

Fuels

Introduction

Sufficient, reliable sources of energy are a necessity for industrialized nations. Useful forms of energy are often obtained from primary energy sources by suitable energy conversions. It is concerned with the transformation of energy from sources such as fossil and nuclear fuels and the Sun into heat and then to conveniently used forms such as electrical energy, rotational and propulsive energy, and heating and cooling. Combustion of various fuels is the most simple and common way how to get heat for following application.

Fuels can be generally classified as non-renewable and renewable. Over 85% of the energy used in the world is from non-renewable supplies. Most developed nations are dependent on non-renewable energy sources such as fossil fuels (coal, oil and nature gas) and nuclear power. These sources are called non-renewable because they cannot be renewed or regenerated quickly enough to keep pace with their use. Some sources of energy are renewable or potentially renewable. Examples of renewable energy sources are: solar, geothermal, hydroelectric, biomass, and wind. Renewable energy sources are more commonly by used in developing nations. By this criteria fuels can be classified to

- fossil – coal, oil shales, tar sands, crude oil, nature gas, shale gas
- renewable – biomass
- alternative – wastes, refuse derived fuels (RDF)

By state fuels can be divided to

- solid – coal, coke, briquettes, biomass, pellets, solid waste
- liquid – petrol, oil, bioalcohols, biodiesel, LPG, LNG
- gas - nature gas, biogas, syngas

Solid fuels

Composition: proximate analysis and ultimate analysis

Solid fuel is a natural composite material, not a single chemical compound, and its composition, being a solid substance, is measured by weight, and referred to either to **as-received** fuel (wet fuel), or on a **dry basis**, or on a **dry-ash-free basis**. Two types of fuel analysis are commonly used:

- Proximate analysis, specifying: combustible (fixed + volatile) + ash + water.
- Ultimate analysis, specifying percentage of C, H, O, N, and S in combustible.

The ultimate analysis is determined in a properly equipped laboratory by a skilled chemist, while proximate analysis can be determined with a simple apparatus.

Proximate analysis

The proximate analysis indicates the percentage by weight of fixed carbon, volatiles, ash, and moisture content in fuel. The amounts of fixed carbon and volatile combustible matter directly contribute to the heating value of fuel. Fixed carbon acts as a main heat generator during burning. High volatile matter content indicates easy ignition of fuel. The ash content is important in the design of the furnace grate, combustion volume, pollution control equipment and ash handling systems of a furnace.

Measurement of moisture

The determination of moisture content is carried out by placing a sample of fuel in an uncovered crucible, which is placed in the oven kept at 108 ± 2 °C along with the lid. Then the sample is cooled to room temperature and weighed again. The loss in weight represents moisture.

Measurement of volatile matter

A dry sample of crushed fuel is weighed, placed in a covered crucible, and heated in a furnace at 900 ± 15 °C. The sample is cooled and weighed. Loss of weight represents volatile matter. The remainder is coke (fixed carbon) and ash.

Measurement of carbon and ash

The cover from the crucible used in the last test is removed and the crucible is heated over the Bunsen burner until all the carbon is burned. The residue is weighed, which is the incombustible ash. The difference in weight

from the previous weighing is the fixed carbon. In actual practice Fixed Carbon or FC can be derived by subtracting from 100 the value of moisture, volatile matter and ash.

Ultimate analysis

In ultimate analysis, once water is eliminated and sulfur and ash measured aside, the percentage in carbon is measured from CO₂ content of complete burning the sample, the amount of hydrogen is computed as 1/9 of the weight of water produced in combustion, the amount of nitrogen (usually less than 1% in weight) is measured aside or neglected, and the amount of oxygen is computed by subtracting from the total.

The following equations describe above mentioned relationships

$$h^r + A^r + W^r = 1 \quad h^{daf} = \frac{h^r}{1 - A^r - W^r} = C^{daf} + H^{daf} + S^{daf} + N^{daf} + O^{daf} = 1$$

$$A^d = A^r \cdot \frac{1}{1 - W^r} \quad C^r = C^{daf} \cdot (1 - A^r - W^r)$$

$$H^r = H^{daf} \cdot (1 - A^r - W^r) \quad \text{etc.}$$

$$C^r + H^r + S^r + N^r + O^r + A^r + W^r = 1$$

where h is combustible, A is ash content, W is water content and index daf is dry-ash-free basis, d is dry basis and r is as-received (wet) fuel.

Heat of combustion

The heat of combustion is the energy released as heat when a fuel undergoes complete combustion with oxygen under standard conditions. The chemical reaction is typically a hydrocarbon reacting with oxygen to form carbon dioxide, water and heat. It may be expressed with the quantities:

- energy/mole of fuel (kJ/mol)
- energy/mass of fuel (kJ/kg)
- energy/volume of fuel (kJ/m³)

The heat of combustion is conventionally measured with a bomb calorimeter. It may also be calculated as the difference between the heat of formation of the products and reactants.

Higher heating value

The quantity known as higher heating value (HHV) (or gross energy or upper heating value or gross calorific value (GCV) or higher calorific value (HCV)) is determined by bringing all the products of combustion back to the original pre-combustion temperature, and in particular condensing any vapor produced. Such measurements often use a standard temperature of 20 (25)°C.

The higher heating value takes into account the latent heat of vaporization of water in the combustion products, and is useful in calculating heating values for fuels where condensation of the reaction products is practical (e.g., in a gas-fired boiler used for space heat). In other words, HHV assumes all the water component is in liquid state at the end of combustion (in product of combustion) and that heat above 150°C can be put to use.

Lower heating value

The quantity known as lower heating value (LHV) (net calorific value (NCV) or lower calorific value (LCV)) is determined by subtracting the heat of vaporization of the water vapor from the higher heating value. This treats any H₂O formed as a vapor. The energy required to vaporize the water therefore is not released as heat.

LHV calculations assume that the water component of a combustion process is in vapor state at the end of combustion, as opposed to the higher heating value (HHV) which assumes that all of the water in a combustion process is in a liquid state after a combustion process.

The LHV assumes that the latent heat of vaporization of water in the fuel and the reaction products is not recovered. It is useful in comparing fuels where condensation of the combustion products is impractical, or heat at a temperature below 150°C cannot be put to use.

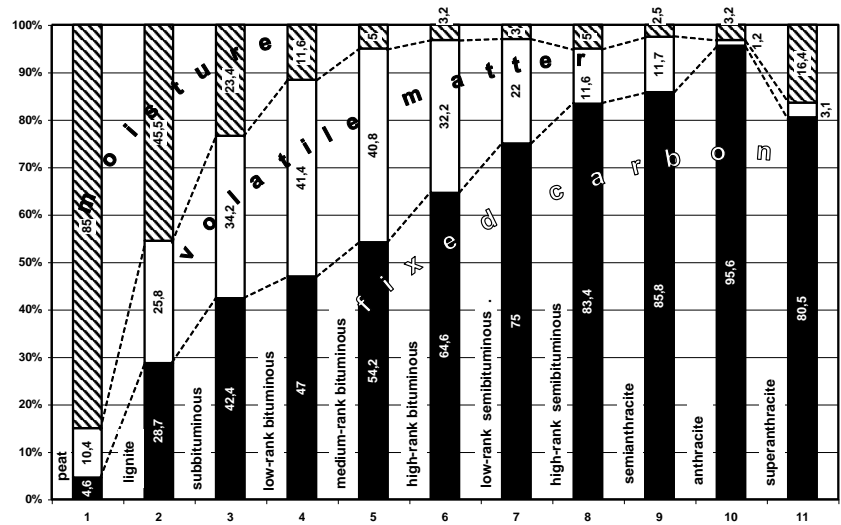
Relationship between above defined heating values is

$$LHV^r = HHV^r - 2453 \cdot (W^r + 8,94 \cdot H^r) \quad [kJ/kg]$$

Coal

Coal is the most abundant fossil fuel in the world with an estimated reserve of one trillion metric tons. Most of the world's coal reserves exist in Eastern Europe and Asia, but the United States also has considerable reserves. Coal formed slowly over millions of years from the buried remains of ancient swamp plants. During the formation of coal, carbonaceous matter was first compressed into a spongy material called "peat", which is about 90% water. As the peat became more deeply buried, the increased pressure and temperature turned it into coal. Different types of coal resulted from differences in the pressure and temperature that prevailed during formation. The various coals can be classified according to intrinsic chemical and physical properties of coal itself due to variation in its origin, constitution, and degree of metamorphism. The various ranks of coals beginning with the youngest are peat, lignite, subbituminous, semibituminous, semi-anthracite, anthracite, and superanthracite. Different terminologies are used in different parts of the world. Subbituminous and bituminous coal is sometimes included to broad group of hard coals. Use of both lignite and brown coal for the same rank of coal is quite common.

The various ranks of coal depend upon how much volatile, moisture and oxygen was excluded from lignite during the process of metamorphism. The distinguishing characteristics of various grades of coal on an ash-free basis are shown in figure. The chart shows how the moisture content varies from a maximum with peat, to a relatively small percentage with anthracite. Volatile matter has maximum with low-rank bituminous coal. The percentage of fixed carbon increases steadily from peat to anthracite by grade of metamorphism and accounts principally for the increase in heating value.



In general, coals with high moisture and low heating value are classified to low-rank coal. Lignites together with some of the lower-rank subbituminous coals are included in this common group. Lignites are brown in color and frequently show distinct woody structure. New-mined lignites have usually high moisture content and upon exposure disintegrate rapidly. They burn with a long yellow flame which has less tendency to smoke than has that from bituminous coal. Lignites can be pulverized and burned when the moisture is reduced to about 28 per cent or lower. Subbituminous coals are black with shiny surfaces and laminar structure. They do not coke but burn freely with a decided tendency to crumble in the fire. They are comparatively soft and pulverize easily, burning with a long yellow flame.

In general, coals with high moisture and low heating value are classified to low-rank coal. Upgrading brings a number of effects reducing most of problems concerning low-rank coal utilization. Washing results in reductions in the amounts of mineral matter present including a proportion of trace elements and part of sulphur, although there may be a small increase in moisture content. Drying reduces the moisture content, and hence increases the heating value. Briquetting improves the combustion characteristics and facilitate the inclusion of additives which will capture the sulphur present. All the processes contribute to the increase in heating value of the coal and improve the fuel consistency resulting in more efficient and controllable combustion.

Variation of selected coal properties with coal rank are as follows:

Rank:	Lignite	Subbituminous	Bituminous	Anthracite
Age:	----- increases ----->			
% Carbon:	65-72	72-76	76-90	90-95
% Hydrogen:	~5	----- decreases -----		~2
% Nitrogen:	<-----		~1-2	----->
% Oxygen:	~30	----- decreases -----		~1
% Sulfur:	~0	----- increases -----	~4	----- decreases ----->
% Water:	70-30	30-10	10-5	~5
LHV (kJ/kg):	~10000	~16000	24000-32000	~34000

Biomass

Here, biomass is synonymous of vegetable matter used as fuel (biofuel), either grown for that purpose, or recovered from other industries waste (forestry, farming, food industry...); urban and animal waste might be included too, but its importance is marginal. Municipal solid waste (MSW) has great organic content and can be used as a fuel in incineration power plants as well. It excludes organic material which has been transformed by geological processes into coal, petroleum, or natural gas (fossil fuels).

Biomass is a renewable fuel, and, to a first approximation, carbon neutral, in the sense that the CO₂ released in biofuel combustion was previously captured from the environment during biomass growth. The traditional biomass through the ages has been wood. Recently residues from timber production, saw mills, agriculture and food industry are utilized. Biomass has high content of volatiles and very variable water content which significantly influences LHV.

%wt water	0	20	40	60
C	50.30	40.24	30.18	20
H	6.20	4.96	3.72	2.7
O	43.08	34.46	25.85	17
N	0.04	0.03	0.02	0.01
S	0.00	0.00	0.00	0.00
ash	0.37	0.31	0.23	0.15
Total	100	100	100	100
LHV kJ/kg	19900	15400	10950	6500

Liquid fuels

Liquid fuels like furnace oil and LSHS are predominantly used in industrial application. The various properties of liquid fuels are given below.

Density

This is defined as the ratio of the mass of the fuel to the volume of the fuel at a reference temperature of 15°C. Density is measured by an instrument called hydrometer. The knowledge of density is useful for quantity calculations and assessing ignition quality. The unit of density is kg/m³.

Specific gravity

This is defined as the ratio of the weight of a given volume of oil to the weight of the same volume of water at a given temperature. The density of fuel, relative to water, is called specific gravity. The specific gravity of water is defined as 1. Since specific gravity is a ratio, it has no units. The measurement of specific gravity is generally made by a hydrometer. Specific gravity is used in calculations involving weights and volumes.

Viscosity

The viscosity of a fluid is a measure of its internal resistance to flow. Viscosity depends on temperature and decreases as the temperature increases. Any numerical value for viscosity has no meaning unless the temperature is also specified. Viscosity is measured in Stokes / Centistokes (mm²/s). Each type of oil has its own temperature - viscosity relationship. The measurement of viscosity is made with an instrument called Viscometer.

Viscosity is the most important characteristic in the storage and use of fuel oil. It influences the degree of preheat required for handling, storage and satisfactory atomization. If the oil is too viscous, it may become difficult to pump, hard to light the burner, and tough to operate. Poor atomization may result in the formation of carbon deposits on the burner tips or on the walls. Therefore pre-heating is necessary for proper atomization.

Flash Point

The flash point of a fuel is the lowest temperature at which the fuel can be heated so that the vapour gives off flashes momentarily when an open flame is passed over it. Flash point for furnace oil is 66 °C.

Pour Point

The pour point of a fuel is the lowest temperature at which it will pour or flow when cooled under prescribed conditions. It is a very rough indication of the lowest temperature at which fuel oil is readily pumpable

Specific Heat

Specific heat is the amount of kJ needed to raise the temperature of 1 kg of oil by 1 K. The unit of specific heat is kJ/kgK. The specific heat determines how much steam or electrical energy it takes to heat oil to a desired temperature. Light oils have a low specific heat, whereas heavier oils have a higher specific heat.

Calorific Value

The definition is the same like for solid fuels.

Sulphur

The amount of sulphur in the fuel oil depends mainly on the source of the crude oil and to a lesser extent on the refining process. The normal sulfur content for the residual fuel oil (furnace oil) is in the order of 2-4 %.

Ash Content

The ash value is related to the inorganic material in the fuel oil. The ash levels of distillate fuels are negligible. Residual fuels have more of the ash-forming constituents. These salts may be compounds of sodium, vanadium, calcium, magnesium, silicon, iron, aluminum, nickel, etc. Typically, the ash value is in the range 0.03-0.07 %. Excessive ash in liquid fuels can cause fouling deposits in the combustion equipment. Ash has erosive effect on the burner tips, causes damage to the refractories at high temperatures and gives rise to high temperature corrosion and fouling of equipments.

Carbon Residue

Carbon residue indicates the tendency of oil to deposit a carbonaceous solid residue on a hot surface, such as a burner or injection nozzle, when its vaporisable constituents evaporate. Residual oil contains carbon residue ranging from 1 percent or more.

Water Content

Water content of furnace oil when supplied is normally very low as the product at refinery site is handled hot and maximum limit of 1% is specified in the standard. Water may be present in free or emulsified form and can cause damage to the inside furnace surfaces during combustion especially if it contains dissolved salts. It can also cause spluttering of the flame at the burner tip, possibly extinguishing the flame and reducing the flame temperature or lengthening the flame.

Fueloil

There are two basic types of fueloil:

- Distillate fueloil - L.D.O. (lighter, thinner, better for cold-start)
- Residual fueloil - LS.H.S. (Low Sulphur Heavy Stock) (heavier, thicker, more powerful, better lubrication).

Typical specification of fuel oil is summarized in the table.

Properties	Fuel Oils		
	Furnace Oil	LS.H.S.	L.D.O.
Density (Approx. g/cc at 15 °C)	0.89-0.95	0.88-0.98	0.85-0.87
Flash Point (°C)	66	93	66
Pour Point (°C)	20	72	18
HHV (MJ/kg)	44.0	44.4	44.8
Sediment, % Wt. Max.	0.25	0.25	0.1
Sulphur Total, % Wt. Max.	Upto 4.0	Upto 0.5	Upto 1.8
Water Content, % Vol. Max.	1.0	1.0	0.25
Ash % Wt. Max.	0.1	0.1	0.02

Heavy fueloil

Heavy fueloil (HFO) is the residue of crude oil distillation that still flows (the quasi-solid residue is asphalt); waste oil from other industries are often added. It is the fuel used in large marine vessels because of price (about half the price of distillates). A typical HFO is IF-300 (Intermediate Fuel), which has a viscosity of $300 \cdot 10^{-6} \text{ m}^2/\text{s}$ at 50 °C (300 cSt), $25 \cdot 10^{-6} \text{ m}^2/\text{s}$ at 100 °C, density is 990 kg/m³ at 15 °C, HHV=43 MJ/kg, and the flash-point at 60..80 °C.

HFO (also named Bunker-C, or Residual fuel) may have a composition of 88% wt C, 10% wt H, 1% wt S, 0.5% wt H₂O, 0.1% wt ash, and may contain dispersed solid or semi-solid particles (asphaltenes, minerals and other leftovers from the oil source, metallic particles from the refinery equipment, and some dumped chemical wastes), plus some 0.5% water. HFO leaves a carbonaceous residue in the tanks, and may have up to 5% of Sulfur.

Gaseous fuels

Gaseous fuels in common use are Natural gas, producer gas, blast furnace gas, coke oven gas etc. The calorific

value of gaseous fuel is expressed in kJ per normal cubic meter (kJ/Nm³) i.e. at normal temperature (0 °C) and pressure (760 mm Hg = 101,325 kPa). Composition of gaseous fuel is specified by volume % of included gases.

Calorific Value

Since some gas combustion appliances can utilize the heat content of the water vapor, higher heating value is often used. This is especially true for natural gas, since increased hydrogen content results in high water formation during combustion.

Typical physical and chemical properties of various gaseous fuels are given in the table

Fuel Gas	Relative Density	Higher Heating Value MJ/Nm ³	Flame Temp. °C	Flame Speed m/s
Natural Gas	0.6	39.1	1954	0.290
Propane	1.52	93.0	1967	0.460
Butane	1.96	119.3	1973	0.870

Natural Gas

Methane is the main constituent of Natural gas and accounting for about 95% of the total volume. Other components are: Ethane, Propane, Butane, Pentane, Nitrogen, Carbon Dioxide, and traces of other gases. Very small amounts of sulphur compounds are also present. Since methane is the largest component of natural gas, generally properties of methane are used when comparing the properties of natural gas to other fuels.

Natural gas is a high calorific value fuel requiring no storage facilities. It mixes with air readily and does not produce smoke or soot. It has no sulphur content. It is lighter than air and disperses into air easily in case of leak.

Example of nature gas composition is:

CH ₄	0,981695
C ₂ H ₆	0,005910
C ₃ H ₈	0,002020
C ₄ H ₁₀	0,000791
C ₅ H ₁₂	0,000212
C ₆ H ₁₄	0,000172
CO ₂	0,000910
N ₂	0,008290
LHV	36 409 kJ/Nm ³