Sustainable Power Generation
MJ2405

Fuels & Combustion basics

- Fuel types and elemental composition
- Fundamentals of combustion processes

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Reading material on combustion

Many books can be used!
Any chapter on fuel composition or combustion can serve as study material.

The main suggested sources:

Advanced Energy Systems (Khartchenko&Kharchenko), *CRC Press 2014* – (chapter 2): sections 2.1 to 2.5.

Energy Conversion – *free e-book by courtesy of the University of Tulsa*, Kenneth C. Weston, 2000 – (chapter 3)
http://www.personal.utulsa.edu/~kenneth-weston/

På svenska:

Energiteknik -Del 1, Henrik Alvarez, *Studentlitteratur 2006* – kapitel 6.

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What is combustion ?

- The simple definition: **A burning process**
- The proper definition: **A chemical reaction between a fuel (combustible substance) and an oxidizing agent,** involving the release of energy (exothermic reaction)
- In practical terms: The reactants are the fuel elements that are oxidized by oxygen available in the air
- The combustion reaction needs to be initiated at first, after which it proceeds by itself (self-feeding)
- The combustion reaction should **proceed in a controlled way**

The combustion process (from an energy conversion perspective)

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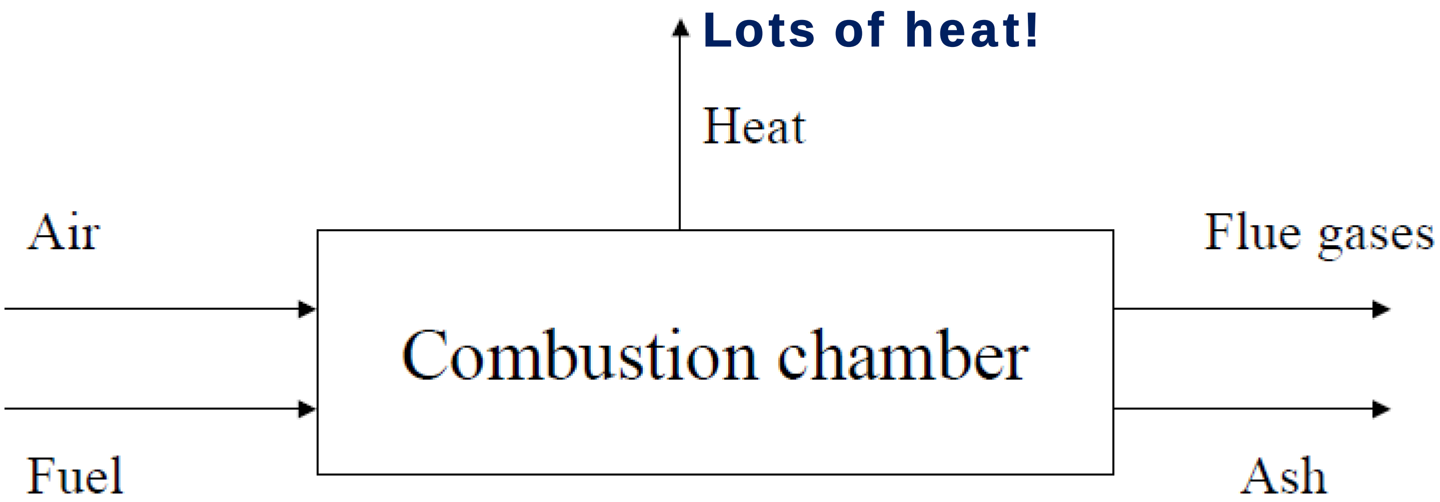

What is a fuel ?

- The simple definition: **Anything that burns**
- The proper definition: **Any substance containing elements that can undergo a sustained combustion reaction**
- For practical purposes: **Any combustible substance that is manageable and available in large-enough quantities**
- Preferably having a high energy content;
- Preferably cheap (low-cost production and delivery)
- **Preferably leading to minimum pollution, both directly** (at the utilization point) **and indirectly** (at the production site or during transportation and handling).

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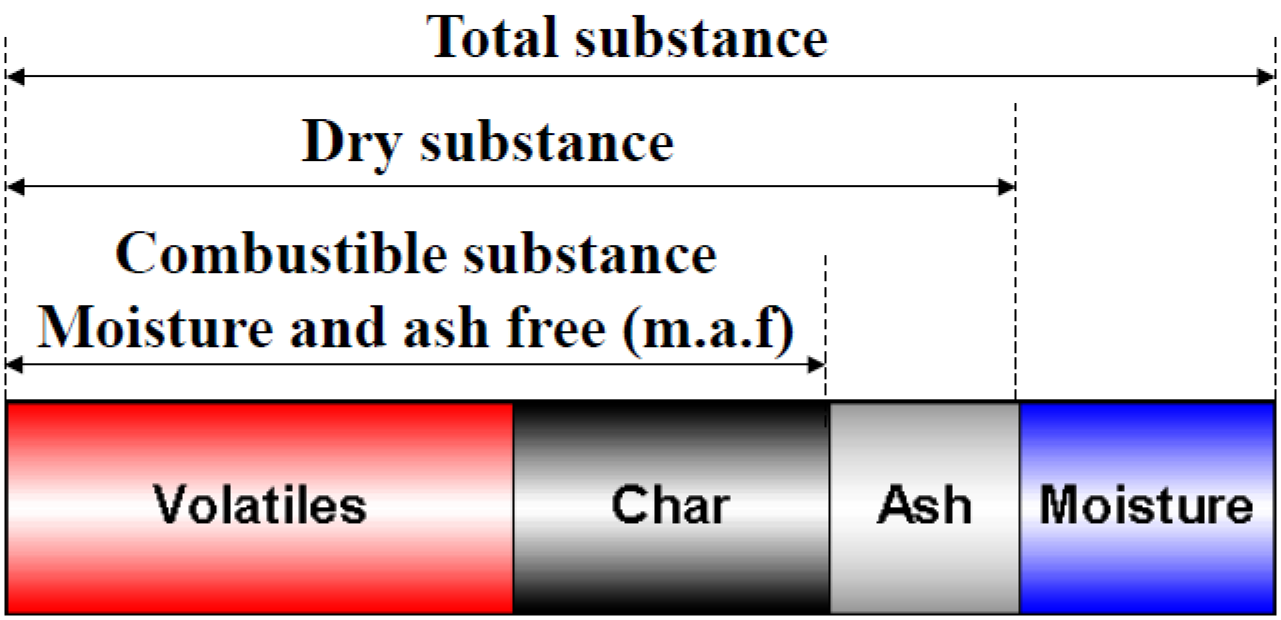
Fuel composition – proximate analysis



Fuel composition – ultimate analysis

The combustible substance of the fuel is ultimately composed of the following chemical elements:

- **Carbon**
- **Hydrogen**
- **Oxygen**
- **Nitrogen**
- **Sulfur**

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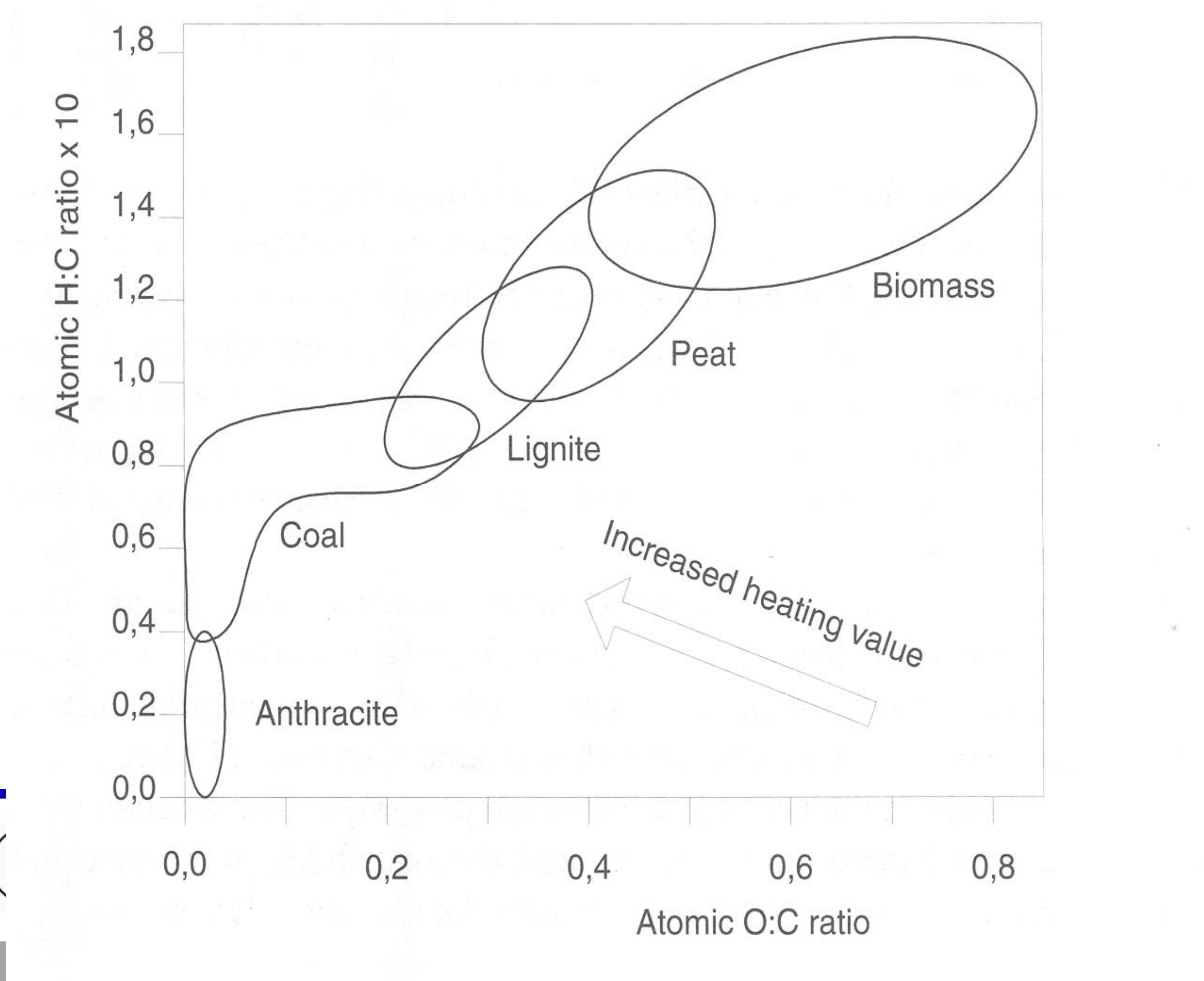
- Every other substance wouldn't burn and can be classified among the ashes (ash content = A)
- + Water (moisture content = M)

C + H + O + N + S (+ A + M) = 100%

Hydrocarbon fuel composition diagram

Molar ratio of H/C and O/C on dry ash-free basis
(also called ”Van Kreulen” diagram):



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Moisture content in fuels

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Moisture in the fuel may result from two different sources:

- **Physical moisture** (surface wetness) - water entrained in the fuel
- **Chemical (inherent) moisture -** water molecules bound inside the fuel in complex molecular structures
- For the combustion process, all sorts of moisture will play a quenching role!
- *Moisture in the <u>combustion process</u> may also derive from water molecules entrained in the oxidizing agent (<u>humid air</u>)*

Ash content in fuels

Ashes can also be traced to several main sources:

- **Soil / stones / dirt** physically carried along with the fuel during its mining and excavation process
- **Inbuilt (inherent) ash –** various inorganic substances involved in the fuel molecules or bound to microparticles of fuel
- Ashes are always incombustible and remain as a solid residue after the burning process
- Ashes are mostly **metal oxides and salts,** but sometimes also free elemental metals or non-metallic salts

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Typical ash content

Fuel	Ash content [% of dry fuel]
Oil	0.01 – 0.3
Coal	5 - 15
Wood	1.5 – 5.3
Peat	0.5 – 6.2
Municipal solid waste (MSW)	12 - 30
Straw	3 – 5.5

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Ashes after combustion

- **Fly ash –** entrained in the flue gas flow, usually in the form of volatile elemental metals or their salts, or halogen products; often toxic heavy metals such as mercury (Hg), cadmium (Cd),...

- **Bottom ash** (residual ash) **–** remaining as a solid residue and precipitating down in the furnace; it can be handled in two ways:

  - **Solid –** a mixture of various ferrous/alumina/silica oxides
  - **Liquid (melted ash) –** usually containing oxides and salts of alkali and alkali-earth elements (Na-, K-, Ca-, Mg-,...)

Ash melting is usually undesired and troublesome, unless the furnace is designed to handle it; so lower combustion T is applied to avoid melting

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Ash analysis example

Feedstock	Aspen wood chips	RWE Fortuna Brown coal
Ash [wt-%]		
SiO_2	3.53	59.5
Al_2O_3	1.03	3.1
Fe_2O_3	1.67	9.3
CaO	28.0	12.1
MgO	6.5	3.9
K_2O	24.0	1.4
SO_3	na	5.3
Heavy metals [mg/kg, dry ash]		
Ba	na	920
Pb	61	75
Cd	1.4	5.3
Cr	65	135
Cu	210	185
Ni	850	550
Hg	na	< 5
Zn	0.26	155
As	< 1	na

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Total analysis example (various biomass sources)

On dry basis (d.b.)	W1 Europ. beech sawdust	W2 Tropic. hardwood (pieces)	W3 Pine wood waste dust	F1 Broad leaves chips	O1 Olive tree chips	V1 Wine tree chips	R1 Robinia chips	P1 Wheat straw	P2 Barley straw	RM1 Dehydr. sludge briquette
Moisture content, wt%	55.7	8.2	8.0	37.6	35.4	44.2	13.2	12.1	13.8	13.7
Proximate analysis, wt% d.b.										
Volatile matter	76.3	74.7	76.3	78.7	78.1	76.6	80.6	73.6	75.0	64.2
Fixed carbon	22.3	23.5	18.1	18.9	18.9	20.7	17.3	18.5	19.3	9.7
Ash	1.4	1.8	5.6	2.4	3.0	2.7	2.1	7.9	5.7	26.1
Ultimate analysis, wt% d.b.										
C	52.6	52.4	47.2	49.2	49.8	49.0	48.2	45.6	45.6	38.7
H	5.9	5.7	5.7	5.7	6.0	5.7	6.0	5.7	5.6	5.8
N	0.3	0.3	2.2	0.6	0.7	0.7	1.2	0.7	0.5	6.3
S	0.02	0.01	0.09	0.04	0.06	0.05	0.05	0.09	0.09	1.97
O (as difference)	39.8	39.8	39.2	42.1	40.4	41.8	42.4	40.0	42.5	21.1
Ash	1.4	1.8	5.6	2.4	3.0	2.7	2.1	7.9	5.7	26.1
LHV (d.b.), MJ/kg	19.9	19.6	18.0	18.3	19.0	18.3	18.2	16.8	17.1	15.7
Trace components, ppm-wt (d.b.)										
Cl	<50	<50	310	150	350	260	300	2 210	4 720	1 580
Na	150	60	1 260	100	290	190	140	710	1 470	2 590
K	1 910	3 380	1 570	2 830	8 710	9 430	3 140	16 200	16 700	2 360
Ash composition, g/kg ash										
SiO_2	10	0.6	17	4	6	2	1.2	55	36	12
Al_2O_3	1.7	0.1	4	1.4	1.9	0.6	0.4	0.5	1.2	19
Fe_2O_3	2.1	0.7	2.0	2.1	1.4	0.5	0.4	0.4	0.8	9
CaO	48	54	27	63	45	38	59	7	7	12
MgO	10	22	14	6	6	10	6	3	4	3
K_2O	12	19	3	13	27	36	18	23	28	1
Na_2O	1.4	0.5	4	0.8	1.3	1.0	1.0	2.0	5	2.2
TiO_2	0.1	-	17	0.1	0.1	-	-	0.04	0.1	1.6
SO_3	3	1	6	4	3	4	6	4	5	12
P_2O_5	5	1	1	5	7	7	7	3	4	12
XRF sum (normalised)	94	99	95	99	99	99	99	97	91	83

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The combustion process steps

Combustion of a fuel particle proceeds along several sub-processes:

- **Drying –** moisture is driven off by heat from the combustion step
- **Pyrolysis –** volatile matter is driven off in the form of gases when the dry particle continues to be heated in the furnace. The remaining solid residue is the char.
- **Combustion of gases –** the combustible volatile gases initiate the oxidation process (typically a blue flame)
- **Char combustion** – the char residue (basically pure carbon) is the slowest to undergo combustion, and burns with a yellow flame or as a red-glowing particle

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Combustion reactions

$C + O_2 \rightarrow CO_2$ +393.5 [MJ/kmol] or 32.765 [MJ/kg]
LHV=HHV for pure carbon

$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$(vapor) +241.8 [MJ/kmol] or 119.95 [MJ/kg]
LHV of pure hydrogen

$S + O_2 \rightarrow SO_2$ +296.9 [MJ/kmol] or 9.261 [MJ/kg]
LHV=HHV for pure sulfur

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- O_2 contained in the fuel would take place in the combustion reactions, reducing the need for external oxygen supply

- For the simplified overall process: N_2 is assumed to remain inert!
- N_2 contained in the fuel would end up in the flue gases as elemental nitrogen – good approximation for energy balance calculations

Combustion in air

"Technical air" used for combustion calculations is simplified to: 21% O_2 and 79% N_2

Each mol of O_2 carries along 3.76 mols of N_2 (3.76=0.79/0.21)

- **$C + O_2 (+ 3.76*N_2) \rightarrow CO_2 + 3.76*N_2$**
- **$H_2 + ½O_2 (+ ½*3.76*N_2) \rightarrow H_2O + ½*3.76*N_2$**
- **$S + O_2 (+ 3.76*N_2) \rightarrow SO_2 + 3.76*N_2$**

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Heating value

- The energy content of a fuel is represented by its heating value, appearing as released heat after the combustion process

- ***To measure the heating value:***

All products of combustion are cooled down to a defined reference temperature, usually taken as 25 ^{o}C (”standard” conditions) or as 0 ^{o}C (”normal” conditions)

- We are practically interested in the specific heating value, that is per unit mass or per unit volume of fuel: **kJ/kg** or **kJ/m^3**

Pressure plays no role as long as all products of combustion can be assumed as perfect gases (ideal gases). Lab tests are always made at ~1 atm pressure.

HHV and LHV

- **Higher Heating Value (HHV) – also called ”calorific”**

The amount of total heat released when all the moisture contained in the flue gases is ultimately condensed back to liquid water

- **Lower Heating Value (LHV) – also called ”effective”**

The amount of heat released when all the moisture contained in the flue gases remains in vapor phase

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The total moisture in the flue gases is derived from:

- **Moisture of the fuel –** evaporated in the combustor;
- Water vapor resulting from **combustion of hydrogen;**
- Water vapor delivered to the combustor **with the air.**

The LHV concept

- **Claimed to make more sense for the practical case –** where no moisture from the flue gas would ever be condensed, at least not for energy recovery purposes
- *This is indeed the case for most combustion processes in any application, including almost all thermal power plants*

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LHV = HHV – 2.44*(8.92*H_2 + M) [MJ/kg]

where:

H_2 = hydrogen mass fraction in the fuel

M (or F) = moisture in the fuel as mass fraction

2.44 = Heat of vaporization of H_2O at 25 ^oC and 1 bar [MJ/kg]

Assuming also that there is no humidity in the air used for combustion

	Tändtemperatur °C
Fasta bränslen	
Torv, lufttorr	225–280
Trä, mjuk	220
Trä, hård	300
Träkol, mjukt	135–300
Träkol, hårt	300–450
Gaskol	214–230
Feta kol	243–260
Magra kol	340–500
Brunkol	210–400
Koks	205–600
Flytande bränslen	
Bensin	330–550
Motorbensol	600–730
Etanol	400–460
Motorfotogen	~270
Dieselolja	330–360
Eldningsolja	~212
Metanol	400–480
Gasformiga bränslen	
Acetylen (C_2H_2)	350
Butan (C_4H_{10})	410–550
Etan (C_2H_6)	470–550
Etylen (C_2H_4)	540
Koloxid (CO)	610
Metan (CH_4)	645
Propan (C_3H_8)	460–580
Propen (C_3H_6)	460
Väte H_2	510
Lysgas	560
Naturgas	650

Ignition temperature

The minimum temperature at which a flammable substance would ignite.

Depending on:

- Type of fuel and its volatile content
- Moisture content
- Ambient temperature
- Other physical factors

Does **not** depend on the heating value!

Heating values of some common fuels

Fuel:	HHV *MJ/kg*	HHV *kJ/mol*	LHV *MJ/kg*
Hydrogen	141.80	286	119.96
Methane	55.50	889	50.00
Ethane	51.90	1,560	47.80
Propane	50.35	2,220	46.35
Butane	49.50	2,877	45.75
Pentane	48.60	3,507	45.35
Paraffin wax	46.00		41.50
Kerosene/gasoline	46.20		43.00
Diesel	44.80		43.4
Light fuel oil (LFO)	45.5		43
Heavy fuel oil (HFO)	42.5		40
Bituminous Coal	22 - 32		18 - 30
Lignite Coal	10 - 20		7 - 16
Wood (d.a.f)	21.7		19
Wood (wet 50%-20%)			7 - 15
Peat (wet - dry)	9 - 17		7 - 15

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Stoichiometry

Stoichiometric air demand:

- **The exact amount of oxygen necessary for the complete combustion process**
- In stoichiometric combustion, all oxygen is consumed in the combustion reactions
- *Practically, combustion should proceed for a limited time, so it's impossible to run it in perfect stoichiometry. Excess air is always supplied to ensure complete combustion. This results in some unused oxygen remaining in the flue gases.*

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Stoichiometric combustion data

Combustion parameters for some representative gaseous fuels:

Tabell 6.1.1-2 Förbränningstekniska data för några gaser. Index t=teoretisk. H_i=effektivt (=undre) värmevärdet, avsnitt 6.1.4.

Gas			Teoretiska mängder av					LHV
Namn	Kemisk formel	Molekyl-massa	Syre O_t	Luft $l_{t_{torr}}$	Rökgas $g_{t_{torr}}$	Rökgas g_t	CO_2, % i torra gaser	H_i MJ/m_n^3
			m_n^3/m_n^3 bränsle					
Koloxid	CO	28,01	0,5	2,385	2,885	2,885	34,65	12,48
Väte	H_2	2,016	0,5	2,385	1,885	2,885	—	10,62
Svavelväte	H_2S	34,09	1,5	7,14	6,64	7,64	—	24,21
Metan	CH_4	16,04	2	9,54	8,54	10,54	11,7	35,33
Etyn	C_2H_2	26,04	2,5	11,93	11,43	12,43	17,5	56,2
Eten	C_2H_4	28,05	3	14,31	13,31	15,31	15,05	59,2
Etan	C_2H_6	30,07	3,5	16,7	15,2	18,2	13,15	63,5
Propen	C_3H_6	42,08	4,5	21,47	19,97	23,07	15,02	88,5
Propan	C_2H_8	44,1	5	23,85	21,85	25,85	13,75	90
Buten	C_4H_8	56,1	6	28,62	26,62	30,62	15,02	115
Butan	C_4H_{10}	58,12	6,5	31,01	28,51	33,51	14,02	117
Pentan	C_5H_{12}	72,15	8	38,16	35,16	41,16	14,23	144

Stoichiometric air / fuel ratio

Minimum mass of necessary combustion air per unit mass of fuel

Denoted usually as "f": stoichiometric air-to-fuel ratio for a given fuel (kg_{air}/kg_{fuel})

For light oil: f = 14.52; For methane: f = 17.16

"*f*" is found from the chemical reaction of stoichiometric combustion in air, for example:

- $CH_4 + 2O_2\ (+2*3.76N_2) \rightarrow CO_2 + 2H_2O + 2*3.76N_2$

1 mol CH_4 needs 2 mols of O_2 (which carries along 2*3.76 mols of N_2) =

16 kg CH_4 need 2*32 kg O_2 + 2*3.76*28 kg N_2 =

1 kg CH_4 needs $\frac{2*32+2*3.76*28}{16}$ kg air ➔ therefore f_{CH4} = 17.16 [kg_{air}/kg_{CH4}]

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“Lean” and “Rich” combustion

- **Air in excess** – lean combustion
- Excess air ratio "m" (air excess factor) = $\dfrac{\textit{actual air supply}}{\textit{needed stoichiometric air}}$
- For a proper combustion in practice - **m > 1**
- **Rich (starved) combustion with insufficient air** (m<1) – in the extreme case this would be gasification of the fuel

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Typical air excess factor examples

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Tabell 6.1.1-3 Vanliga värden på luftfaktorn n.

Bränsle	*n*
Stenkol:	
handeldning	1,7 . . . 2
mekanisk eldning	1,4 . . . 1,7
kedjerost	1,35 . . . 1,55
Brunkol:	
mekanisk eldning	1,3 . . . 1,4
Antracit och koks	1,4 . . . 1,5
Kolpulver	1,2 . . . 1,3
Cykloneldstad	1,1 . . . 1,2
Fluidiserad bädd	1,2 . . . 1,35
Olja	1,05 . . . 1,1
Gas	1,05 . . . 1,1
Trä	1,25–1,4
Svart lut, sulfitlut	1,2–1,3
Sopor	1,5–1,6

FUELS** (in English)**:

Bituminous coal

Brown coal (Lignite)

Anthracite and coke
Pulverized coal
Cyclone furnace
Fluidized bed
oil
gas
wood
black liquor
municipal waste

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Implications of large air excess factors

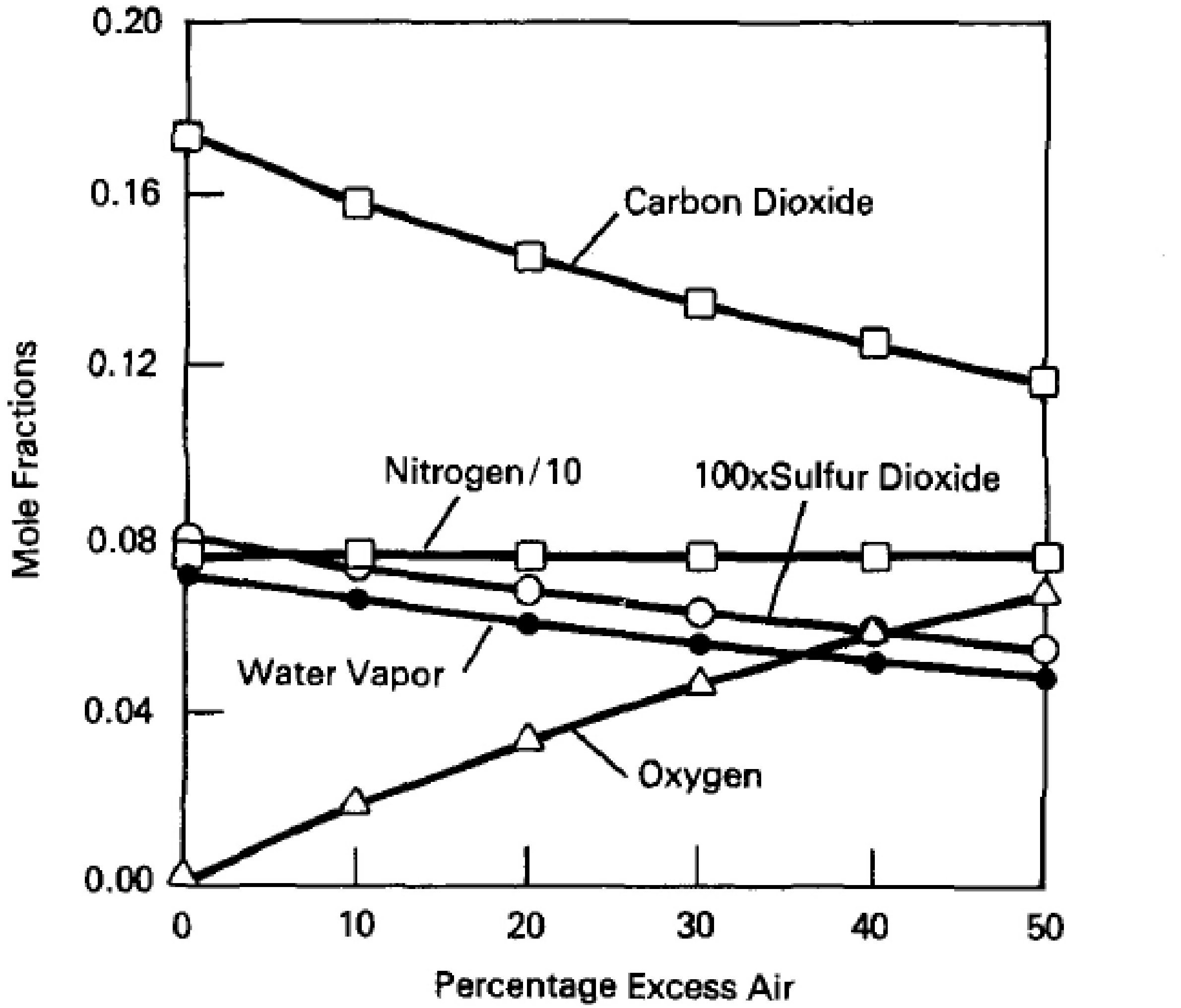

FIGURE 3.5 Wet flue gas composition for Kanawha, W. Va., raw coal.

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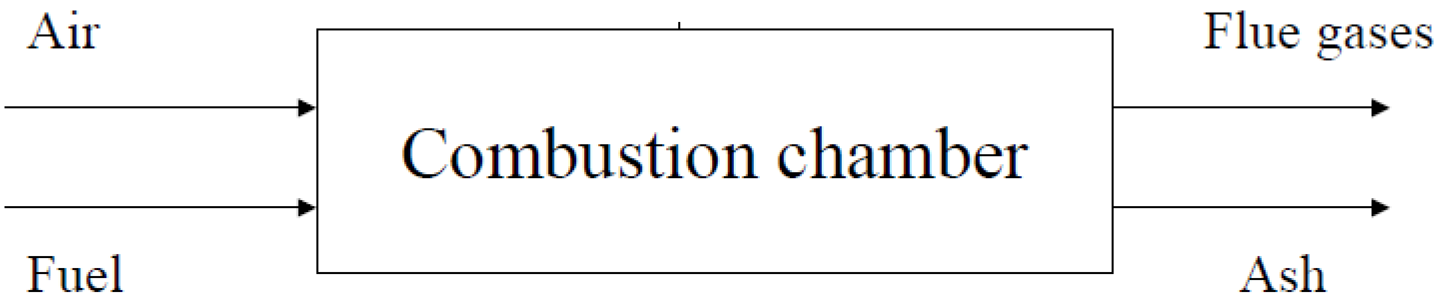
Adiabatic temperature of combustion

Adiabatic combustion –
all heat remains in the combustor *–*
a perfectly isolated combustion chamber



- Any excess air factor away from unity (far from stoichiometry) would decrease the adiabatic temperature

Emissions

Environmentally harmful or unhealthy and undesired substances.
Typical emissions from the combustion process include:

- **Soot** (unburned carbon particles)
- **Dust** (flyash)
- **CO** (carbon monoxide)
- **SOx** (sulfuric oxides, mainly SO_2 & SO_3)
- **NOx** (various oxides of nitrogen)
- **N_2O** (nitrous oxide = laughing gas)
- **Polyaromatic hydrocarbons (PAH) -** dioxins, furans, etc.
- **Heavy metals** (either in the flue gases or in the bottom ash)

and

- **CO_2** (from fossil fuels)

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