



Exercise 5 (Industrial Furnace)

A liquid fuel $_{C16.5}H_{34.44}$ is burned in an industrial furnace using a rich mixture, excess air coefficient of 0.88451. The molar ratio CO2 / CO = 1.8448.

If the air and fuel enter under standard conditions (25°C, 1 atm), and the combustion products leave at 750°C. Get:

a) Obtain the composition on a dry and wet basis of the exhaust gases.

b) The Ostwald diagram.

c) Adiabatic temperature of the flame.

d) Energy balance.

e) Solve the case assuming that there are unburned hydrocarbons in the form of ethane (10,000 ppm), also obtaining the entropy generated and the exergy analysis.

Known data:

Fuel formation enthalpy of -320 kJ / mol fuel Entropy at 1 atm and 25°C of 122 J / mol fuel K



The air used in combustion reactions is atmospheric air. Because neither N_2 nor inert gases in air react during combustion, they are often lumped together, and air is considered to be 21% O_2 and 79% N_2 .

AIR COMPOSITION	?	\times					
Molecular Weight (Molecular Weight (Dry air) kg / kmol						
Only two compone	nts: N2 ,O2	28.8507	•				
More components:	N ₂ ,O ₂ , Ar, CO	28.9700					
DRY AIR Composition							
	<u>Weight (%)</u>	<u>Mole (%)</u>					
N ₂	76.7075	79.0000					
O ₂	23.2923	21.0000					
Ar	0.0000	0.0000					
CO ₂	0.0000	0.0000					
Trace gasses	0.0000	0.0000					



Industrial furnaces are used in metallurgical production for smelting at high temperatures, in heat treatment, tempering, in some areas such as the food industry, for drying, and for fermentation at low temperatures. The metal industry has a significant share in total industrial energy consumption.

•	-	-
FUEL selection	Oxidizer	Cor
Fuel compos	ition	•
Hydrocarbon	mixture	•
Jet fuel		
Unknown fue	el CxHy	
Empirical for	mula	

	R FORMULA				
C	H	0	_N_	_ <u>S</u>	
16.50	00 🕂 34.44	00 🛨	÷	÷	-
				Liquid fuel	•
Formula know	/n				





Molar Analysis mol/kg fuel Molar ratio %	Ultimate Analysi Mass ratio %	s	FUEL	
70.847 32.39	85.0947 🛨	С	CARBON	-
147.877 67.60	9 14.9053 🛨	Н	HYDROGEN	-
	0.0000 ÷	N	NITROGEN	-
	0.0000 ÷	0	OXYGEN	-
	0.0000 ÷	S	SULPHUR	-
	0.0000 ÷	H ₂ O	MOISTURE	-
	0.0000 ÷		ASH	-
	Total: 100.0000			
	PRODUCT	S CO ratio		
	Molar Ratio CO ₂ /CO	1.84	480 ÷	
	Mass Ratio CO ₂ /CO	2.89	857 🕂	

Incomplete combustion is generally due to poor mixing of the air and fuel, insufficient residence time, insufficient temperature and low total excess air. Incomplete combustion (where there is not enough oxygen present) can lead to the formation of carbon or carbon monoxide. As a simple way of thinking about it, the hydrogen in the hydrocarbon gets the first chance at the oxygen, and the carbon gets whatever is left over.

	AS (Combus	tion Products)		
			On wet basis	On dry basis
•	🖣 mol/mol fuel	🗌 kg/kg fuel	Mole %	Mass %
CO ₂	10.700005	2.021960	9.1241	14.3386
CO	5.799995	0.697560	4.9458	4.9467
H ₂ O	17.220000	1.332030	14.6838	9.4460
N ₂	83.552076	10.049950	71.2463	71.2687
O ₂	0.000016	0.000002	0.0000	0.0000
SO ₂				
H ₂				
Ar				
<mark>unburned</mark>				
TOTAL	117.2721	14.1015	100.00 %	100.00 %







O₂(%)

The Ostwald diagram shows that there is no O2 presence in the combustion products.





Settings		
Final Report Definition		
Water gas shift reaction (mass balance)	×	
Chemical dissociation hypothesis		
Model Substances (oxidizer and combustion products)	•	Actual Gas
Combustion Products	۲	✓ Ideal gas
Reactants	×	Perfect gas

Products Temperature		
750.0	0 °C	
Adiabatic Flame Tompo	raturo	Absolute Error, AE (Actual)
Autobalie Flame Fempe		AE= H _{reactants} -H _{products}
For $\lambda = 0.8845$ (2028.6	<mark>6)</mark> ⁰C	
(Actual)		0.2 kJ/mol fuel
For λ = 1.0 (max) (Theoretical) 2153.0	0 °C (25℃, 1atm)	H _{products} -320.2 kJ/mol fuel

Energy Balance (25 °C, 1 atm) Energy Balance (25 °C, 1 atm)	Enthalpy of formation
Experimental correlations (mass fractions)	I -320.000 → kJ/mol fuel
Boie: C,H,O,N,S	Entropy at 1 atm & 25°C
(Based on the dry and mineral matter free elemental fuel composition)	✓ 122.0000 ÷ J/mol fuel K

Heat (Released or Abso 5875.058 kJ/mol fuel	erbed) i Exothermic ENERGY Exo = release
Reactants	$Q_f = \sum_{\text{Products}} n_{\text{out}} \mathbf{h}_{\text{out}}(\mathbf{T}_{\text{out}}) - \sum_{\text{Reactants}} n_{\text{in}} \mathbf{h}_{\text{in}}(\mathbf{T}_{\text{in}})$
J♥ Products	$\begin{array}{c} \hline & & \\ \hline \hline & & \\ \hline \hline & & \\ \hline & & \\ \hline \hline & & \\ \hline \hline \\ \hline & & \\ \hline \hline \\ \hline & & \\ \hline \hline \hline \\ \hline \hline \hline \\ \hline \hline \hline \hline \\ \hline \hline \hline \hline \hline \hline \hline \hline \\ \hline \hline$
🔽 kJ/mol fuel 🔲 kJ/kg fuel 🗆	kW $H = H_{form} + H(T,P) - H(25^{\circ}C, 1 \text{ atm})$

	Indrocarbon Fuels	Combus	stion			Ts
	kJ/mol	kJ/mol fuel				
O ₂	0.0000	0.0000	Α		ENERGY BAL	ANCE: FLUE GAS
N ₂	0.0000	0.0000	Ι	-		
H ₂ O	0.0000	0.0000	D			
TOTAL	0.0000	0.0000				kJ/mol
FUEL	-320.0000	-320.0000				

-320.0000

-320.0000)

TOTAL

TOTAL

	_				
0.0000	R				
0.0000				kJ/mol	kJ/mol fuel
-320.0000	_		CO2	-358.8609	-3839.7913
	E.		CO	-88.0788	-510.8620
	U		H ₂ O	-214.8900	-3700.4065
	E		O ₂	23.5112	0.0011
	L		N ₂	22.2137	1856.0007
-320.0000		Г			
-320.0000	(AIR+FUEL)		TOTAL	-616.1049	-6195.0576

ThermoSuite

 \times

?







If we assume a combustion that generates unburned hydrocarbons, in the form of C_2H_6 (10,000 ppm which is equivalent to 1%):

Unburned hydro	carbon		•	Negligible unburned hydrocarbon
Chemical Properties			 Unburned hydrocarbon 	
Air composition				Pure carbon soot
				unburned (ppm)
	C ₂ H ₆	Ethane		▼ 10000 ÷





FLUE GAS (Combustion Products)				
V	mol/mol fuel	🗌 kg/kg fuel	Mole %	Mass %
CO ₂	10.592944	2.001729	9.0382	14.1779
CO	5.742056	0.690592	4.8993	4.8913
H ₂ O	16.972500	1.332030	14.4814	9.4345
N ₂	83.552076	10.049950	71.2890	71.1818
O ₂	0.259796	0.035696	0.2217	0.2528
SO ₂				
H ₂				
Ar				
C ₂ H ₆	0.082500	0.0086661	0.0704	0.0614
TOTAL	117.2019	14.1187	100.00 %	(100.00) %
Dew Point	(and P _{sat})	□ 100%		mol/mol fuel
53.24 14.48) °C H₂O (kPa	(liquid)	%	kg/kg fuel

Products Temperature		
	2010.00 °C	
Adiabatic Flame	Temperature	Absolute Error, AE (Actual)
$F_{0}(r) = 0.9945$		$AE = H_{reactants} - H_{products} $
(Actual)	2010.16	0.1 kJ/mol fuel
For λ = 1.0 (max) (Theoretical)	2153.00 °C (25°C, 1atm)	H _{products} -320.1 kJ/mol fuel

As expected, the presence of unburned hydrocarbons in them, products of combustion, slightly decreases the adiabatic temperature of the flame.







🛞 ENERGY BA	LANCE: REACTA	NTS	? ×				
	kJ/mol	kJ/mol fuel					
O ₂	0.0000	0.0000	Α				
N ₂	0.0000	0.0000	I	🖲 E	NERGY BA	LANCE: FLUE GAS	s?×
H ₂ O	0.0000	0.0000	R	Γ			
TOTAL	0.0000	0.0000				kJ/mol	kJ/mol fuel
FUEL	-320.0000	-320.0000			CO ₂	-358.8609	-3801.3936
			F		CO	-88.0788	-505.7534
			U		H ₂ O	-214.8901	-3647.2214
			E		O ₂	23.5112	6.1081
			i l		N ₂	22.2137	1856.0007
			- L		C_2H_6	-17.3321	-1.4299
TOTAL	-320.0000	-320.0000					
TOTAL	-320.0000	-320.0000	(AIR+FUEL)		TOTAL	-633.4370	-6093.6895
-							
Direct method							
Combus	tion Efficie	ncy	Referenc	e state:	To=25 °C	, Po=100 kPa	i
η _{comb =}	$=\frac{Q_{f(T_0)}}{LHV}$		83.09 %		(i		

(Incomplete Combustion Loss)

(100% for complete combustion)

Qf(T0) (8588.92) kJ/kg fuel







The presence of unburned elements makes the useful energy available in the furnace less.

Entropy Terms (J/mol fuel K)	0
Generated Entropy (S ₉) 12910.38428	$S_g = -\frac{Q_f}{T_f} + \sum_{\text{Products}} n_{\text{out}} S_{\text{out}} - \sum_{\text{Reactants}} n_{\text{in}} S_{\text{in}}$
Entropy balance Reactants Products	i 5772.82 (7137.56445) i



ENTROPY BALANCE: REACTANTS ? X



	J/mol K	J/mol fuel K					
O ₂	217.9542	4840.7729	Α		NTROPY B	ALANCE: ELUE GA	s 7
N ₂	193.4071	16159.5654	I				
H ₂ O	0.0000	0.0000	R				
TOTAL	411.3613	21000.3379				kJ/mol K	J/mol fuel I
FUEL	122.0000	122.0000			CO ₂	290.4378	3076.591
			F		CO	260.2536	1494.390
			ii I		H₂O	249.6024	4236.376
			E		O ₂	295.0810	76.660
			E		N ₂	231.6156	19351.960
			L		C ₂ H ₆	289.9528	23.921
TOTAL	122.0000	122.0000		L			
TOTAL	533.3613	21122.3379	(AIR+FUEL)		TOTAL	1616.9431	28259.902