

CHAPTER 2

COMBUSTION PROPERTIES



Combustion Properties

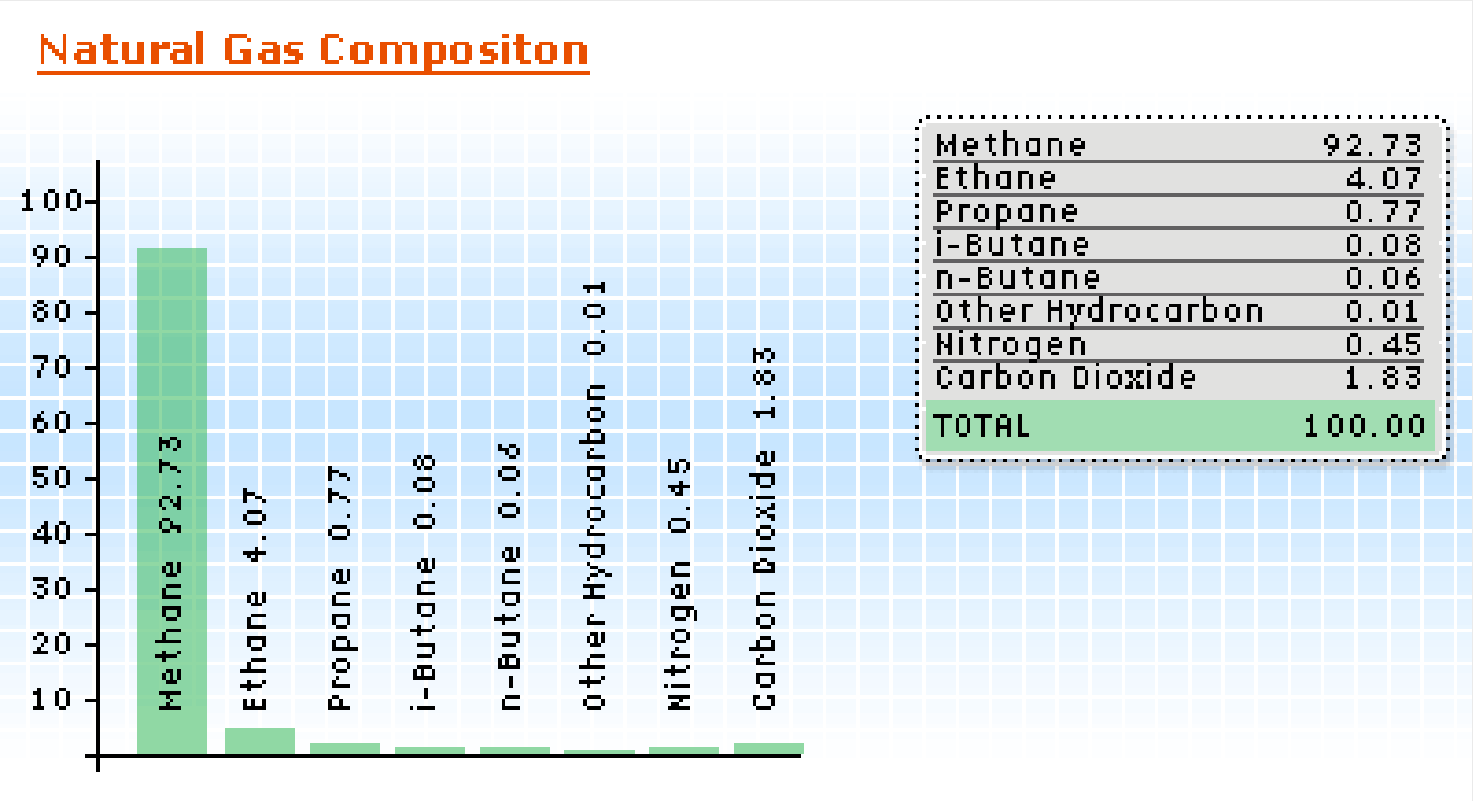
1. Calorific value (CV)
2. Specific Gravity (SG)
3. Wobbe Number
4. Heat of Combustion
5. Flammability Limit
6. Flame Speed
7. Ignition Temperature
8. Flame Temperature



Combustion Properties

Combustion properties are important due to setting up the gas burner and for designing the combustion chamber.

Component of Natural Gas



Methane	92.73
Ethane	4.07
Propane	0.77
i-Butane	0.08
n-Butane	0.06
Other Hydrocarbon	0.01
Nitrogen	0.45
Carbon Dioxide	1.83
TOTAL	100.00

hydrocarbon

Non-hydrocarbon

1. Calorific Value (CV)

- Also known as 'heating value'
- Defined as the amount of heat released (including the heat of condensation of water vapour) when stoichiometric air/gas is completely burned to yield specified products, with both reactants and products at 25°C and 1 atm.
- Unit are MJ/kg, Kcal/kg atau Kcal/m^3, MJ/m^3
- The more C and H atom in each molecule of a fuel, the higher its CV

$$CV \text{ for } CH_4 < C_2H_6 < C_3H_8 < C_4H_{10}$$

- Normally given in 'gross' or 'net'

Gross CV or Higher CV (HCV)

- **when liquid water is considered as a combustion product**
- **taking account the presence of water vapor in flue gases**

Net CV or lower CV (LCV)

- when vapour water act as a combustion product
- the difference between higher CV and the heat absorbed (latent heat) by water in having its phase changing to vapour

Higher heating value ------> H_2O is in (liq) state
Lower heating value -------> H_2O is in (g) state

Calorific value for NG in Malaysia

CV	Unit	NG	NG	LPG
		Before '95	**After '95**	**Commercial**
Gross	Kcal/m^3	9582	9253	28059
	Btu/m^3	38024	36718	111345
	Kcal/kg	11992	12487	11889
Net	Kcal/m^3	8644	8333	25844
	Btu/m^3	34302	33067	102556
	Kcal/kg	10816	11246	10951

CV for NG component

Component		Caloric value per unit volume				Per unit weight	
		Gross	Net	Gross	Net	Gross	Net
Name	Symbol	Kcal/Nm³ Btu/Nm³		Kcal/Sm³ Btu/Sm³		Kcal/kg Btu/kg	
Hydrogen	H_2	3053 12115	2573 10210	2893 11480	2439 9679	33998 134913	28653 113702
Carbon Monoxide	CO	2016 11968	3016 11968	2859 11345	2859 11345	2412 9575	2413 9575
Methane	CH_4	9537 3784	8574 3402	9041 35877	8128 32254	13307 52806	11963 47472
Ethylene	C_2H_4	15179 60234	14211 56392	14389 57099	13471 53456	12005 47639	11239 44599
Ethane	C_2H_6	16834 66802	15379 61028	15958 63325	14578 57849	12408 49238	11336 44984
Propylene	C_2H_6	22385 88829	20917 83004	21220 84206	19828 78683	11690 46389	10923 43345
Propane	C_3H_8	24229 96147	22267 88361	22968 91143	21108 83762	11995 47599	11023 43742
Butylene	C_4H_8	29110 115516	27190 107897	27595 10950	25775 102282	11602 46040	10837 43004
N-Butane	C_4H_{10}	32022 127071	29520 117143	30355 120456	27983 111044	12323 48901	11360 45079
I-Butane	C_4H_{10}	31781 126115	29289 116226	30127 119552	27764 110175	12231 48536	11272 44730

Calorific Value

CV of multi-component fuel can be calculated as follows:

$$CV_{vol,mix} = \sum_{i=1}^{i=n} y_i CV_{vol,i} \quad \text{or} \quad CV_{weight,mix} = \sum_{i=1}^{i=n} x_i CV_{weight,i}$$

CV - CV of component i in the mixture

y – fraction of component i

Calculation of CV

Component	Gross CV (pure comp.) Btu/Nm^3	Net CV (pure comp.) Btu/Nm^3	Vol%	Gross CV Btu/Nm^3	Net CV Btu/Nm^3
CH_4	37840	34024	70	26488	23816
C_2H_6	66802	61028	15	10020	9154
C_3H_8	96147	88361	10	9615	8836
C_4H_{10}	127071	117143	5	6353	5857
Total			100	52476	47664

CV gross = 52476 Btu/Nm^3
CV net = 47664 Btu/Nm^3

Example 2 (page 18)

Calculate the gross CV of a substitute natural gas produced by the gas recycle hydrogenator process and of the following composition by volume:

CO	3.0%
CH_4	34.1%
C_2H_6	12.9%
H_2	38.4%
C_3H_8	11.6%

Calorific Value

<u>Example 1</u>

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O\ (liq)$$

Gross CV

$$= \sum n\Delta H_{f\ product} - \sum n\Delta H_{f\ reactant}$$

$$= 1(\Delta H_{f\ CO2}) + 2(\Delta H_{f\ H2O}) - 1(\Delta H_{f\ CH4}) - 2(\Delta H_{f\ O2})$$

$$= 1(-393.5) + 2(-285.84) - 1(-74.85) - 2(0)$$

$$= -890.3\ kJ/mol$$

Calorific Value

Similarly, net CV can also be determined from tabulated heat of formation data as shown below

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O\ (vap)$$

Net CV

$$= \sum n\Delta H_{f\ product} - \sum n\Delta H_{f\ reactant}$$

$$= 1(\Delta H_{f\ CO2}) + 2(\Delta H_{f\ H2O}) - 1(\Delta H_{f\ CH4}) - 2(\Delta H_{f\ O2})$$

$$= 1(-393.5) + 2(-241.83) - 1(-74.85) - 2(0)$$

$$= -802.31\ kJ/mol$$

$$CV_{gross} = CV_{net} + \Delta H_{vap}\ H2O$$

Net CV is approximately equal to 90% of the gross CV

$$CV_{net} = 0.9CV_{gross}$$

2. Specific Gravity (SG)

Ratio between the gas density and the density of dry air at the same condition (P, T and V)

Natural gas standard condition : 15°C dan 101.325 kPa

$$SG_g = \frac{\rho_g}{\rho_a}$$

2. Specific Gravity

SG of multi-component fuel can be calculated as follows:

$$SG = \sum_{i=1}^{i=n} yiSGi$$

y_i – mole fraction (vol%) of fuel component i
SG_i – specific gravity of fuel component i

SG < 1 → lighter than air
SG>1 → heavier than 1

2. Specific Gravity

SG will determine whether the gas will dispersed into air or fall on the ground if released or leaked

Two practical importance's which are:

- Effect on the flow of gases through orifices or pipe
- Rating of burners – burner conversion

Also effects gas flow in pipes: a given driving pressure at a pipe inlet moves more lighter gas than heavier gas through that pipe

Natural gas SG Table

Component				
Name	**Symbol**	**Relative weight (mol)**	**Specific weight (Kg/Nm^3)**	**(SG) (Air=1)**
Hydrogen	H_2	2.02	0.0898	0.0695
Carbon Monoxide	CO_2	28.01	1.2501	0.967
Methane	CH_4	16.04	0.7167	0.555
Ethane	C_2H_6	30.07	1.3567	1.048
Etyelen	C_4H_4	28.05	1.2644	0.975
Propane	C_3H_8	44.10	2.0200	1.554
Propylene	C_3H_8	42.08	1.9149	1.479
Butane	C_4H_{10}	58.12	2.5985	2.085
Carbon dioxide	CO_2	44.01	1.9768	1.5291
Oxygen	O_2	32.00	1.4289	1.1053
Nitrogen	N_2	28.02	1.2507	0.9674
Water vapour	H_2O	18.02	0.804	0.622
Air	(1)*	28.97	1.2928	1.0000

(1)* N_2 = 1.5606, O_2 = 0.4204, Ar = 0.0093 dan C = 0.0003

Example of SG calculation for natural gas before 1995

Symbol	Composition (vol%) (A)	Specific Graviti (B)	(A) X (B) / 100
CH_4	84.75	0.555	0.4704
C_2H_6	10.41	1.048	0.1091
C_3H_8	0.98	1.554	0.0152
$I\text{-}C_4H_{10}$	0.07	2.085	0.0015
$N\text{-}C_4H_{10}$	0.04	2.085	0.0008
N_2	0.39	0.9674	0.0038
CO_2	3.36	1.5291	0.0514
TOTAL	100.0	-	**0.6522**

Solution;

Specific gravity, SG = 0.6522

Specific weight = 0.6522 x 1.2928 kg/Nm^3

= 0.843 kg/Nm^3

$$= 0.843 \times \frac{273.15}{273.15+15}$$

= 0.799 kg/Sm^3

SG NG < 1

- (Lighter than air thus will be released in the air)

SG calculation for LPG (butane 70% and propane 30%)

Symbol	Composition (vol%) (A)	Specifik graviti (B)	(A) X (B) / 100
C_3H_8	30.00	1.554	0.4662
C_4H_{10}	70.00	2.085	1.4595
Total	100.00	-	**1.9257**

Then

Specific gravity, SG = 1.9257

Specific weight = 1.9257 x 1.2928 kg/Nm^3

= 2.490 kg/Nm^3

= 2.360 kg/Sm^3

SG > 1

- **(heavier than air thus will fall to the ground – collected at the bottom/drain)**

Example 3 (Page 20)

Calculate the specific gravity of Malaysian natural gas compositions after 1995.

3. Wobbe Number

Also known as 'Wobbe Index'

- Indicate the interchange ability of fuels gases
- WI obtained by dividing the heating value of a gas by the square root of its specific gravity

$$WI = \left[\frac{CV}{\sqrt{SG}} \right]$$

Wobbe Number

Family	Wobbe Number,MJ/m^3	Type of gas
1st	22.4 – 30.0	Manufactured Gas or Town Gas, LPG/Air Mixtures
2nd	39.1 – 45 (Group L) 45.7 – 55 (Group H)	Natural Gas Substitute Natural Gas
3rd	73.5 – 87.5	LPG, Propane, Butane

Gaseous fuels having the same WI can be interchanged with no significant physical changes to the burner

Example 4 (page 23)

Calculate Wobbe Number

4. Heat of Combustion

The heat of the reaction of that combustible with oxygen to yield specific products (i.e. CO_2 and H_2O), with both reactants and products at reference state 25°C and 1 atm.

$$CV = -\Delta H_c$$

$$\downarrow$$

Hence CV is always positive

Example 5 (page 23)

Calculate the heat of combustion of methane and ethane with these two condition where

a) liquid water as a combustion product

b) vapour water as a combustion product

Question?

THE END

Thank You for the Attention



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5. Flammability Limit

A range of fuel and air proportion in which combustion can be self-sustaining is known as flammability limits - These limits have limiting lean (lower limit) and limiting rich (upper limit)

Fuel	Lower limit		Upper limit	
	Vol. %	Air/Gas ratio	Vol. %	Air/Gas ratio
Hydrogen (H_2)	4.0	10.1	75.6	0.14
Methane (CH_4)	5.0	2.0	15.0	0.60
Ethane (C_2H_6)	3.0	1.9	12.5	0.42
Propane (C_3H_8)	2.1	2.0	9.5	0.4
Butane (n-C_4H_{10})	1.9	1.7	8.5	0.35
Natural gas	4.3	2.0	14.5	0.54

5. Flammability Limit

Fuel	Lower limit		Upper limit	
	Vol. %	Air/Gas ratio	Vol. %	Air/Gas ratio
Hydrogen (H_2)	4.0	10.1	75.6	0.14
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Natural gas	4.3	2.0	14.5	0.54

	LFL		UFL
CH_4	5%	$\longleftrightarrow$	15%
C_3H_8	2.1%	$\longleftrightarrow$	9.5%

Burn only in this range with ignition depend on T & P

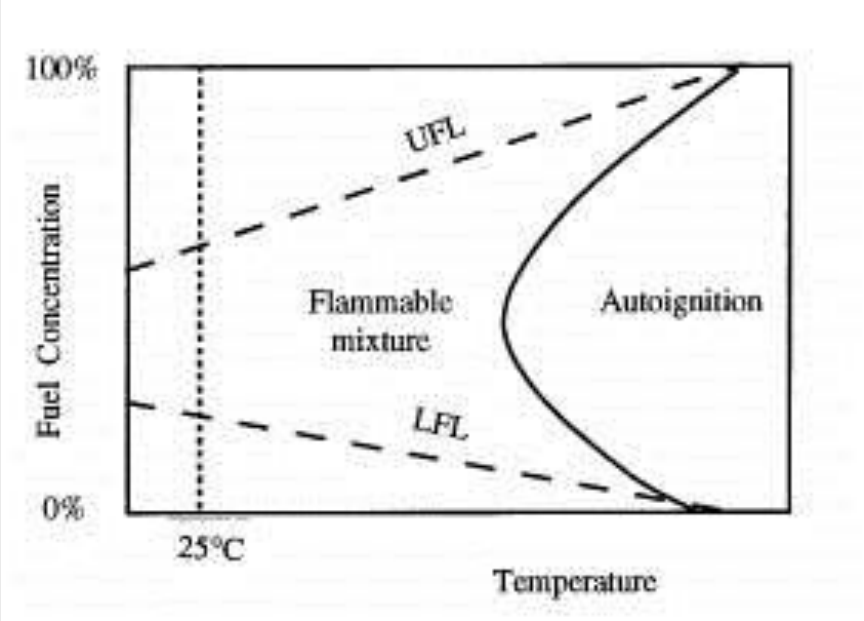
5. Flammability Limit

Flammability limits for fuel mixtures may be calculated by Le Chatelier's law:

$$LFL_{Mix} = \frac{100}{C_1/LFL_1 + C_2/LFL_2 + \cdots + C_i/LFL_i}$$

where C_1, C_2 ....C_i [vol.%] is the proportion of each gas in the fuel mixture without air.

Flammability Limit



flammability range is widen when temperature is increased

Flammability Limit

Effect of oxidant (O_2)

Expand the flammable range by increasing the upper limit

	Inflammability limit, % gas in the mixture			
Gases	**In Air**		**In oxygen**	
	Lower	Upper	Lower	Upper
Ethylene	3.1	32.0	3.0	80.0
Methane	5.3	15.0	5.1	61.0
Ethane	3.0	12.5	3.0	66.0
Hydrogen	4.0	75.0	4.0	94.0
Carbon monoxide	12.5	74.0	15.5	94.0

Flammability Limit

Effect on diluent (CO_2, N_2)

Narrow down the flammability limits by increasing the lower limit

Flammability limit of combustibles containing diluents can be represented as below;

$$FL_{mix,dil} = FL_{mix}\left(\frac{100}{100 - y_{dil}}\right)$$

$FL_{mix,\,dil}$ = vol. % flammability limit (lower or upper) of the combustibles containing diluents in air

FL_{mix} = vol. % flammability limit (lower or upper) of the pure combustibles in air

Y_{dil} = vol.% of diluents in the fuel mixture

Example 6

Calculate the limits of lower and upper flammability limits in air of a gas mixture containing (by vol.)

30% CO
45% H_2
25% CH_4

*Refer to Table 2-4 (pg 26) for LL and UL value of CO, H_2 and CH_4

Example 7

Calculate the limits of lower and upper flammability limits in air of a gas mixture containing (by vol.)

10% CO
55% H_2
25% CH_4
5% CO_2
5% N_2

→ Diluent present so cannot use Le Chtelier's law

6. Flame speed

- The rate of flame surface propagation into the un-burnt combustible mixture to ensure continuous and successful flame propagation

- Also known as burning velocity or combustion velocity.

Fuel	Max. flame speed (cm/sec)	Air/gas Ratio	Vol. % fuel in mixture
Hydrogen (H_2)	282	0.58	42
Methane (CH_4)	39.2	0.90	10.5
Ethane (C_2H_6)	42.6	0.90	6.2
Propane (C_3H_8)	45.5	0.96	4.2
n-Butane (n-C_4H_{10})	37.5	1.0	3.1
i-Butane (i-C_4H_{10})	37.5	1.0	3.1
Natural gas	39	0.9	9

Flame speed

For any gaseous mixture the flame speed can be approximated by the following formula:

$$S = \frac{aS_a + bS_b + cS_c + \ldots\ldots}{a + b + c + \ldots\ldots}$$

where

S - flame velocity of the mixture

a, b, c - % vol. composition of constituent combustible gases

S_a, S_b, S_c - flame velocity of constituent gases

Example 8

Calculate the maximum flame velocity of a gas mixture containing (by vol.)

85% CH_4
10.4% C_2H_6
0.98% C_3H_8
0.11% C_4H_{10}
0.39% N_2
3.12% CO_2

$$S = \frac{aS_a + bS_b + cS_c + \ldots\ldots}{a + b + c + \ldots\ldots}$$

7. Ignition Temperature

An amount of energy externally supplied to initiate combustion is called ignition energy and its corresponding temperature is known as ignition temperature.

Fuel	Min. Ignition temperature (°C)
Hydrogen (H_2)	560
Methane (CH_4)	595
Ethane (C_2H_6)	515
Propane (C_3H_8)	470
n-Butane (n-C_4H_{10})	460
i-Butane (i-C_4H_{10})	460
LPG	~ 450-470
Natural gas	~ 630-730

(Source : Physical property data)

→ Lowest Tempt for combustion to initiate

8. Flame Temperature

The temperature of the flame corresponds to heat generated during combustion process

Flame temperature of fuel depends on

- Calorific value
- Volume and specific heat of total gaseous products
- Losses by radiation
- Latent heat in water vapour in the combustion products
- Endothermic dissociation of gaseous molecules, mainly CO_2 and H_2O

COMPARISON OF THE PROPERTIES OF TYPICAL GASES

Property	Units	NG	Commercial Propane	Butane/Air Mixtures
CV	MJ/m3	39.3	97.3	23.75
SG	air=1	0.58	1.5	1.19
Wobbe #	MJ/m3	51.64	79.4	21.79
Air Required	Vol air/Vol gas	9.75	23.8	4.89
Flammability Limits	% gas in air	5 to 15	2 to 10	1.6 to 7.75
Flame Speed	m/s	0.36	0.46	0.38
Ignition T	°C	704	530	500

Question?

THE END

Thank You for the Attention