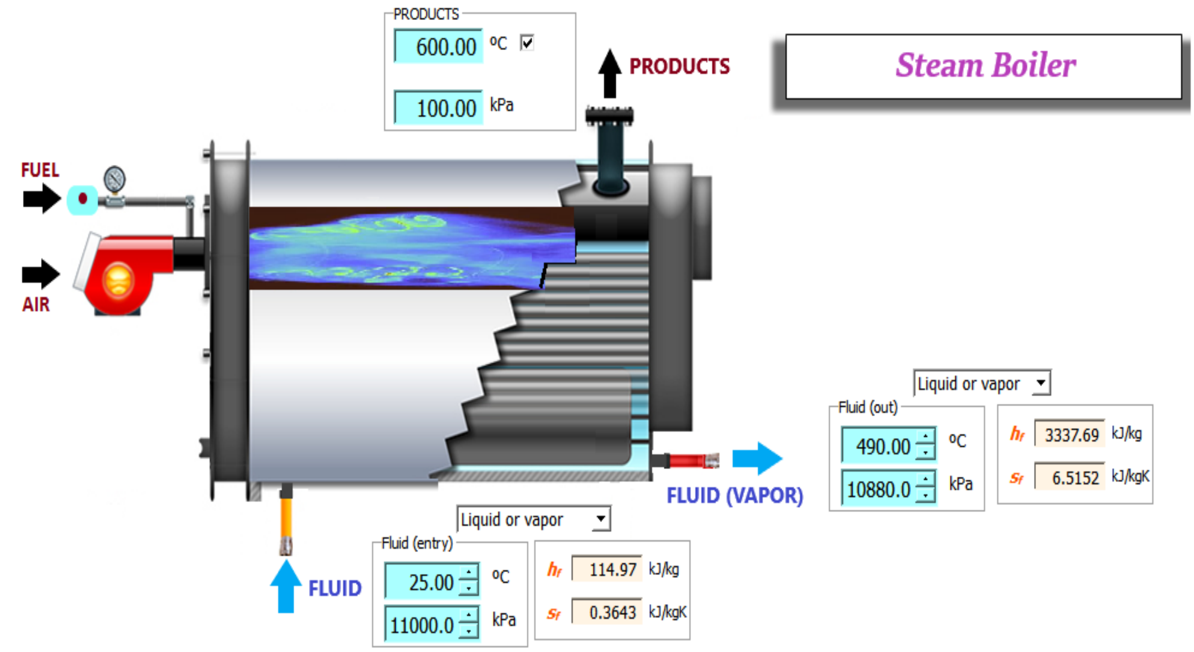


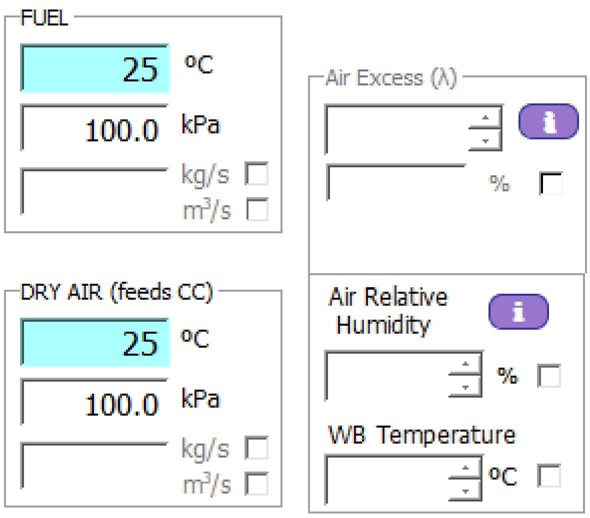
Combustion boilers are widely used to generate steam for industrial applications and power generation. While all kinds of energy sources - fossil fuels, biomass, nuclear and solar energy, electricity - can be used to generate heat and steam, the scope of this brief is limited to combustion boilers using fossil fuels. Boilers can be grouped into two broad categories: water-tube boilers and fire-tube boilers. In the water-tube boilers, tubes containing water are heated by combustion gases that flow outside the tubes, while in the firetube boilers hot combustion gases flow inside the tubes and water flows outside.
Boilers account for a significant share of industrial energy consumption and are the key components in power generation and industrial plants.

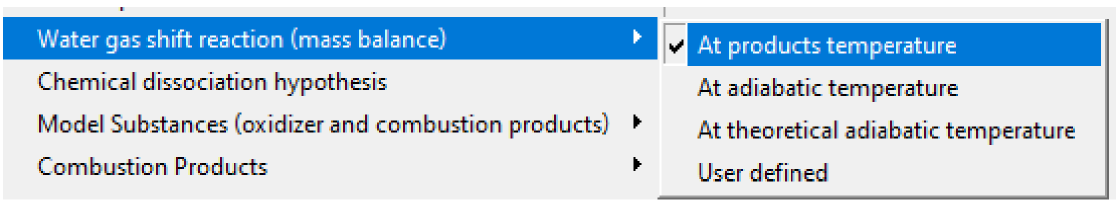




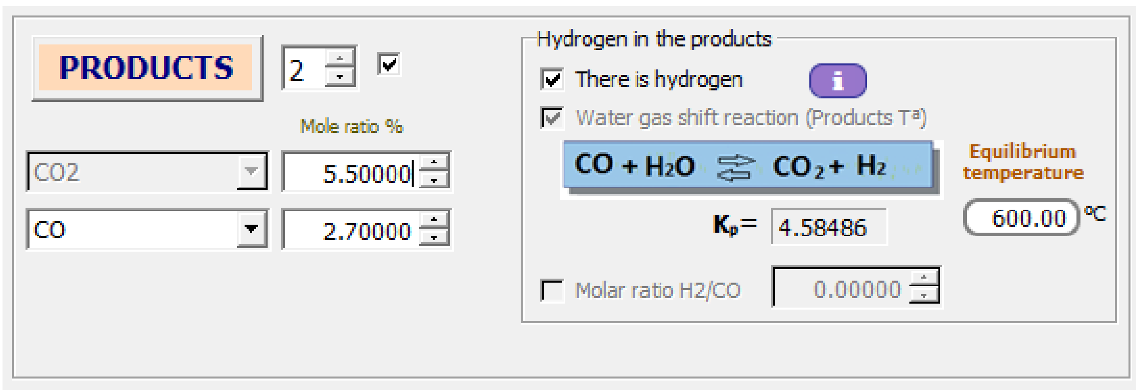
The peak adiabatic flame temperature occurs at around λ = 1 in an ideally insulated combustion chamber. Figure is a typical graph of flame temperature for a natural gas–air mixture. As percent combustion air increases, that is, as we deviate from the stoichiometric condition, some of the heat generated is used to heat up the excess air. As a result, the flame temperature will drop. By the same token, it is important to note that increasing the fuel at stoichiometric conditions will reduce the flame temperature as is indicated by the left-hand side of the temperature peak in Figure. Therefore, under controlled conditions, flame temperature can be a useful measure of air-fuel ratio, that is, how far we deviate from stoichiometric conditions and whether the combustion is fuel-lean or fuel-rich.







Water gas shift is a well-known reaction in which carbon monoxide reacts with steam to give carbon dioxide and hydrogen, representing an important step in the industrial production of hydrogen. Here, water and carbon monoxide molecules react to generate hydrogen and carbon dioxide. From the thermodynamics aspect, pressure does not have an impact, whereas low-temperature conditions are suitable for high hydrogen selectivity because of the exothermic nature of the WGSR reaction.



ThermoCombustion
Hidrocarbon Fuels

ThermoSuite
Technical Software Suite

Molar Mass FUEL
17.0785
g/mol fuel

Mole CO_2 (maximum)
11.9126 %

Excess Air Coefficient
1.1107

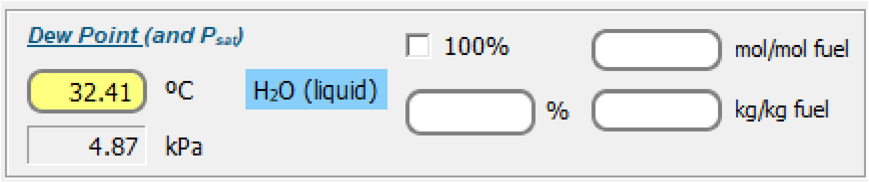
Equivalence Ratio (Relative Ratio, F_R)
0.9003

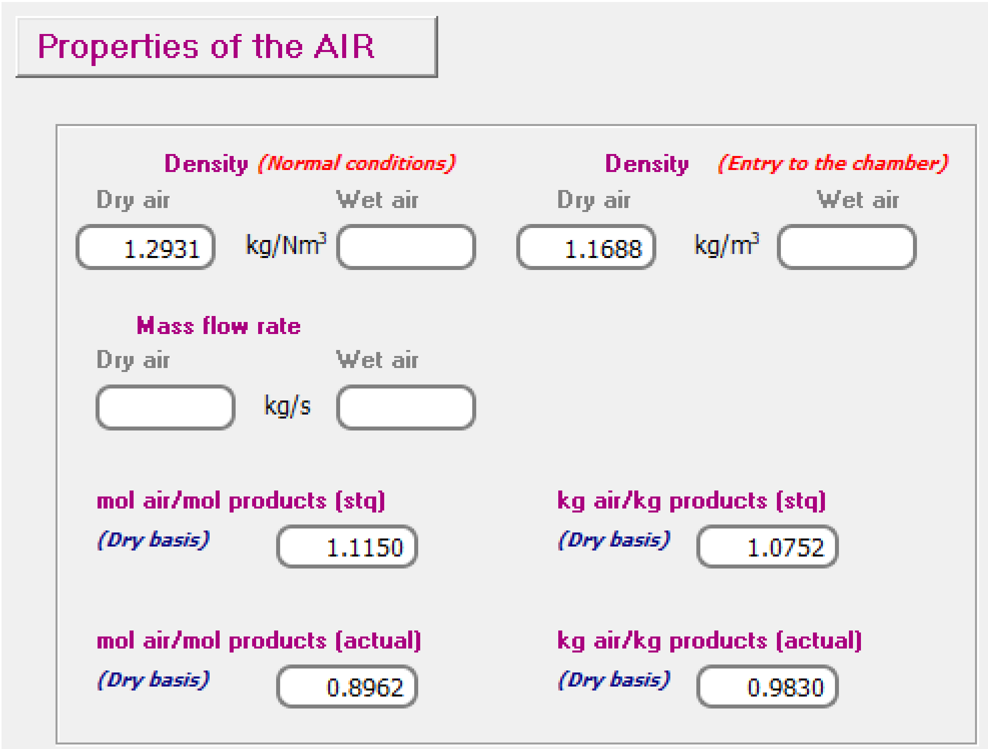
FUEL-AIR gravimetric and volumetric analysis

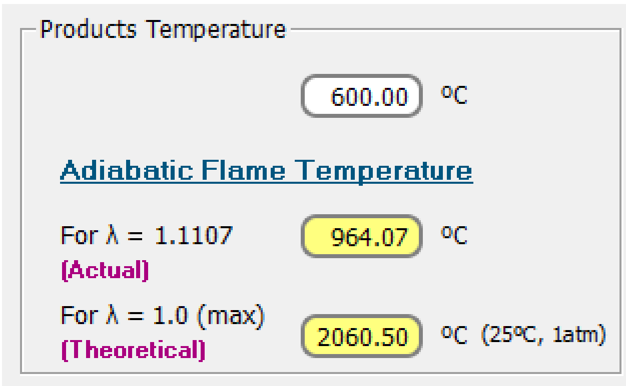
		Molar ratio, x_i (%)	Weight molecular, MW_i	$x_i\ MW_i$	mf_i (%)
AIR	O_2	19.2736	32.0000	6.1676	22.1197
	N_2	72.5054	28.0135	20.3113	72.8450
	Ar	0.0000	39.9480	0.0000	0.0000
	CO_2	0.0000	44.0098	0.0000	0.0000
	H_2O (Air HR)	0.0000	18.0153	0.0000	0.0000
FUEL	CH_4	7.6140	16.0428	1.2215	4.3808
	C_2H_6	0.6070	30.0690	0.1825	0.6545
		100.0000		27.8829 (kg/kmol)	100.0000

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

	☑ mol/mol fuel	☐ kg/kg fuel	Mole %	Mass %
CO_2	0.720256	1.856043	5.5000	9.3461
CO	0.353580	0.579902	2.7000	2.9201
H_2O	0.637957	0.672952	4.8715	3.3886
N_2	8.819498	14.466474	67.3470	72.8456
O_2	1.128399	2.114287	8.6166	10.6464
H_e				
H_2	1.435880	0.169488	10.9646	0.8535
Ar				
unburned				
TOTAL	13.0956	19.8591	100.00 %	100.00 %


Dew Point (and P sat)
32.41 ºC
4.87 kPa
H2O (liquid)
100%
%
mol/mol fuel
kg/kg fuel

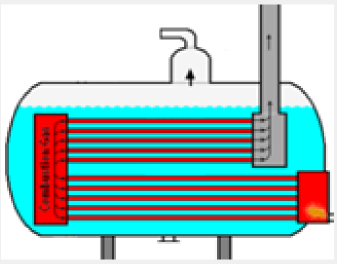

Properties of the AIR
Density (Normal conditions)
Dry air
Wet air
1.2931 kg/Nm3
Density (Entry to the chamber)
Dry air
Wet air
1.1688 kg/m3
Mass flow rate
Dry air
Wet air
kg/s
mol air/mol products (stq)
(Dry basis) 1.1150
kg air/kg products (stq)
(Dry basis) 1.0752
mol air/mol products (actual)
(Dry basis) 0.8962
kg air/kg products (actual)
(Dry basis) 0.9830


Products Temperature
600.00 ºC
Adiabatic Flame Temperature
For λ = 1.1107
(Actual)
964.07 ºC
For λ = 1.0 (max)
(Theoretical)
2060.50 ºC (25ºC, 1atm)

ThermoCombustion
Hidrocarbon Fuels

ThermoSuite
Technical Software Suite

Boiler Efficiency



19.40 %

(•) LHV
( ) HHV

Stack heat losses

683.91 kJ/mol fuel

80.60 % (of the calorific value of the fuel)

Direct method

Combustion Efficiency

Reference state: To=25 °C, Po=100 kPa

$$\eta_{comb} = \frac{Q_f(T_0)}{LHV}$$

47.28 %

(Incomplete Combustion Loss)

(100% for complete combustion)

$Q_f(T_0)$ 401.211 kJ/mol fuel

Combustion is generated with the presence of a large number of unburned.

Results of the Energy Analysis

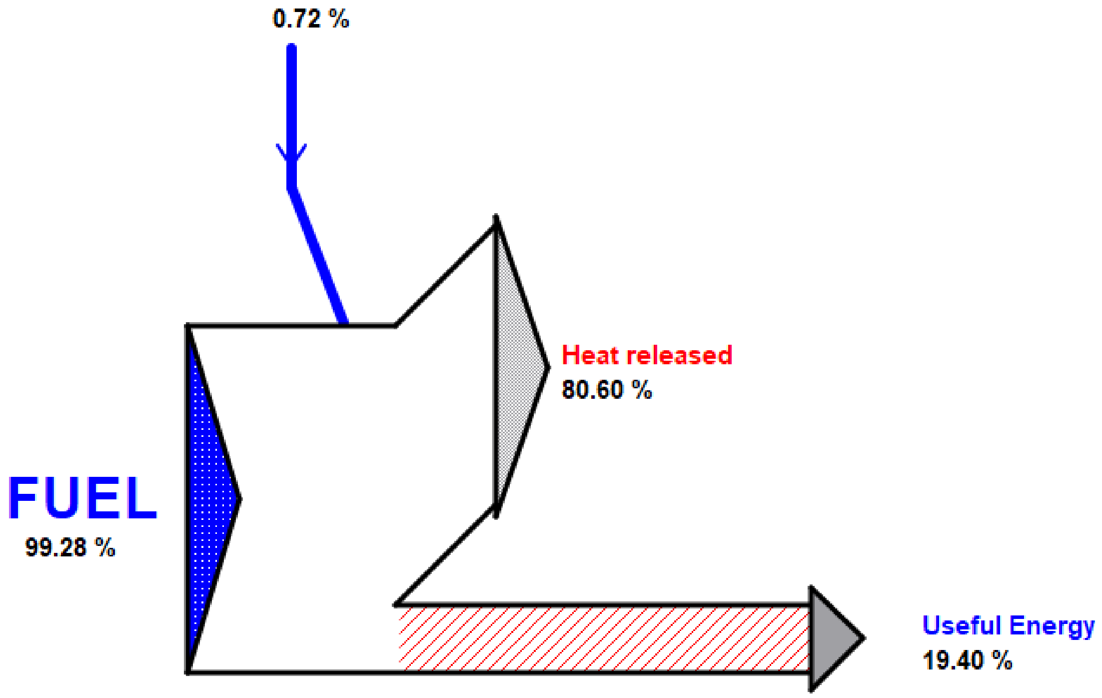
STEAM GENERATOR

Useful heat	164.58	kJ/mol fuel
Thermal efficiency	19.40	%
Exhaust products loss	683.91	kJ/mol fuel

Mass ratio (fuel consumption)

1.6432	Mol fuel/kg fluid	0.0281	kg fuel/kg fluid

Heat exchanger effectiveness	38.77	%



Method Exergy Applied to Chemically Reactive Systems

Fuel chemical exergy

b_{fuel} 882.44 kJ/mol fuel

b_{fuel}/LHV 1.0400

About

Chemical exergy (flue gas)

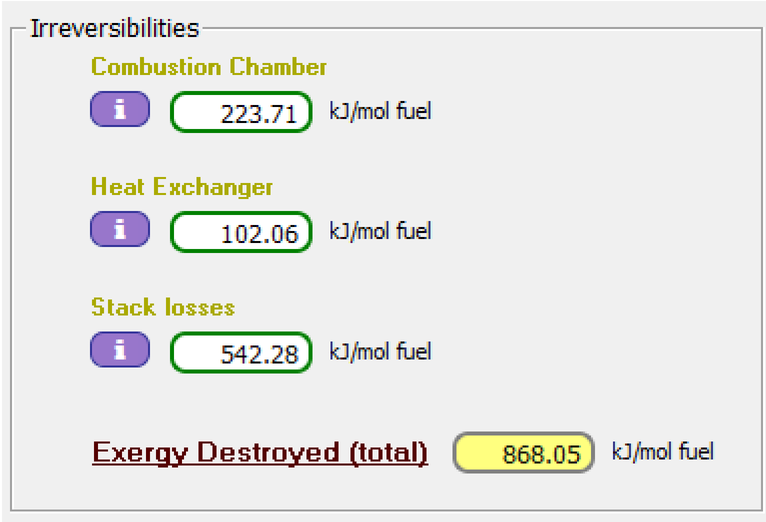
436.144 kJ/mol fuel

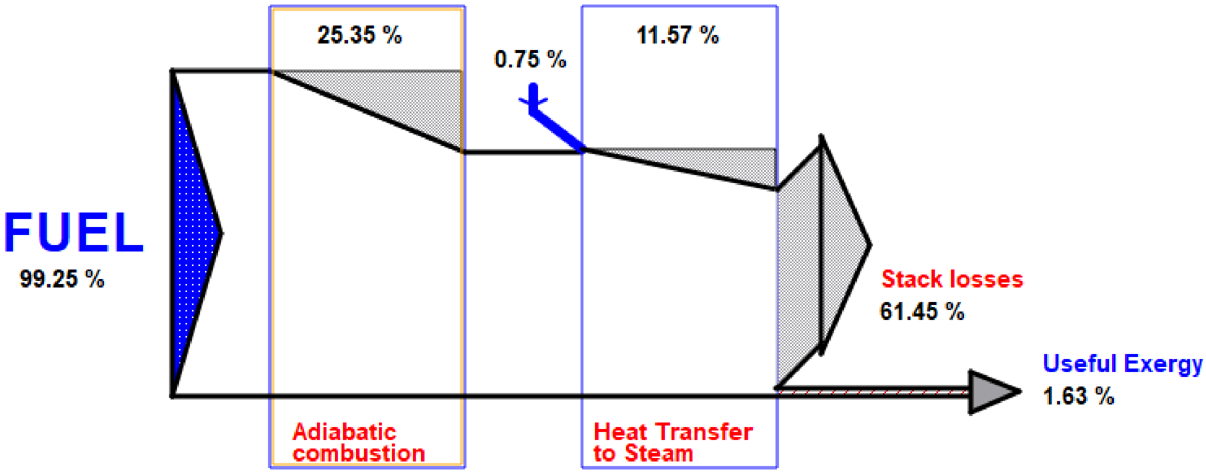
Exergy efficiency

Steam generator

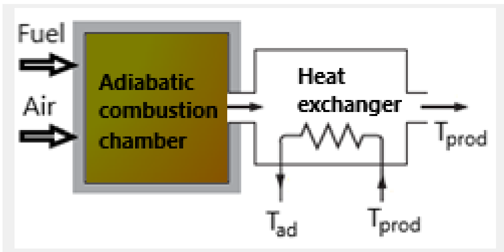
? 1.77 %

Useful exergy 15.65 kJ/mol fuel



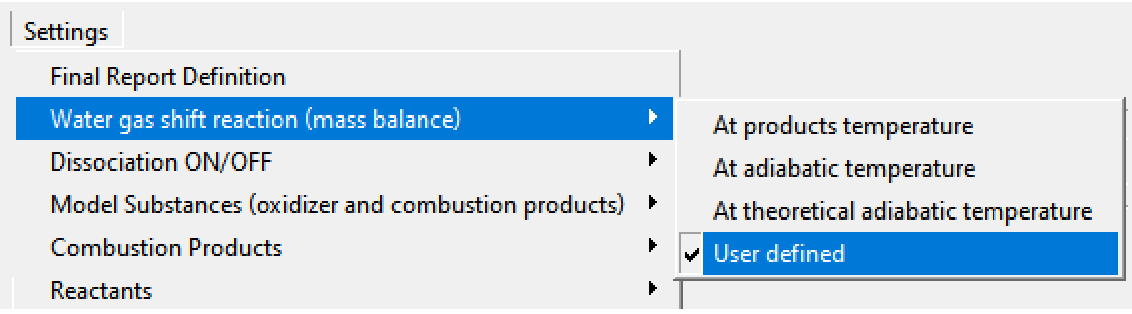


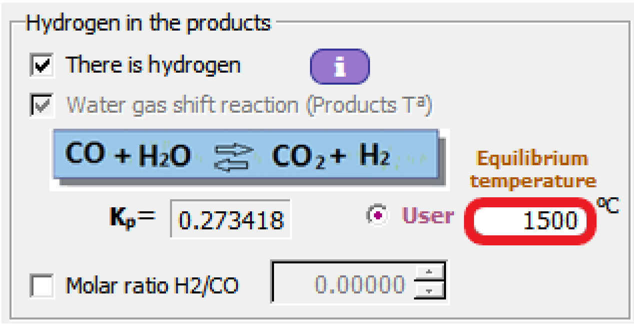
The main reason for the low efficiency, both thermal and exergetic, is the low temperature reached by the combustion products (the combustion chamber working adiabatically), 964ºC. The temperature margin to generate useful heat is small (964-600 = 364ºC), requiring 0.0281 kg fuel / kg water..

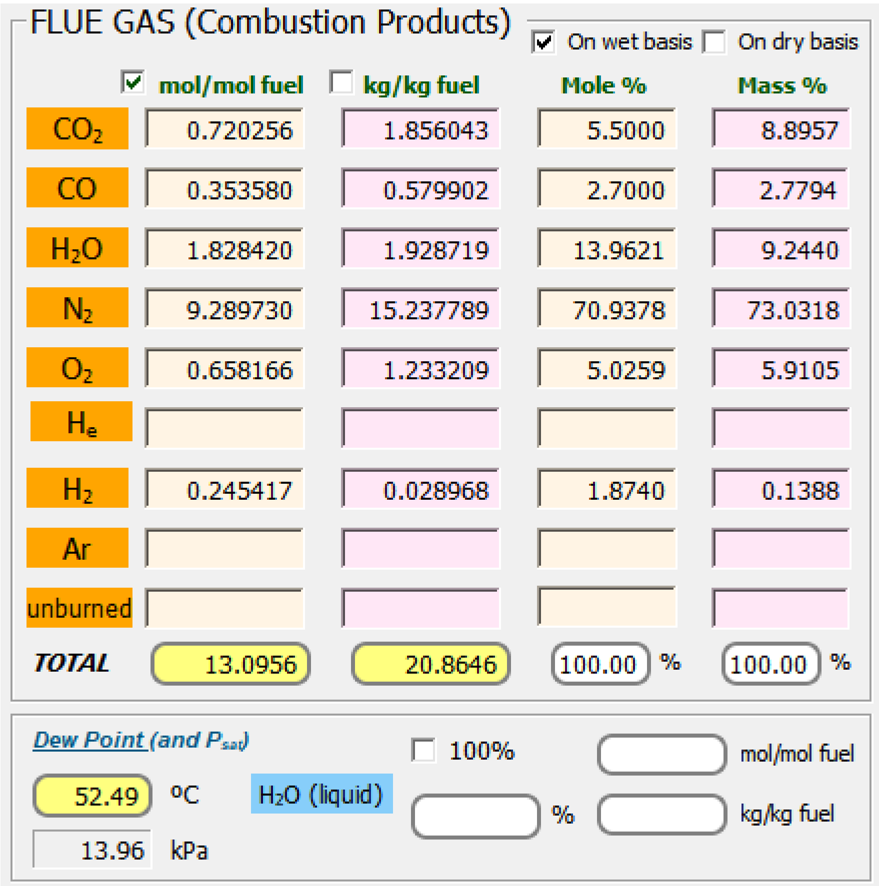


The temperature of 600ºC is the exit temperature of the combustion fumes to the environment, it does not seem very appropriate to consider it as the equilibrium temperature of the combustion process, this temperature should be the adiabatic temperature of the flame or close to it.

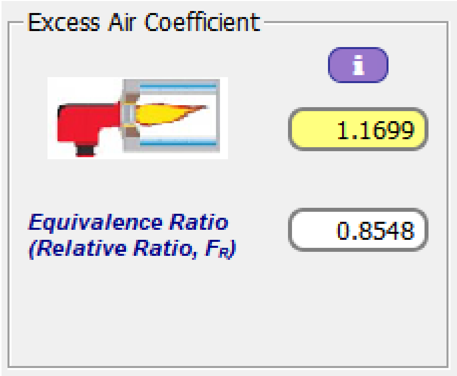
We redo the calculations for an equilibrium temperature of 1500ºC (it will be verified that the adiabatic temperature is 1525ºC), verifying that it is close to the adiabatic temperature of the flame, without exceeding it.

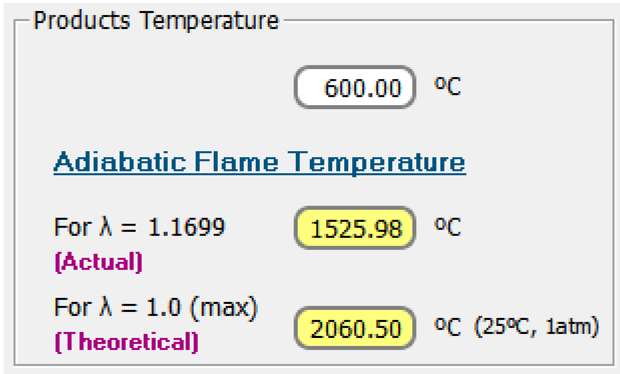


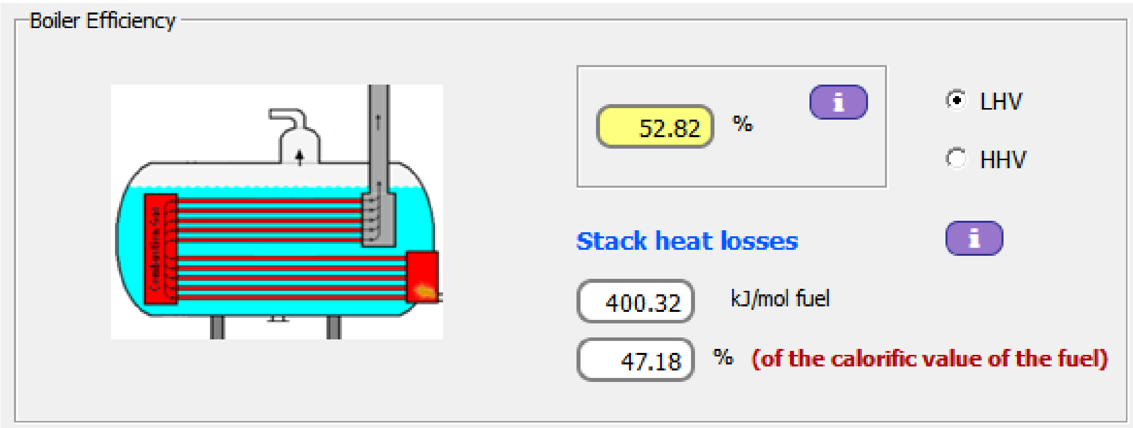


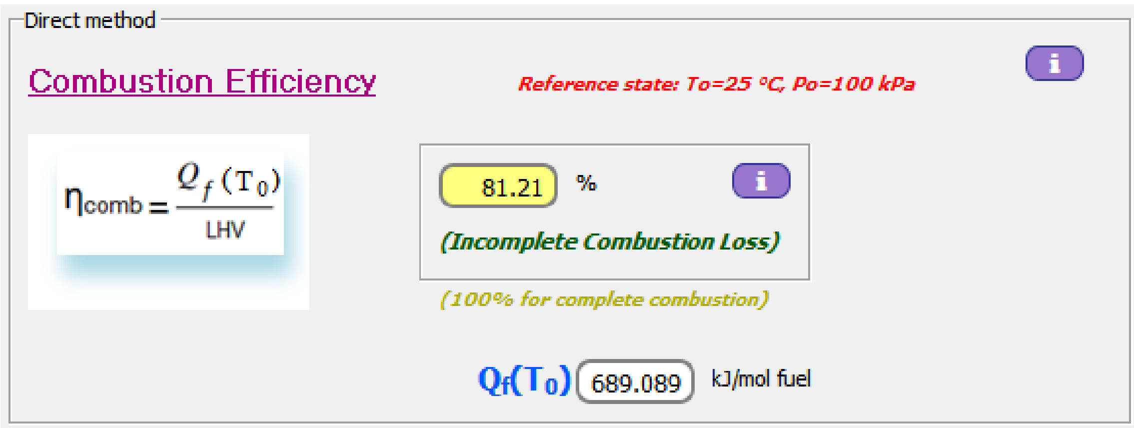


	mol/mol fuel	kg/kg fuel	Mole %	Mass %
CO_2	0.720256	1.856043	5.5000	8.8957
CO	0.353580	0.579902	2.7000	2.7794
H_2O	1.828420	1.928719	13.9621	9.2440
N_2	9.289730	15.237789	70.9378	73.0318
O_2	0.658166	1.233209	5.0259	5.9105
H_e				
H_2	0.245417	0.028968	1.8740	0.1388
Ar				
unburned				
TOTAL	13.0956	20.8646	100.00 %	100.00 %

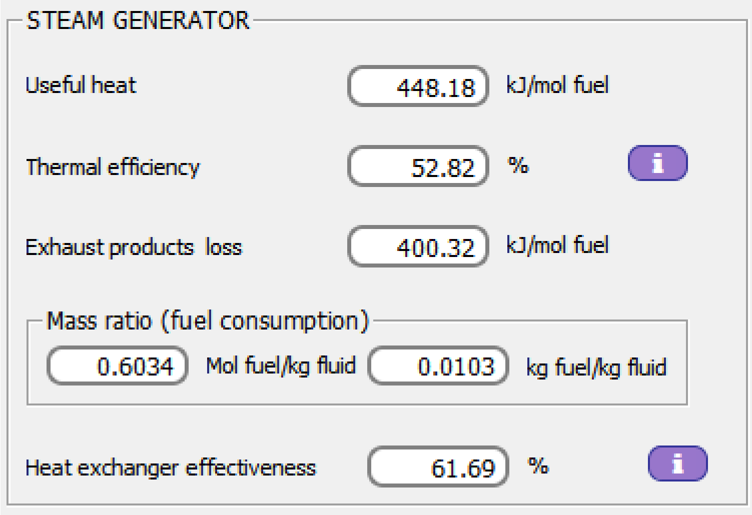




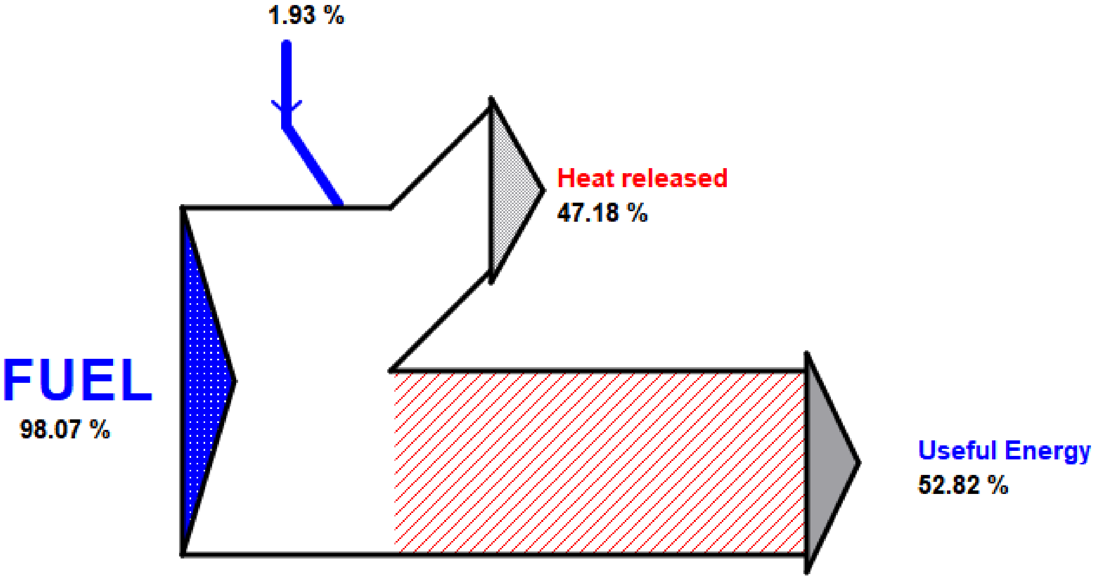




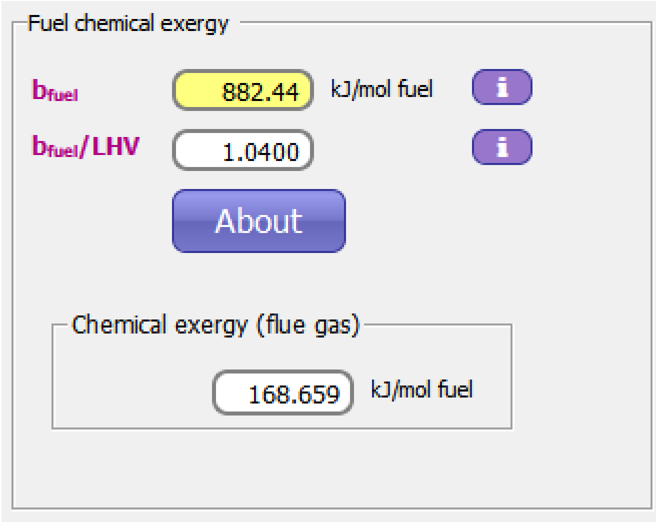
The unburned decrease drastically.

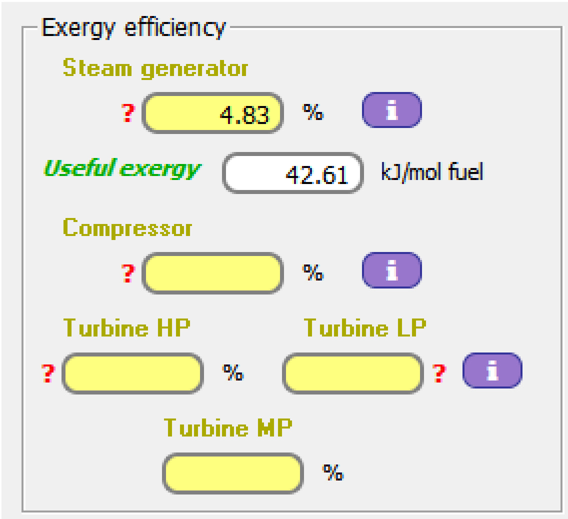


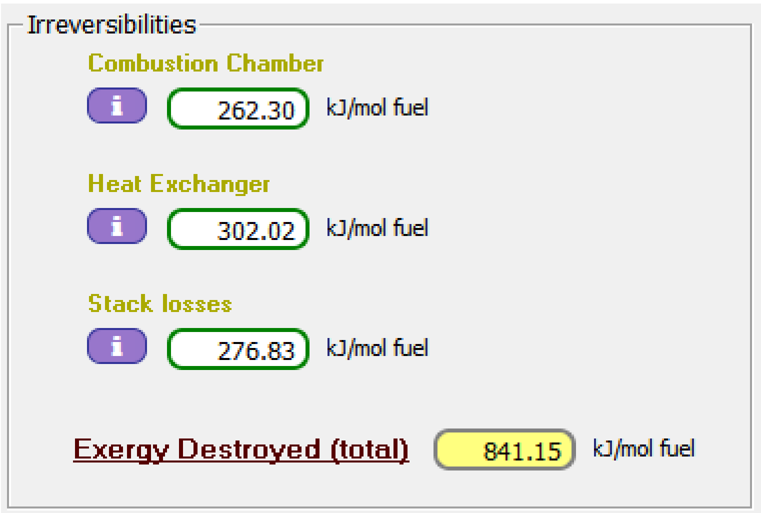
Fuel consumption decreases.

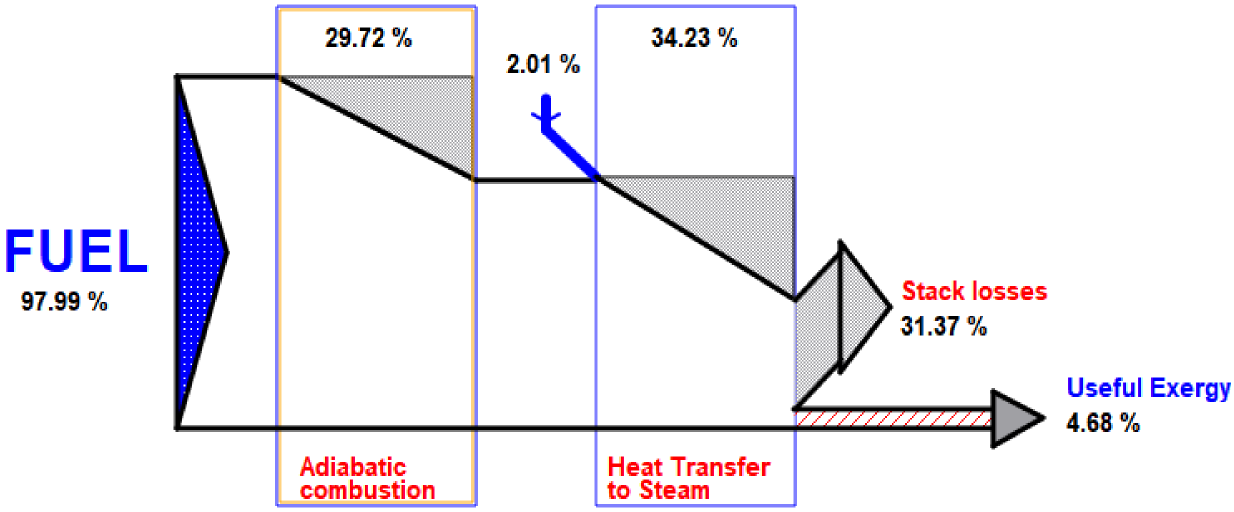


Method Exergy Applied to Chemically Reactive Systems

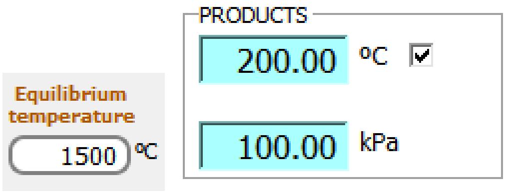

Fuel chemical exergy
bfuel
882.44
kJ/mol fuel
bfuel/LHV
1.0400
About
Chemical exergy (flue gas)
168.659
kJ/mol fuel

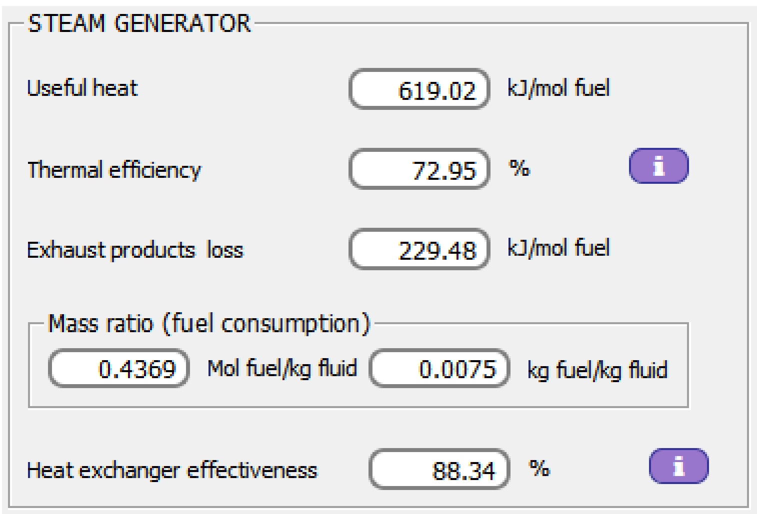

Exergy efficiency
Steam generator
4.83
%
Useful exergy
42.61
kJ/mol fuel
Compressor
%
Turbine HP
Turbine LP
%
Turbine MP
%


Irreversibilities
Combustion Chamber
262.30
kJ/mol fuel
Heat Exchanger
302.02
kJ/mol fuel
Stack losses
276.83
kJ/mol fuel
Exergy Destroyed (total)
841.15
kJ/mol fuel



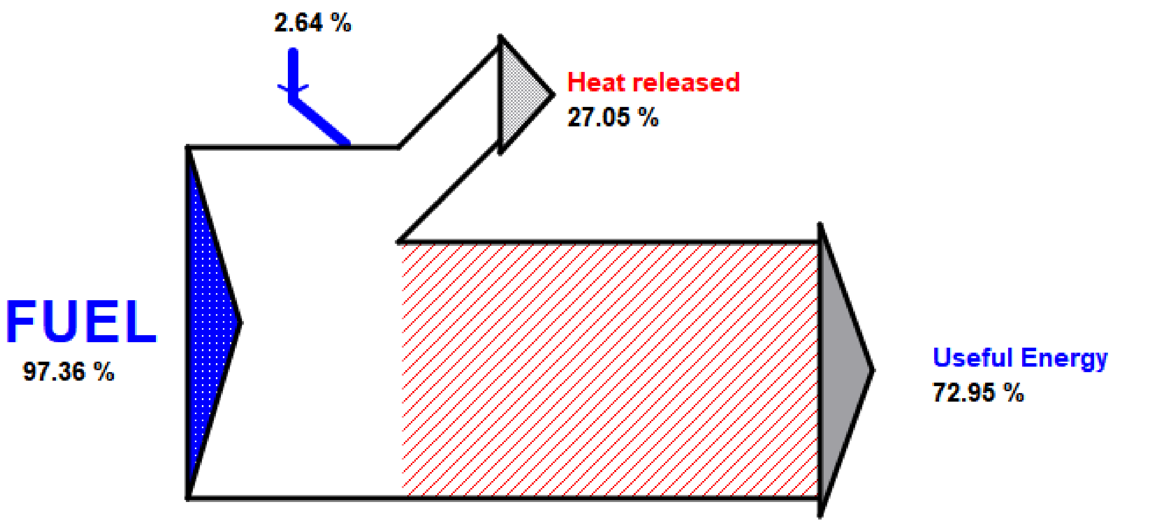
If we decrease the expulsion temperature of the gases into the atmosphere:

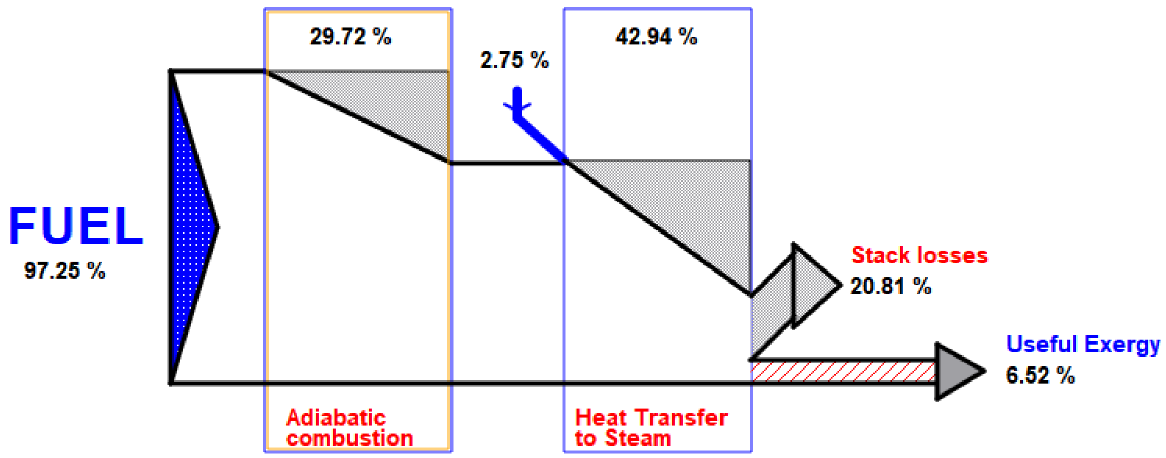




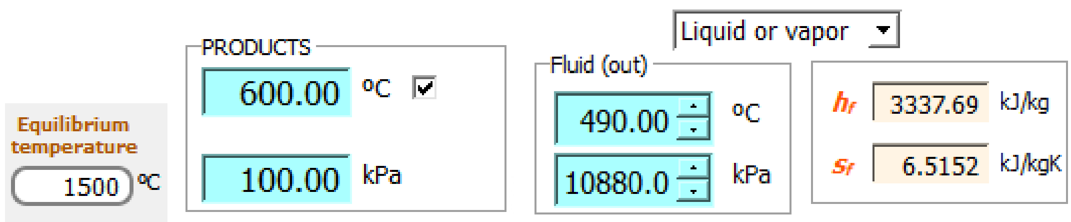
Fuel consumption continues decreasing.

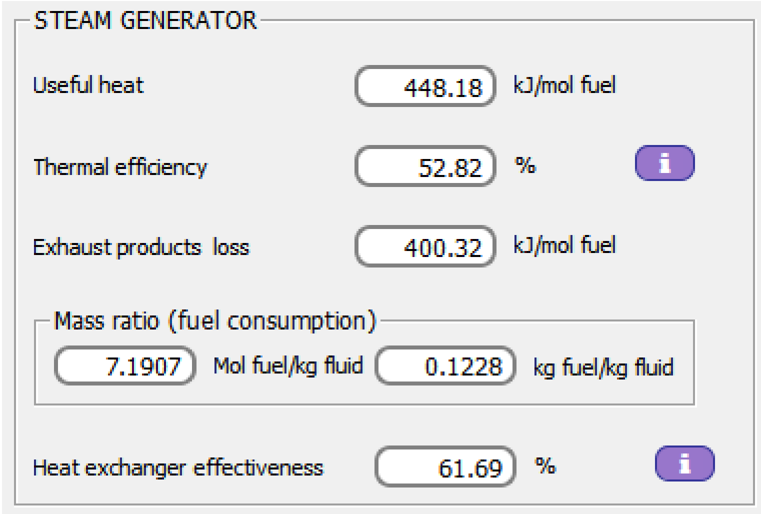
It can be seen that the efficiencies, thermal and exergy, continue to increase. As expected, the energy and exergetic losses due to the chimney fumes expelled into the environment are drastically reduced. This increases the thermal performance considerably. However, the irreversibilities in the heat exchanger increase (from 34% to 43%), as the thermal jump in it increases (1500-200 = 1300ºC), which causes that the exergetic efficiency hardly increases.

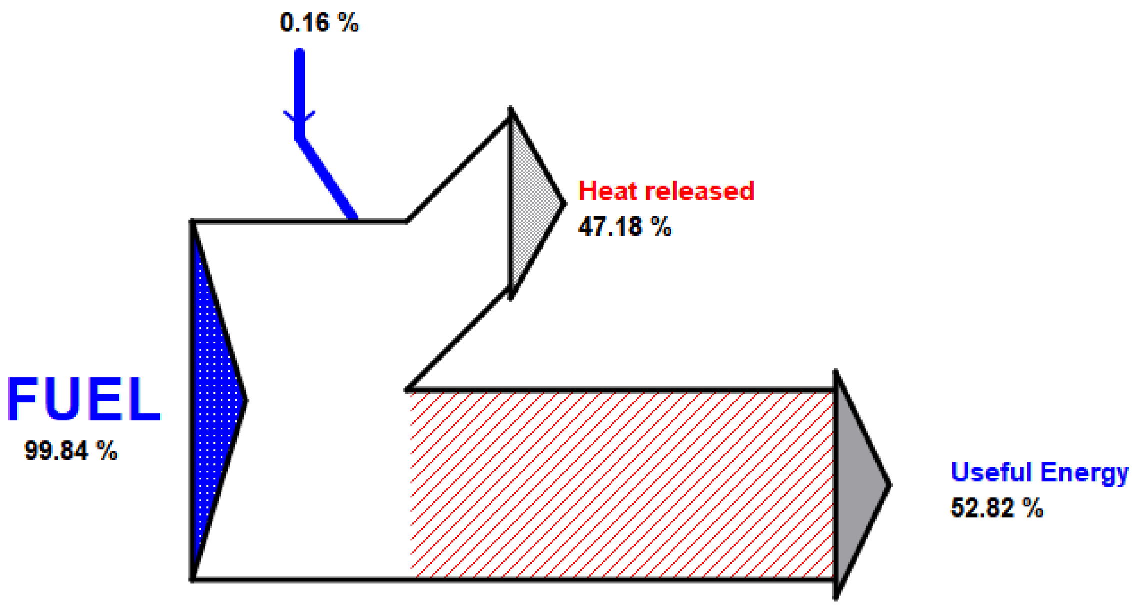




If we now use the heat of the combustion gases to generate water vapor at 490 ºC, we are making better use of the energy put into play and the exergetic efficiency should increase:

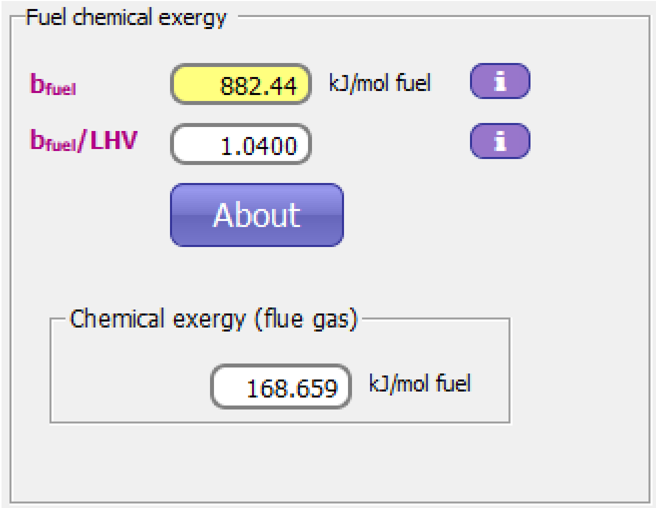


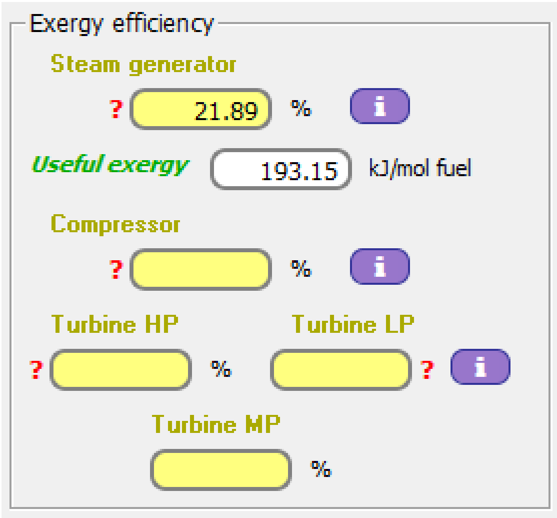


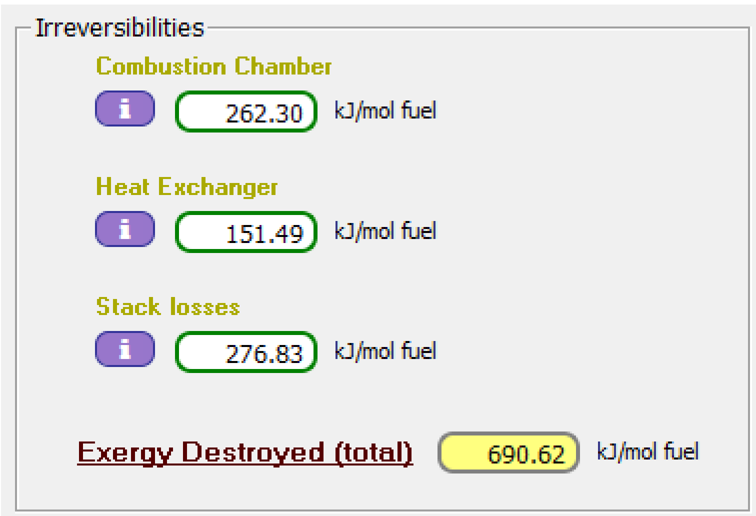


In this case, the energy analysis shows us that to maintain thermal efficiency it is necessary to increase fuel consumption.

Method Exergy Applied to Chemically Reactive Systems


Fuel chemical exergy
bfuel
882.44
kJ/mol fuel
bfuel/LHV
1.0400
About
Chemical exergy (flue gas)
168.659
kJ/mol fuel


Exergy efficiency
Steam generator
21.89
%
Useful exergy
193.15
kJ/mol fuel
Compressor
%
Turbine HP
Turbine LP
%
Turbine MP
%


Irreversibilities
Combustion Chamber
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kJ/mol fuel
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151.49
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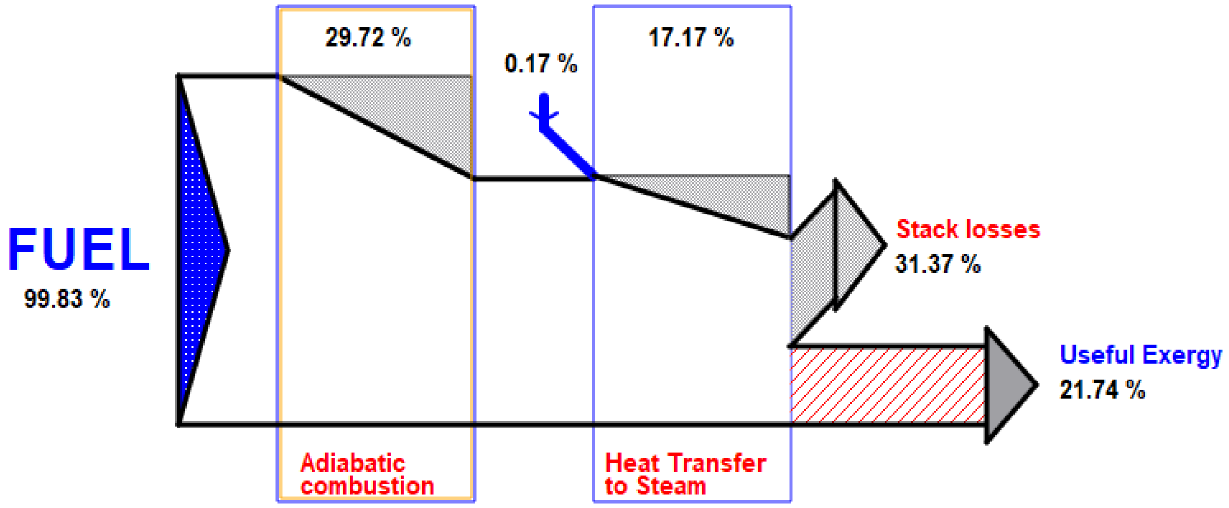
Stack losses
276.83
kJ/mol fuel
Exergy Destroyed (total)
690.62
kJ/mol fuel


29.72 %
0.17 %
17.17 %
FUEL
99.83 %
Stack losses
31.37 %
Useful Exergy
21.74 %
Adiabatic combustion
Heat Transfer to Steam