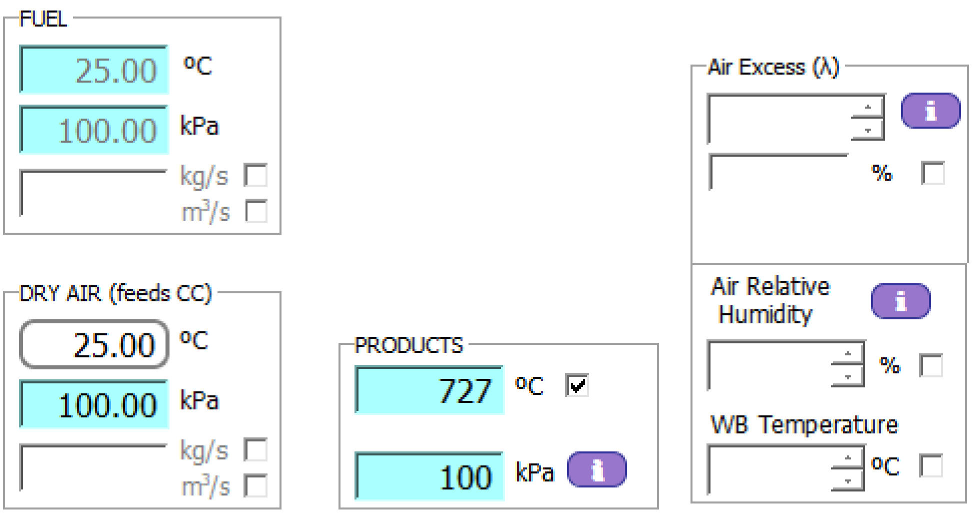
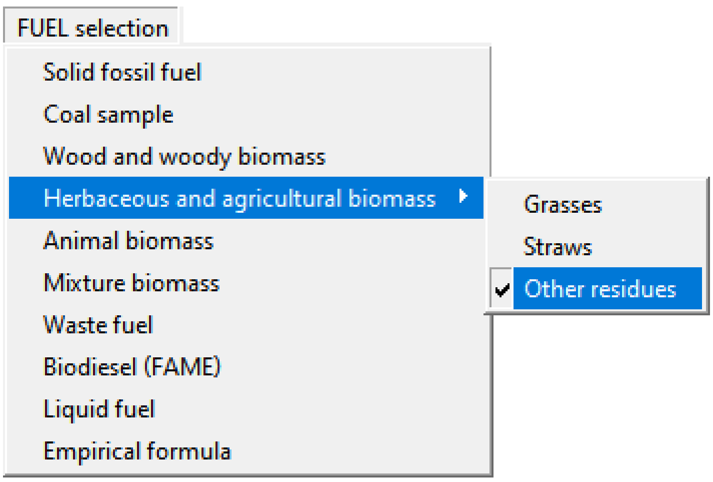
Exercise 2 (biomass)

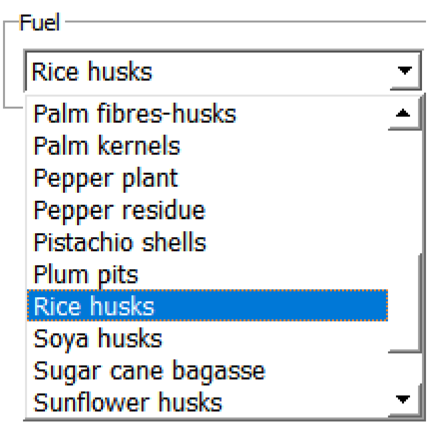
A solid fuel (rice husks) is burned in a non-adiabatic furnace. Knowing that dry air and fuel enter in standard conditions (25ºC and 1 atm) and the flue-gas leaves at 727ºC. The heat released to the environment is approximately 12502.7 kJ/kg of fuel.

Decide:
a) Excess air coefficient assuming rich combustion
b) Excess air coefficient assuming poor combustion
c) Dry and wet combustion products
d) Dew point temperature of combustion products
e) Calorific powers
f) Efficiency
g) Irreversibility
h) Ostwald diagram
i) Kissel diagram

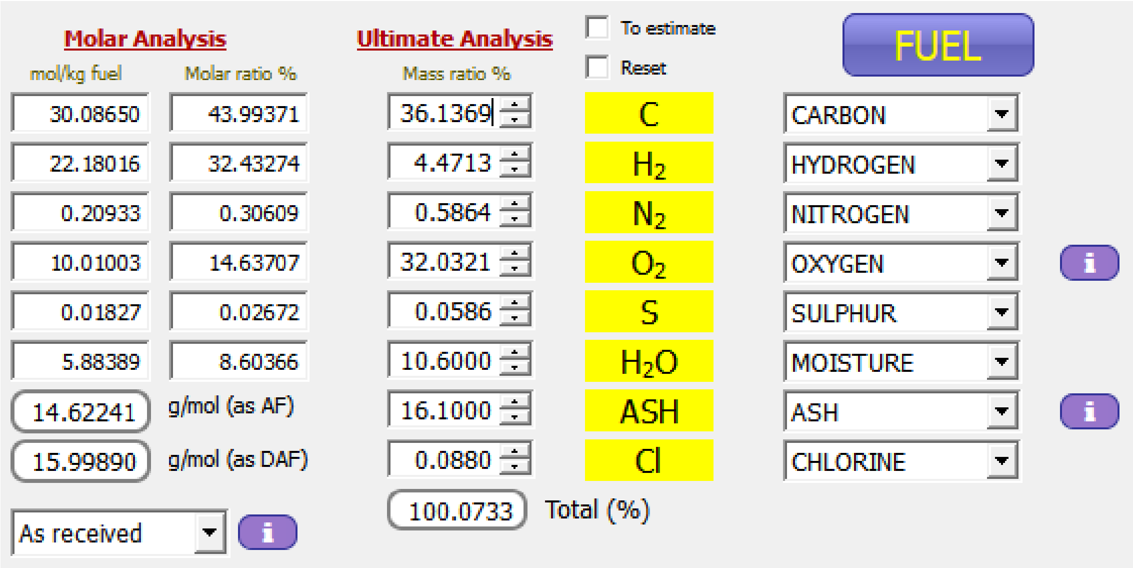
Solution by means THERMOCombustion:





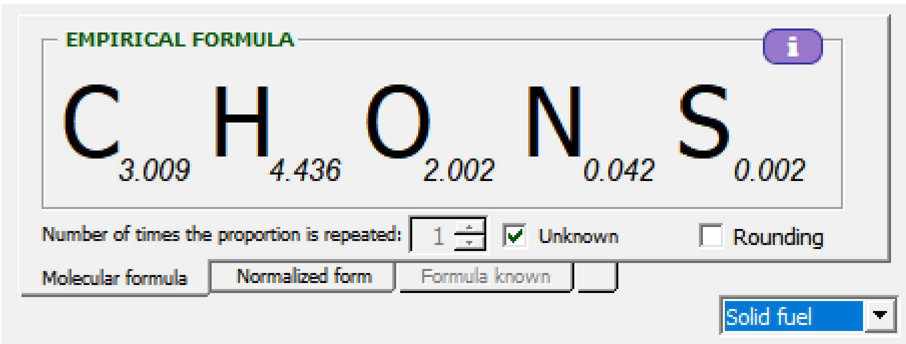


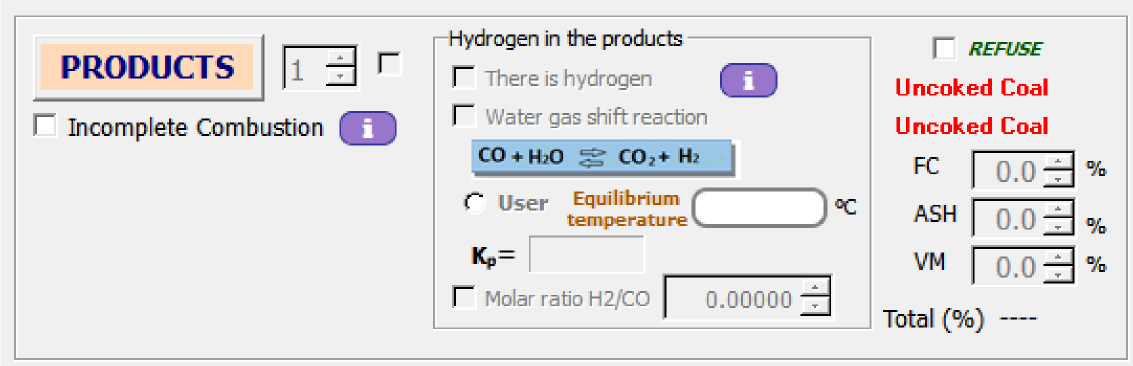
Biomass is used as a renewable solid fuel on power plants to provide CO_2-neutral electricity and heat, where mainly woodand, in some cases, also straw have been applied in recent years. Biomass combustion has mainly been performed in grate boilers; however, wood and straw are used as fuels in suspension-fired power-plant boilers.



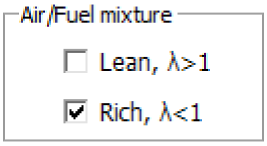
Rice husk is the main byproduct of industrial processing of rice, and is a widely used byproduct in worldwide as biomass in energy production, reducing environmental impacts associated with improper disposal. Rice husk is the most prolific agricultural residue in rice producing countries around the world. It is one of the major by-products from the rice milling process and constitutes about 20% of paddy by weight. Rice husk, which consists mainly of lingo-cellulose and silica, is not utilized to any significant extent and has great potential as an energy source.

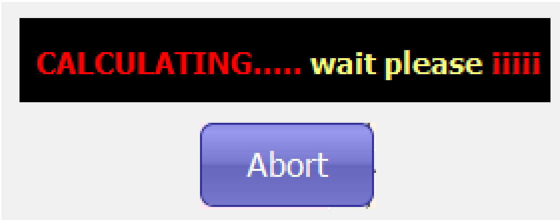
The ash generated in rice husk combustion has potential economic applications in a variety of sectors. However, the properties of rice husk ash are strongly dependent on the combustion method used. Rice is the second most consumed food item worldwide, with annual global demand of approximately 471 million tons and mean per capita consumption around 57 kg year. Accounting for roughly 20% of the bulk grain weight, rice husk is the most representative byproduct of industrial processing of rice.

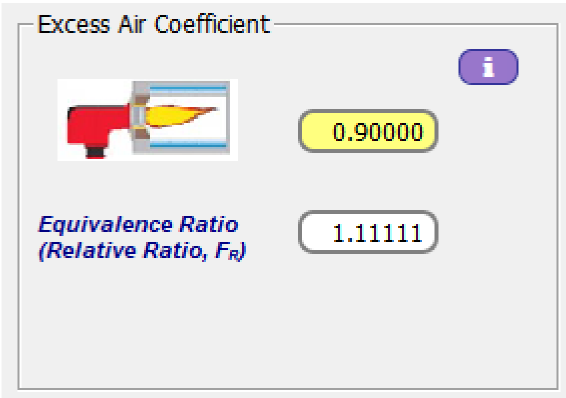




Through an iterative process applied to the energy balance, previously determined the enthalpy of biomass formation, the software determines that variable not defined in the initial menu (coefficient of excess air, heat exchanged, temperature of combustion products), in this case the coefficient of excess air. It is necessary to know a priori if the air-fuel mixture is rich or lean (both cases have been done in this problem).







Flue gas (combustion products) composition is significantly affected by the combustion conditions. Where combustion takes place in complete, oxidizing gas species such as CO_2, O_2, SO_2, and H_2O. Neutral complete combustion is termed here when carbon and hydrogen in fuel is totally oxidized to carbon dioxide and water vapor, and no additional oxygen is present in the flue gases. In contrast, when combustion reactions proceed in air-deficient conditions, reducing gas species such as CO and H_2. This last situation can also occur even with extra air in the combustion

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

	mol/kg fuel	☐ kg/kg fuel	Mole %	Mass %
CO_2	23.84962	1.04962	14.5448	22.3542
CO	6.23688	0.17470	3.8036	3.7207
H_2O	28.05165	0.50536	17.1074	10.7629
N_2	105.79256	2.96362	64.5180	63.1175
O_2				
SO_2	0.01827	0.00117	0.0111	0.0249
H_2				
Ar				
HCl	0.02468	0.00090	0.0151	0.0192
TOTAL	163.9736	4.6954	100.00 %	100.00 %

Water Dew Point T (and P_{sat}): 56.73 ºC, 17.11 kPa

H_2O (liquid): mol/mol fuel; %; kg/kg fuel

The dew point is the temperature where air is no longer capable of holding the water vapor that is contained within it. At the dew point temperature, water vapor condenses into liquid water. At all times, the dew point temperature is equal to or less than the air temperature. We can observed that this temperature is 56.73ºC. A thorough knowledge about dew point temperature is very important in various industries because moisture can affect corrosion rates.

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FLUE GAS (Combustion Products)

☐ On wet basis ☑ On dry basis

	mol/kg fuel	☐ kg/kg fuel	Mole %	Mass %
CO_2	23.84962	1.04962	17.5466	25.0506
CO	6.23688	0.17470	4.5886	4.1695
H_2O				
N_2	105.79256	2.96362	77.8333	70.7308
O_2				
SO_2	0.01827	0.00117	0.0134	0.0279
H_2				
Ar				
HCl	0.02468	0.00090	0.0182	0.0215
TOTAL	135.9220	4.1900	100.00 %	100.00 %

Total O2 (REACTIVE)

FUEL without moisture+DRY AIR

38.063 mol/kg fuel — 1.218 kg/kg fuel

FUELwith moisture+WET AIR

38.066 mol/kg fuel — 1.218 kg/kg fuel

Reactants (fuel + dry air)

4.85588 ***kg/kg fuel***

(Assume 1 kg fuel is being combusted)

Air/fuel ratio (dry air)

AIR

	Theoretical Dry air	***Actual*** Dry air
mol/kg fuel	148.500	133.649
☐ kg/kg fuel	4.28432	3.85588

☑ Experimental correlations (mass fractions)

Burnham: C,H,N,O,S

(Based on the dry and mineral matter free elemental fuel composition)

Lower Heating, LHV	(DAF)	Higher Heating, HHV
18095.60	kJ/kg fuel	19435.16

We can checked the calculation of the enthalpy of formation of a solid fuel:

For λ=1 (neutral reaction condition):

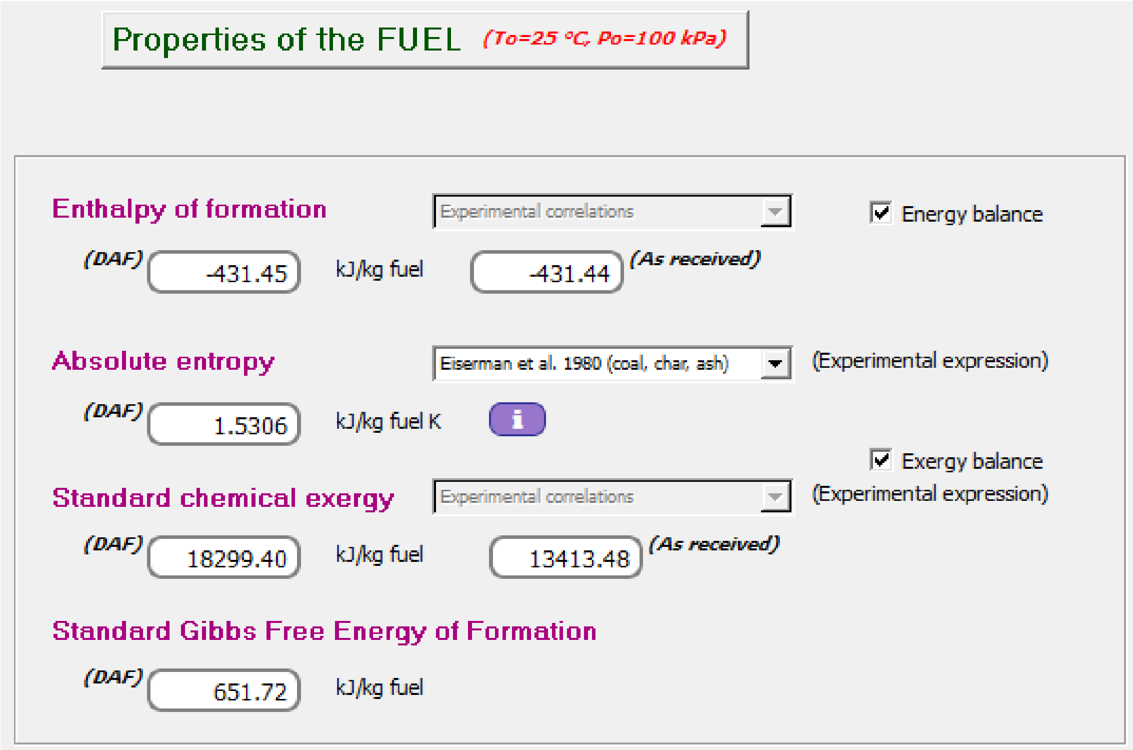
FLUE GAS (Combustion Products) ☑ On wet basis ☐ On dry basis

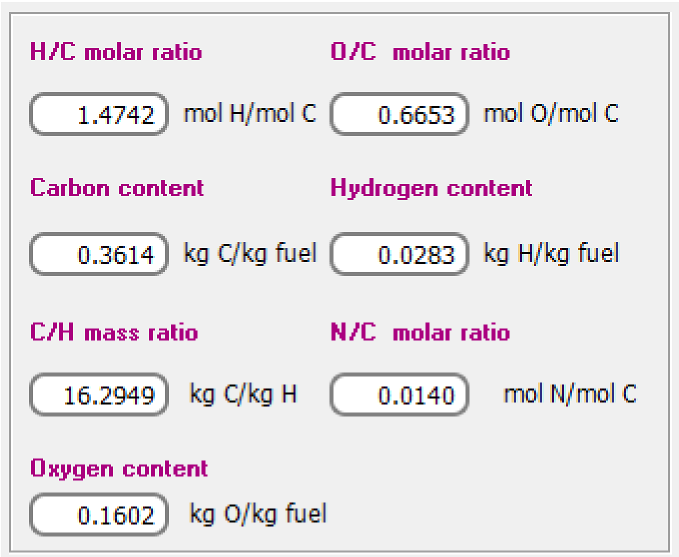
	mol/kg fuel	☐ kg/kg fuel	Mole %	Mass %
CO_2	30.08648	1.32410	17.1236	25.8427
H_2O	28.05016	0.50533	15.9647	9.8626
N_2	117.52191	3.29220	66.8872	64.2543
SO_2	0.01840	0.00118	0.0105	0.0230

H_{form} (kJ/mol fuel) = PCS + n_{H2O} $H_f(liq)_{H2O}$ + n_{CO2} $H_f(gas)_{CO2}$ + n_{SO2} $H_f(gas)_{SO2}$ =

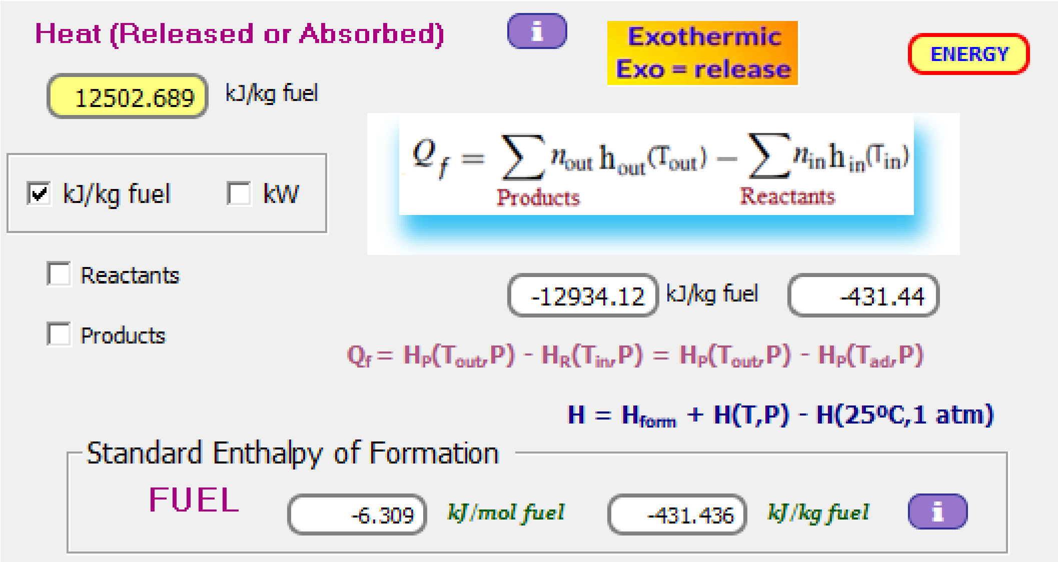
19435.16 kJ/kg fuel + 28.05016 moles H_2O/kg fuel $\cdot$ (-285.83) kJ/mol H_2O + 30.08648 moles CO_2/kg fuel $\cdot$ (-393.52) kJ/mol CO_2 + 0.0184 moles SO_2/kg fuel $\cdot$ (-296.991) kJ/mol SO_2 =

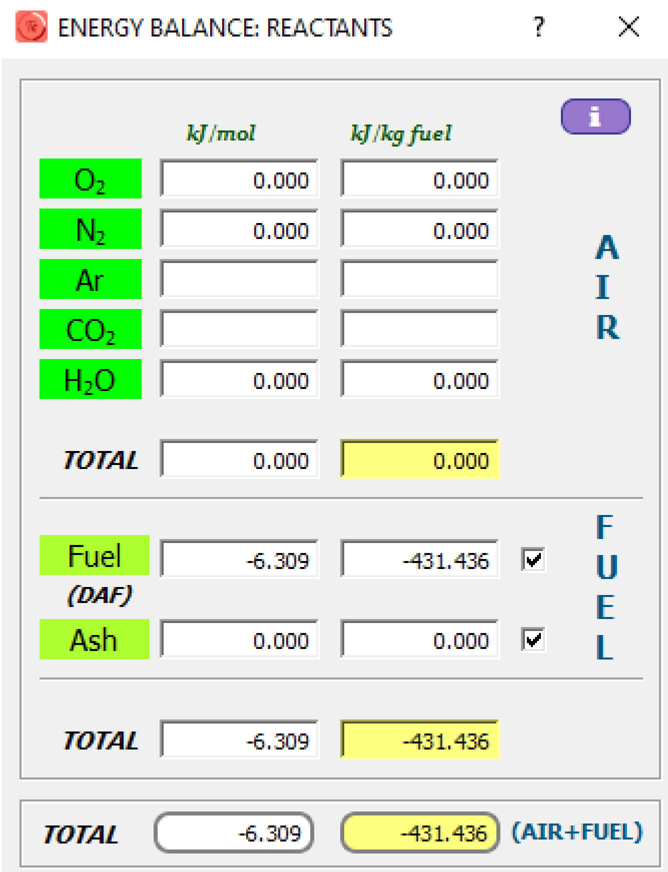
= 19434.16 – 8017.57 – 11834.63 – 5.46 = - 427.5 kJ/mol fuel (approximate value to that obtained by ThermoCombustion, the differences are due to the decimals used)





We can check the heat transferred to the environment:


Heat (Released or Absorbed)
Exothermic
Exo = release
ENERGY
12502.689
kJ/kg fuel
$Q_f = \sum_{Products} n_{out} h_{out}(T_{out}) - \sum_{Reactants} n_{in} h_{in}(T_{in})$
kJ/kg fuel
kW
Reactants
Products
-12934.12
kJ/kg fuel
-431.44
$Q_f = H_P(T_{out},P) - H_R(T_{in},P) = H_P(T_{out},P) - H_P(T_{ad},P)$
$H = H_{form} + H(T,P) - H(25^oC,1\ atm)$
Standard Enthalpy of Formation
FUEL
-6.309
kJ/mol fuel
-431.436
kJ/kg fuel


ENERGY BALANCE: REACTANTS
kJ/mol
kJ/kg fuel
O_2 0.000 0.000
N_2 0.000 0.000
Ar
CO_2
H_2O 0.000 0.000
AIR
TOTAL 0.000 0.000
Fuel -6.309 -431.436
(DAF)
Ash 0.000 0.000
FUEL
TOTAL -6.309 -431.436
TOTAL -6.309 -431.436 (AIR+FUEL)

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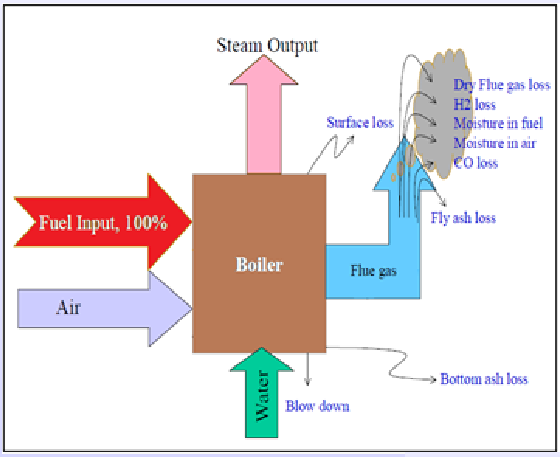
ENERGY BALANCE: FLUE GAS

	kJ/mol	kJ/kg fuel
CO_2	-360.1150	-8588.6064
CO	-88.8440	-554.1094
H_2O	-215.8420	-6054.7241
O_2	0.0000	0.0000
N_2	21.4600	2270.3081
H_2	0.0000	0.0000
SO_2	-262.7260	-4.8000
HCl	-88.8377	-2.1925
Ar	0.0000	0.0000
TOTAL	-994.9047	-12934.1230

Indirect Method: Heat Loss Method

Boiler/Furnace Efficiency

Dry flue gas loss (Sensible heat)	19.448	%
Presence of H_2 in fuel (Latent heat)	7.929	%
Unburned fuel, CO	9.299	%
Moisture in fuel, H_2O	2.104	%
Moisture in air, RH	0.000	%
*Unburned carbon * in fly ash*	0.000	%
*Unburned carbon * in botton ash*	0.000	%
Surface loss (radiation, convection) & unaccounted losses — Industrial fire tube/packaged boiler	2.000	%



** Only for solid fuel*

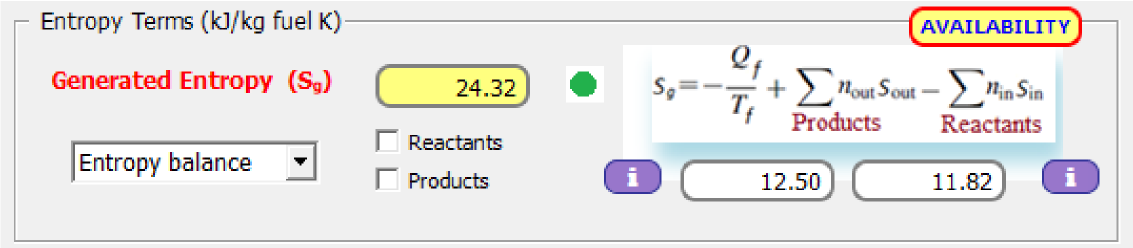
DAF

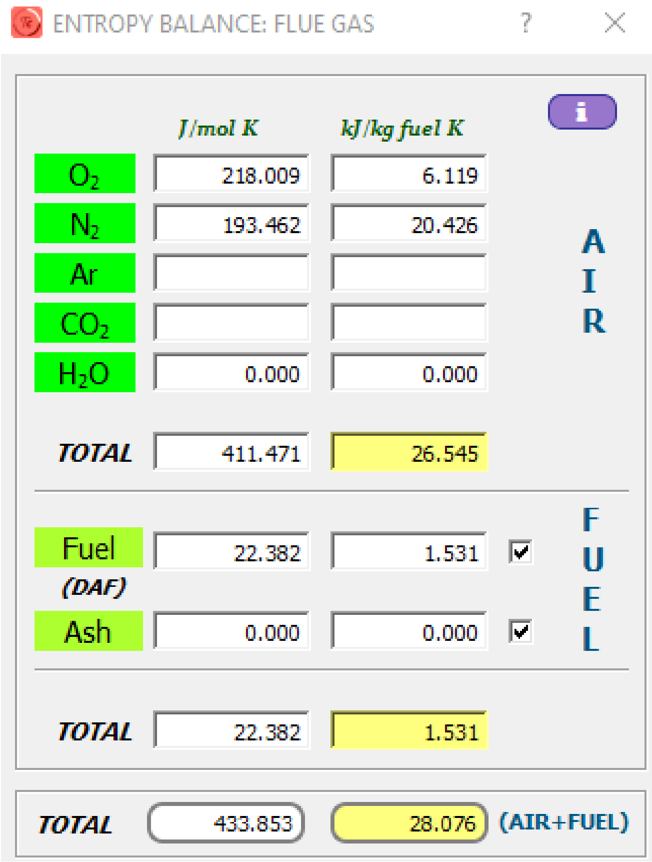
Referred to HHV

100 - Σ loss 59.220 %

Dry Refuse LOST

%C	
%VM	
%HHV	


Entropy Terms (kJ/kg fuel K)
AVAILABILITY
Generated Entropy (S_g)
24.32
$S_g = -\frac{Q_f}{T_f} + \sum n_{out} s_{out} - \sum n_{in} s_{in}$
Products
Reactants
Entropy balance
Reactants
Products
12.50
11.82


ENTROPY BALANCE: FLUE GAS
J/mol K
kJ/kg fuel K
O_2 218.009 6.119
N_2 193.462 20.426
Ar
CO_2
H_2O 0.000 0.000
TOTAL 411.471 26.545
A I R
Fuel 22.382 1.531
(DAF)
Ash 0.000 0.000
F U E L
TOTAL 22.382 1.531
TOTAL 433.853 28.076 (AIR+FUEL)

ENTROPY BALANCE: FLUE GAS

	J/mol K	kJ/kg fuel K
CO_2	285.2448	6.8030
CO	261.6030	1.6316
H_2O	247.2776	6.9365
O_2	0.0000	0.0000
N_2	231.7007	24.5122
H_2	0.0000	0.0000
SO_2	358.2118	0.0065
HCl	307.6989	0.0076
Ar	0.0000	0.0000
TOTAL	1691.7367	39.8975

Considering a lean mixture, with excess air:

Air/Fuel mixture
- [x] Lean, λ>1
- [ ] Rich, λ<1

FLUE GAS (Combustion Products) — [ ] On wet basis [x] On dry basis

	mol/kg fuel	kg/kg fuel	Mole %	Mass %
CO_2	30.08648	1.32410	14.0763	20.2927
CO				
H_2O				
N_2	169.73137	4.75477	79.4107	72.8700
O_2	13.87781	0.44409	6.4929	6.8060
SO_2	0.01827	0.00117	0.0085	0.0179
H_2				
Ar				
HCl	0.02468	0.00090	0.0115	0.0138
TOTAL	213.7386	6.5250	100.00 %	100.00 %

FLUE GAS (Combustion Products)

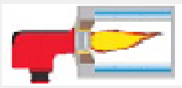
☑ On wet basis ☐ On dry basis

	mol/kg fuel	☐ kg/kg fuel	Mole %	Mass %
CO_2	30.08648	1.32410	12.4432	18.8339
CO				
H_2O	28.05165	0.50536	11.6016	7.1882
N_2	169.73137	4.75477	70.1978	67.6316
O_2	13.87781	0.44409	5.7396	6.3167
SO_2	0.01827	0.00117	0.0076	0.0166
H_2				
Ar				
HCl	0.02468	0.00090	0.0102	0.0128
TOTAL	241.7903	7.0304	100.00 %	100.00 %

Water Dew Point T^a (and P_{sat}): 48.75 ºC, 11.61 kPa

H_2O (liquid): mol/mol fuel; % ; kg/kg fuel

Excess Air Coefficient



1.44502

Equivalence Ratio (Relative Ratio, F_R): 0.69203

We verify the heat transferred to the environment:

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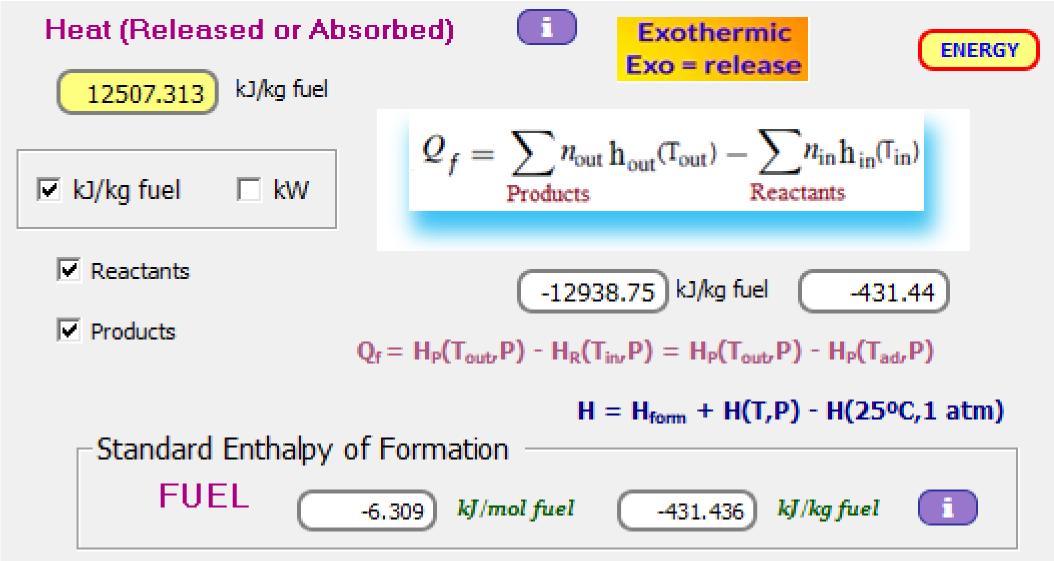
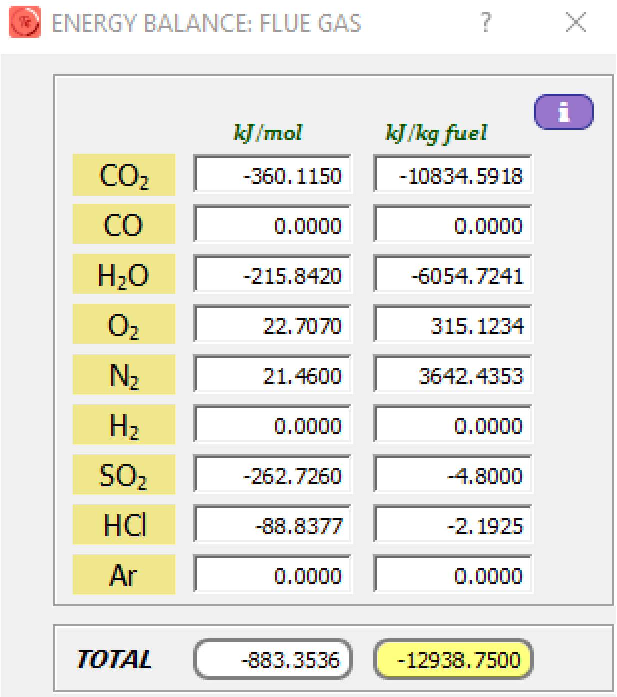
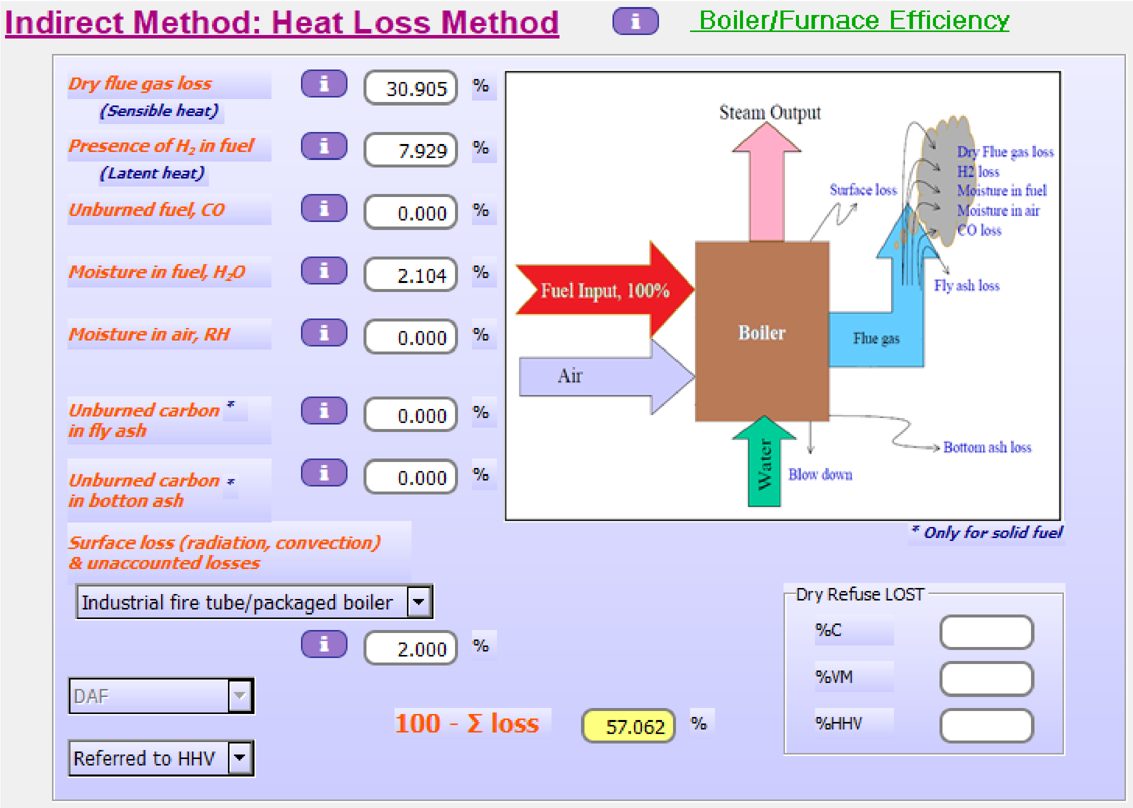
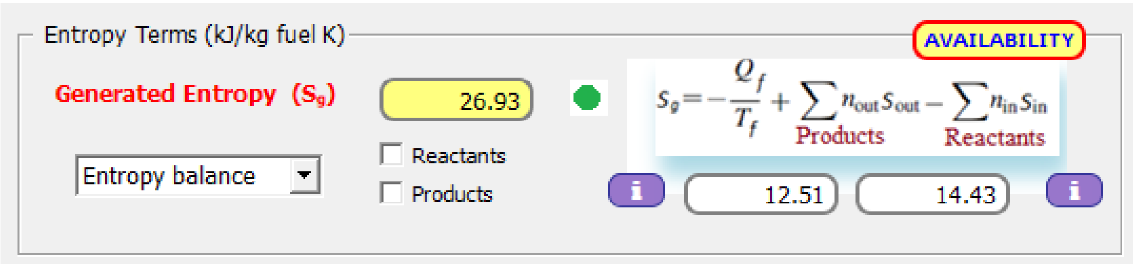




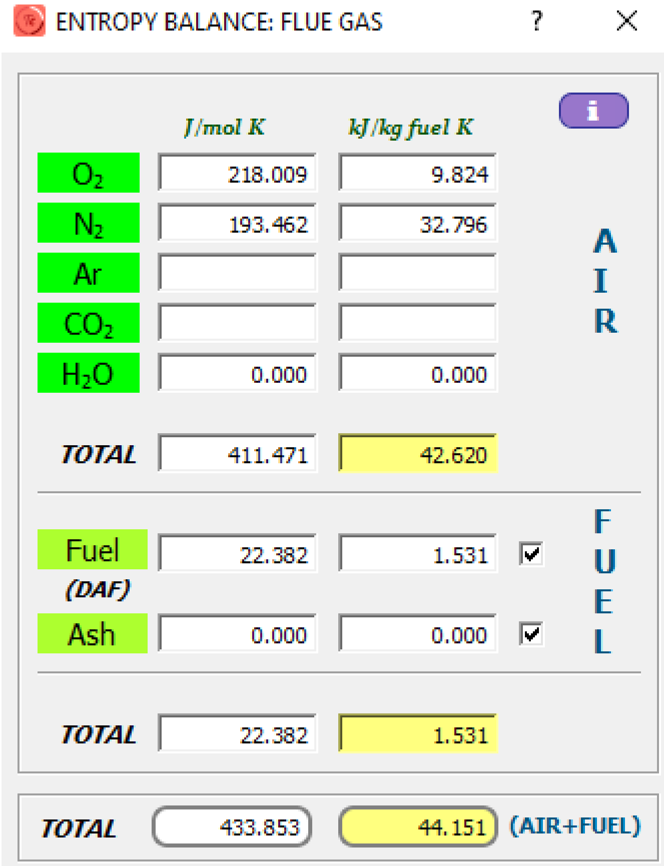
	kJ/mol	kJ/kg fuel
CO_2	-360.1150	-10834.5918
CO	0.0000	0.0000
H_2O	-215.8420	-6054.7241
O_2	22.7070	315.1234
N_2	21.4600	3642.4353
H_2	0.0000	0.0000
SO_2	-262.7260	-4.8000
HCl	-88.8377	-2.1925
Ar	0.0000	0.0000
TOTAL	-883.3536	-12938.7500



There is a higher efficiency (indirect method), because there is no loss due to unburnt.

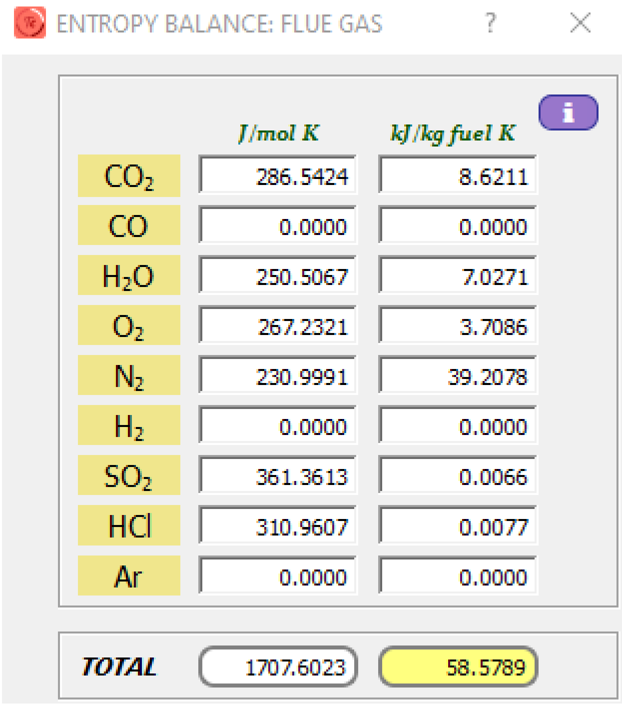


In this case, the exergy destruction is greater than in the rich mixture case.



ENTROPY BALANCE: FLUE GAS

	J/mol K	kJ/kg fuel K	
O_2	218.009	9.824	AIR
N_2	193.462	32.796	
Ar			
CO_2			
H_2O	0.000	0.000	
TOTAL	411.471	42.620	
Fuel (DAF)	22.382	1.531	FUEL
Ash	0.000	0.000	
TOTAL	22.382	1.531	
TOTAL	433.853	44.151	(AIR+FUEL)

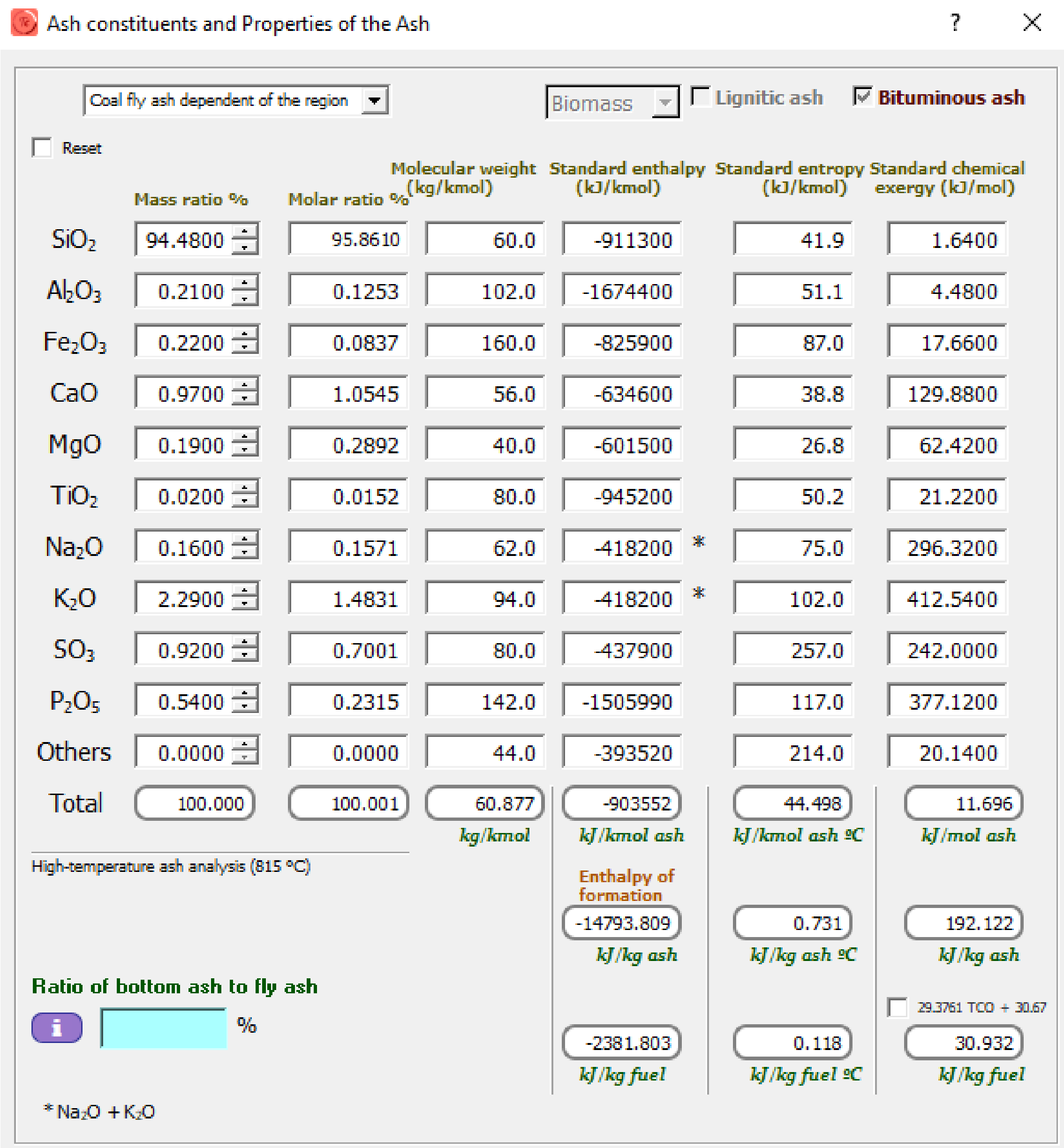


ENTROPY BALANCE: FLUE GAS

	J/mol K	kJ/kg fuel K
CO_2	286.5424	8.6211
CO	0.0000	0.0000
H_2O	250.5067	7.0271
O_2	267.2321	3.7086
N_2	230.9991	39.2078
H_2	0.0000	0.0000
SO_2	361.3613	0.0066
HCl	310.9607	0.0077
Ar	0.0000	0.0000
TOTAL	1707.6023	58.5789

ThermoCombustion Biomass & Biodiesel ThermoSuite Technical Software Suite

Thermodynamic analysis of ashes:



Ash constituents and Properties of the Ash

Coal fly ash dependent of the region | Biomass | Lignitic ash | ☑ Bituminous ash

Reset

	Mass ratio %	Molar ratio %	Molecular weight (kg/kmol)	Standard enthalpy (kJ/kmol)	Standard entropy (kJ/kmol)	Standard chemical exergy (kJ/mol)
SiO_2	94.4800	95.8610	60.0	-911300	41.9	1.6400
Al_2O_3	0.2100	0.1253	102.0	-1674400	51.1	4.4800
Fe_2O_3	0.2200	0.0837	160.0	-825900	87.0	17.6600
CaO	0.9700	1.0545	56.0	-634600	38.8	129.8800
MgO	0.1900	0.2892	40.0	-601500	26.8	62.4200
TiO_2	0.0200	0.0152	80.0	-945200	50.2	21.2200
Na_2O	0.1600	0.1571	62.0	-418200 *	75.0	296.3200
K_2O	2.2900	1.4831	94.0	-418200 *	102.0	412.5400
SO_3	0.9200	0.7001	80.0	-437900	257.0	242.0000
P_2O_5	0.5400	0.2315	142.0	-1505990	117.0	377.1200
Others	0.0000	0.0000	44.0	-393520	214.0	20.1400
Total	100.000	100.001	60.877 kg/kmol	-903552 kJ/kmol ash	44.498 kJ/kmol ash ºC	11.696 kJ/mol ash

High-temperature ash analysis (815 °C)

Enthalpy of formation		
-14793.809 kJ/kg ash	0.731 kJ/kg ash ºC	192.122 kJ/kg ash
-2381.803 kJ/kg fuel	0.118 kJ/kg fuel ºC	30.932 kJ/kg fuel

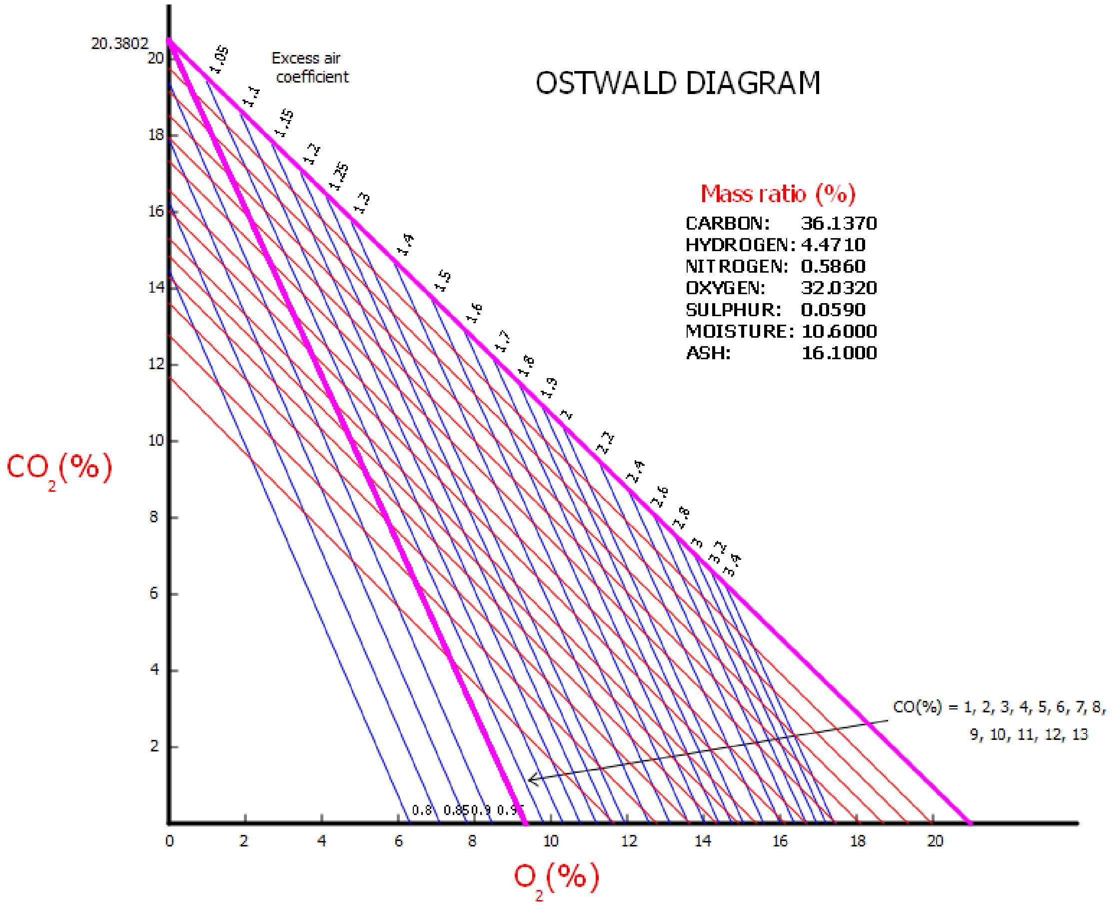
29.3761 TCO + 30.67

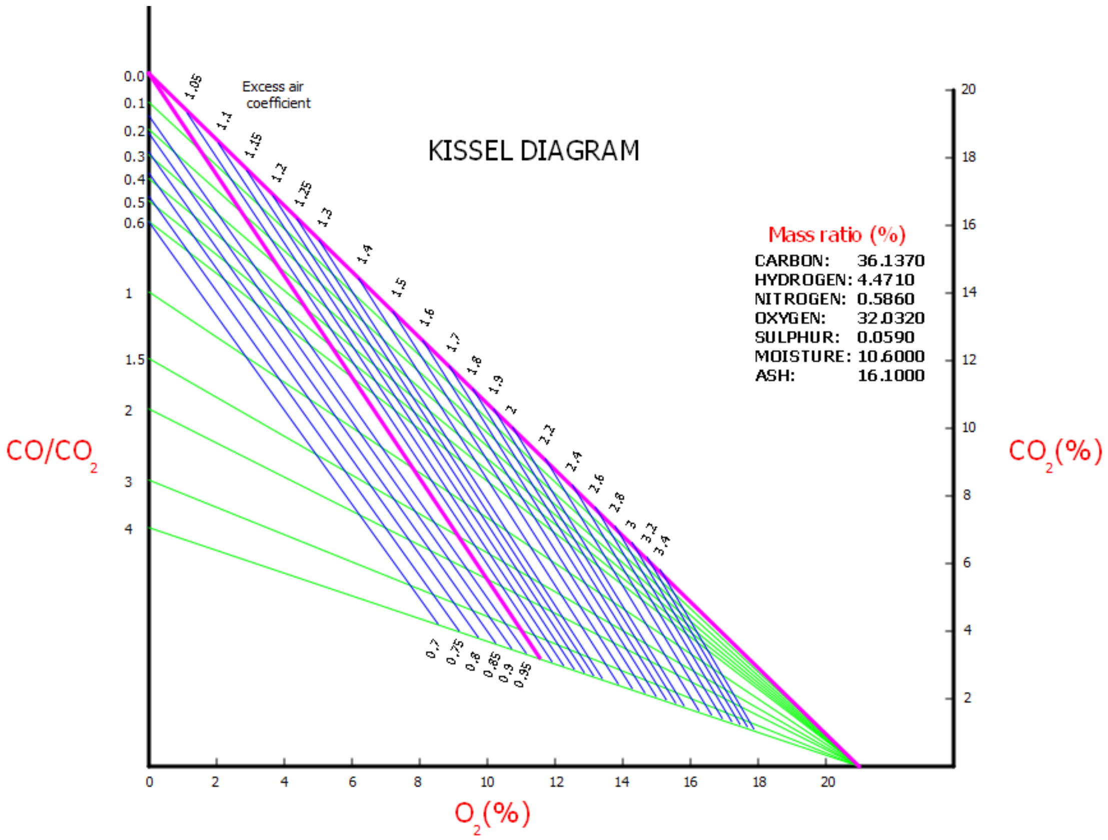
Ratio of bottom ash to fly ash

i %

* $Na_2O + K_2O$

One of the main problems of substituting fossil fuels by biomass in power-plant boilers is the biomass ash properties. Biomass fuels usually have a high content of alkali metals, which, together with other mineral components of the ash, give rise to severe ash deposition, thereby reducing the heat transfer and inducing increased boiler tube corrosion.


OSTWALD DIAGRAM
Excess air coefficient
20.3802
Mass ratio (%)
CARBON: 36.1370
HYDROGEN: 4.4710
NITROGEN: 0.5860
OXYGEN: 32.0320
SULPHUR: 0.0590
MOISTURE: 10.6000
ASH: 16.1000
CO(%) = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13
CO2(%)
O2(%)


KISSEL DIAGRAM
Excess air coefficient
Mass ratio (%)
CARBON: 36.1370
HYDROGEN: 4.4710
NITROGEN: 0.5860
OXYGEN: 32.0320
SULPHUR: 0.0590
MOISTURE: 10.6000
ASH: 16.1000
CO/CO2
CO2(%)
O2(%)