

FUELS & COMBUSTION

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1. INTRODUCTION

This section briefly describes the main features of fuels.

Energy from the Sun is converted into chemical energy by photosynthesis. But, as we know, when we burn dried plants or wood, producing energy in the form of heat and light, we are releasing the Sun's energy originally stored in that plant or in that wood through photosynthesis. We know that, in most of the world today, wood is not the main source of fuel. We generally use natural gas or oil in our homes, and we use mainly oil and coal to heat the water to produce the steam to drive the turbines for our huge power generation systems. These fuels - coal, oil, and natural gas - are often referred to as fossil fuels.

The various types of fuels (like liquid, solid and gaseous fuels) that are available depend on various factors such as costs, availability, storage, handling, pollution and landed boilers, furnaces and other combustion equipments.

The knowledge of the fuel properties helps in selecting the right fuel for the right purpose and for the efficient use of the fuel. Laboratory tests are generally used for assessing the nature and quality of fuels.

2 TYPE OF FUELS

This section describes types of fuels: solid, liquid, and gaseous.

2.1 Liquid Fuels

Liquid fuels like furnace oil and LSHS (low sulphur heavy stock) are predominantly used in industrial applications. The various properties of liquid fuels are given below.

2.1.1 Density

Density 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 a hydrometer. The knowledge of density is useful for quantitative calculations and assessing ignition qualities. The unit of density is kg/m³.

2.1.2 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. The specific gravity of various fuel oils are given in Table below:

Table 1. Specific gravity of various fuel oils (adapted from Thermax India Ltd.)

Fuel Oil	L.D.O (Light Diesel Oil)	Furnace oil	L.S.H.S (Low Sulphur Heavy Stock)
Specific Gravity	0.85 - 0.87	0.89 - 0.95	0.88 - 0.98

2.1.3 Viscosity

The viscosity of a fluid is a measure of its internal resistance to flow. Viscosity depends on the 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. Sometimes viscosity is also quoted in Engler, Saybolt or Redwood. Each type of oil has its own temperature - viscosity relationship. The measurement of viscosity is made with an instrument called a Viscometer.

Viscosity is the most important characteristic in the storage and use of fuel oil. It influences the degree of pre-heating 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 difficult to handle. 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.

2.1.4 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. The flash point for furnace oil is 66 °C.

2.1.5 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 ready to be pumped.

2.1.6 Specific Heat

Specific heat is the amount of kCals needed to raise the temperature of 1 kg of oil by 1°C. The unit of specific heat is kcal/kg°C. It varies from 0.22 to 0.28 depending on the oil specific gravity. 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.

2.1.7 Calorific Value

The calorific value is the measurement of heat or energy produced, and is measured either as gross calorific value or net calorific value. The difference is determined by the latent heat of condensation of the water vapour produced during the combustion process. Gross calorific value (GCV) assumes all vapour produced during the combustion process is fully condensed. Net calorific value (NCV) assumes the water leaves with the combustion products without fully being condensed. Fuels should be compared based on the net calorific value.

The calorific value of coal varies considerably depending on the ash, moisture content and the type of coal while calorific value of fuel oils are much more consistent. The typical GCVs of some of the commonly used liquid fuels are given below:

Table 2. Gross calorific values for different fuel oils (adapted from Thermax India Ltd.)

<u>Fuel Oil</u>	<u>Gross Calorific Value (kCal/kg)</u>
Kerosene	- 11,100
Diesel Oil	- 10,800
L.D.O	- 10,700
Furnace Oil	- 10,500
LSHS	- 10,600

2.1.8 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 %. Typical figures for different fuel oils are shown in Table 3.

Table 3. Percentages of sulphur for different fuel oils (adapted from Thermax India Ltd.)

<u>Fuel oil</u>	<u>Percentage of Sulphur</u>
Kerosene	0.05 - 0.2
Diesel Oil	0.05 - 0.25
L.D.O	0.5 - 1.8
Furnace Oil	2.0 - 4.0
LSHS	< 0.5

The main disadvantage of sulphur is the risk of corrosion by sulphuric acid formed during and after combustion, and condensation in cool parts of the chimney or stack, air pre-heater and economizer.

2.1.9 Ash Content

The ash value is related to the inorganic material or salts in the fuel oil. The ash levels in distillate fuels are negligible. Residual fuels have higher ash levels. 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 an 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.

2.1.10 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 vaporizable constituents evaporate. Residual oil contains carbon residue of 1 percent or more.

2.1.11 Water Content

The water content of furnace oil when it is supplied is normally very low because the product at refinery site is handled hot. An upper limit of 1% is specified as a standard.

Water may be present in free or emulsified form and can cause damage to the inside surfaces of the furnace during combustion especially if it contains dissolved salts. It can also cause spluttering of the flame at the burner tip, possibly extinguishing the flame, reducing the flame temperature or lengthening the flame.

Typical specifications of fuel oils are summarized in the Table below.

Table 4. Typical specifications of fuel oils (adapted from Thermax India Ltd.)

Properties	Fuel Oils		
	Furnace Oil	L.S.H.S	L.D.O
Density (Approx. g/cc at 150C)	0.89 - 0.95	0.88 - 0.98	0.85 - 0.87
Flash Point (0C)	66	93	66
Pour Point (0C)	20	72	18
G.C.V. (kCal/kg)	10500	10600	10700
Sediment, % Wt. Max.	0.25	0.25	0.1
Sulphur Total, % Wt. Max.	Up to 4.0	Up to 0.5	Up to 1.8
Water Content, % Vol. Max.	1.0	1.0	0.25
Ash % Wt. Max.	0.1	0.1	0.02

2.1.12 Storage of Fuel oil

It can be potentially hazardous to store furnace oil in barrels. A better practice is to store it in cylindrical tanks, either above or below the ground. Furnace oil that is delivered may contain dust, water and other contaminants.

The sizing of the storage tank facility is very important. A recommended storage size estimate is to provide for at least 10 days of normal consumption. Industrial heating fuel storage tanks are generally vertical mild steel tanks mounted above the ground. It is prudent for safety and environmental reasons to build bund walls around tanks to contain accidental spillages.

As a certain amount of settlement of solids and sludge will occur in tanks over time, tanks should be cleaned at regular intervals: annually for heavy fuels and every two years for light fuels. Care should be taken when oil is decanted from the tanker to the storage tank. All leaks from joints, flanges and pipelines must be attended to at the earliest. Fuel oil should be free from possible contaminants such as dirt, sludge and water before it is fed to the combustion system.

2.2 Solid Fuel (Coal)

2.2.1 Coal classification

Coal is classified into three major types namely anthracite, bituminous, and lignite. However, there is no clear demarcation between them. Coal is further classified as semi-anthracite, semi-bituminous, and sub-bituminous. Anthracite is the oldest coal from a geological perspective. It is a hard coal composed mainly of carbon with little volatile content and practically no moisture. Lignite is the youngest coal from a geological perspective. It is a soft coal composed mainly of volatile matter and moisture content with low fixed carbon. Fixed carbon refers to carbon in its free state, not combined with other elements. Volatile matter refers to those combustible constituents of coal that vaporize when coal is heated.

The common coals used in for example Indian industry are bituminous and sub-bituminous coal. The gradation of Indian coal based on its calorific value is as follows:

Grade	Calorific Value Range (in kCal/kg)
A	Exceeding 6200
B	5600 – 6200
C	4940 – 5600
D	4200 – 4940
E	3360 – 4200
F	2400 – 3360
G	1300 – 2400

Normally D, E and F coal grades are available to Indian industry.

The chemical composition of coal has a strong influence on its combustibility. The properties of coal are broadly classified as physical properties and chemical properties.

2.2.2 Physical and chemical properties of coal

Physical properties of coal include the heating value, moisture content, volatile matter and ash.

The chemical properties of coal refer to the various elemental chemical constituents such as carbon, hydrogen, oxygen, and sulphur.

The heating value of coal varies from coal field to coal field. The typical GCVs for various coals are given in the Table below.

Table 5. GCV for various coal types

Parameter	Lignite (Dry Basis)	Indian Coal	Indonesian Coal	South African Coal
GCV (kCal/kg)	4,500*	4,000	5,500	6,000

*GCV of lignite on 'as received basis' is 2500 –3000

2.2.3 Analysis of coal

There are two methods to analyze coal: ultimate analysis and proximate analysis. The ultimate analysis determines all coal component elements, solid or gaseous and the proximate analysis determines only the fixed carbon, volatile matter, moisture and ash percentages. The ultimate analysis is determined in a properly equipped laboratory by a skilled chemist, while proximate analysis can be determined with a simple apparatus. (It may be noted that proximate has no connection with the word “approximate”).

Measurement of moisture

The determination of moisture content is carried out by placing a sample of powdered raw coal of size 200-micron size 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 fresh sample of crushed coal 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 moisture and volatile matter. The remainder is coke (fixed carbon and ash). For detailed methodologies (including for determination of carbon and ash content), refer to IS 1350 part I: 1984, part III, IV.

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 derived by subtracting from 100 the value of moisture, volatile matter and ash.

Proximate analysis

The proximate analysis indicates the percentage by weight of fixed carbon, volatiles, ash, and moisture content in coal. The amounts of fixed carbon and volatile combustible matter directly contribute to the heating value of coal. 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. A typical proximate analysis of various coal types is given in Table 6.

Table 6. Typical proximate analysis of various coals (percentage)

Parameter	Indian Coal	Indonesian Coal	South African Coal
Moisture	5.98	9.43	8.5
Ash	38.63	13.99	17
Volatile matter	20.70	29.79	23.28
Fixed Carbon	34.69	46.79	51.22

These parameters are described below.

Fixed carbon:

Fixed carbon is the solid fuel left in the furnace after volatile matter is distilled off. It consists mostly of carbon but also contains some hydrogen, oxygen, sulphur and nitrogen not driven off with the gases. Fixed carbon gives a rough estimate of the heating value of coal.

Volatile matter:

Volatile matters are the methane, hydrocarbons, hydrogen and carbon monoxide, and incombustible gases like carbon dioxide and nitrogen found in coal. Thus the volatile matter is an index of the gaseous fuels present. A typical range of volatile matter is 20 to 35%.

Volatile matter:

- Proportionately increases flame length, and helps in easier ignition of coal
- Sets minimum limit on the furnace height and volume
- Influences secondary air requirement and distribution aspects
- Influences secondary oil support

Ash content:

Ash is an impurity that will not burn. Typical range is 5% to 40%. Ash

- Reduces handling and burning capacity
- Increases handling costs
- Affects combustion efficiency and boiler efficiency
- Causes clinkering and slagging

Moisture content:

Moisture in coal must be transported, handled and stored. Since it replaces combustible matter, it decreases the heat content per kg of coal. Typical range is 0.5 to 10%. Moisture:

- Increases heat loss, due to evaporation and superheating of vapour
- Helps to a certain extent with binding fines
- Aids radiation heat transfer

Sulphur content:

Typical range is 0.5 to 0.8% normally. Sulphur:

- Affects clinkering and slagging tendencies
- Corrodes chimney and other equipment such as air heaters and economizers
- Limits exit flue gas temperature

Ultimate analysis

The ultimate analysis indicates the various elemental chemical constituents such as carbon, hydrogen, oxygen, sulphur, etc. It is useful in determining the quantity of air required for combustion and the volume and composition of the combustion gases. This information is required for the calculation of flame temperature and the flue duct design etc. Typical ultimate analyses of various coals are given in the table below.

Table 7. Typical ultimate analysis of coals

Parameter	Indian Coal, %	Indonesian Coal, %
Moisture	5.98	9.43
Mineral Matter (1.1 x Ash)	38.63	13.99
Carbon	41.11	58.96
Hydrogen	2.76	4.16
Nitrogen	1.22	1.02
Sulphur	0.41	0.56
Oxygen	9.89	11.88

Table 8. Relationship between ultimate analysis and proximate analysis

%C	=	$0.97C + 0.7(VM - 0.1A) - M(0.6 - 0.01M)$
%H	=	$0.036C + 0.086(VM - 0.1xA) - 0.0035M^2(1 - 0.02M)$
%N ₂	=	$2.10 - 0.020 VM$
Where		
C	=	% of fixed carbon
A	=	% of ash
VM	=	% of volatile matter
M	=	% of moisture

Note: the above equation is valid for coal with a greater than 15% moisture content

2.2.4 Storage, handling and preparation of coal

Uncertainty in the availability and transportation of fuel necessitates storage and subsequent handling. Storing coal has its own disadvantages like build-up of inventory, space constraints, deterioration in quality and potential fire hazards. Other minor losses associated with the storage of coal include oxidation, wind and carpet loss. A 1% oxidation of coal has the same effect as 1% ash in coal. Wind losses may account for nearly 0.5 – 1.0 % of the total loss.

The main goal of good coal storage is to minimize carpet loss and the loss due to spontaneous combustion. Formation of a soft carpet, comprising of coal dust and soil, causes carpet loss. On the other hand, if the temperature gradually rises in a coal heap, then oxidation may lead to spontaneous combustion of coal stored. Carpet losses can be reduced by:

1. Preparing a hard solid surface for coal to be stored
2. Preparing standard storage bays of concrete and brick

In industry, coal handling methods range from manual and conveyor systems. It would be advisable to minimize the handling of coal so that further generation of fines and segregation effects are reduced.

The preparation of coal prior to feeding into the boiler is an important step for achieving good combustion. Large and irregular lumps of coal may cause the following problems:

- Poor combustion conditions and inadequate furnace temperature
- Higher excess air resulting in higher stack loss
- Increase of unburnts in the ash
- Low thermal efficiency

Note: A detailed description for the preparation of coal is given under the section “Energy Efficiency Opportunities”.

2.3 Gaseous Fuel

Gas fuels are the most convenient because they require the least amount of handling and are used in the simplest and most maintenance-free burner systems. Gas is delivered "on tap" via a distribution network and so is suited for areas with a high population or industrial density. However, large individual consumers do have gasholders and some produce their own gas.

2.3.1 Types of gaseous fuel

The following is a list of the types of gaseous fuel:

- Fuels naturally found in nature:
 - Natural gas
 - Methane from coal mines
- Fuel gases made from solid fuel
 - Gases derived from coal
 - Gases derived from waste and biomass
 - From other industrial processes (blast furnace gas)
- Gases made from petroleum
 - Liquefied Petroleum gas (LPG)
 - Refinery gases
 - Gases from oil gasification
- Gases from some fermentation process

Gaseous fuels in common use are liquefied petroleum gases (LPG), Natural gas, producer gas, blast furnace gas, coke oven gas etc. The calorific value of gaseous fuel is expressed in Kilocalories per normal cubic meter (kCal/Nm³) i.e. at normal temperature (20 °C) and pressure (760 mm Hg).

2.3.2 Properties of gaseous fuels

Since most gas combustion appliances cannot utilize the heat content of the water vapour, gross calorific value is of little interest. Fuel should be compared based on the net calorific value. 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 Table 9.

Table 9. Typical physical and chemical properties of various gaseous fuels

Fuel Gas	Relative Density	Higher Heating Value kcal/Nm ³	Air/Fuel ratio- m ³ of air to m ³ of Fuel	Flame Temp. ° C	Flame Speed m/s
Natural Gas	0.6	9350	10	1954	0.290
Propane	1.52	22200	25	1967	0.460
Butane	1.96	28500	32	1973	0.870

2.3.3 LPG

LPG is a predominant mixture of propane and Butane with a small percentage of unsaturates (Propylene and Butylene) and some lighter C₂ as well as heavier C₅ fractions. Included in the LPG range are propane (C₃H₈), Propylene(C₃H₆), normal and iso-butane (C₄H₁₀) and Butylene(C₄H₈). LPG may be defined as those hydrocarbons, which are gaseous at normal atmospheric pressure, but may be condensed to the liquid state at normal temperature, by the application of moderate pressures. Although they are normally used as gases, they are stored and transported as liquids under pressure for convenience and ease of handling. Liquid LPG evaporates to produce about 250 times volume of gas.

LPG vapour is denser than air: butane is about twice as heavy as air and propane about one and a half times as heavy as air. Consequently, the vapour may flow along the ground and into drains sinking to the lowest level of the surroundings and be ignited at a considerable distance from the source of leakage. In still air vapour will disperse slowly. Escape of even small quantities of the liquefied gas can give rise to large volumes of vapour / air mixture and thus cause considerable hazard. To aid in the detection of atmospheric leaks, all LPG's are required to be odorized. There should be adequate ground level ventilation where LPG is stored. For this very reason LPG cylinders should not be stored in cellars or basements, which have no ventilation at ground level.

2.3.4 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 contains no sulphur. It is lighter than air and disperses into air easily in case of leak. A typical comparison of carbon contents in oil, coal and gas is given in the table below.

Table 10. Comparison of chemical composition of various fuels

	Fuel Oil	Coal	Natural Gas
Carbon	84	41.11	74
Hydrogen	12	2.76	25
Sulphur	3	0.41	-
Oxygen	1	9.89	Trace
Nitrogen	Trace	1.22	0.75
Ash	Trace	38.63	-
Water	Trace	5.98	-

3. PERFORMANCE EVALUATION OF FUELS

This section explains the principles of combustion, how fuel performance can be evaluated using the stoichiometric calculation of air requirement, the concept of excess air, and the draft system of exhaust gases.

3.1 Principles of Combustion

3.1.1 Combustion process

Combustion refers to the rapid oxidation of fuel accompanied by the production of heat, or heat and light. Complete combustion of a fuel is possible only in the presence of an adequate supply of oxygen.

Oxygen (O₂) is one of the most common elements on earth making up 20.9% of our air. Rapid fuel oxidation results in large amounts of heat. Solid or liquid fuels must be changed to a gas before they will burn. Usually heat is required to change liquids or solids into gases. Fuel gases will burn in their normal state if enough air is present.

Most of the 79% of air (that is not oxygen) is nitrogen, with traces of other elements. Nitrogen is considered to be a temperature reducing diluter that must be present to obtain the oxygen required for combustion.

Nitrogen reduces combustion efficiency by absorbing heat from the combustion of fuels and diluting the flue gases. This reduces the heat available for transfer through the heat exchange surfaces. It also increases the volume of combustion by-products, which then have to travel through the heat exchanger and up the stack faster to allow the introduction of additional fuel-air mixture.

This nitrogen also can combine with oxygen (particularly at high flame temperatures) to produce oxides of nitrogen (NO_x), which are toxic pollutants. Carbon, hydrogen and sulphur in the fuel combine with oxygen in the air to form carbon dioxide, water vapour and sulphur dioxide, releasing 8,084 kcals, 28,922 kcals and 2,224 kcals of heat respectively. Under certain conditions, carbon may also combine with oxygen to form carbon monoxide, which results in the release of a smaller quantity of heat (2,430 kcals/kg of carbon). Carbon burned to CO₂ will produce more heat per unit of fuel than when CO or smoke are produced.

C	+ O ₂	→	CO ₂	+ 8,084 kcals/kg of Carbon
2C	+ O ₂	→	2 CO	+ 2,430 kcals/kg of Carbon
2H ₂	+ O ₂	→	2H ₂ O	+ 28,922 kcals/kg of Hydrogen
S	+ O ₂	→	SO ₂	+ 2,224 kcals/kg of Sulphur

Each kilogram of CO formed means a loss of 5654 kCal of heat (8084 – 2430).

3.1.2 Three T's of combustion

The objective of good combustion is to release all of the heat in the fuel. This is accomplished by controlling the "three T's" of combustion which are (1) Temperature high enough to ignite and maintain ignition of the fuel, (2) Turbulence or intimate mixing of the fuel and oxygen, and (3) Time, sufficient for complete combustion.

Commonly used fuels like natural gas and propane generally consist of carbon and hydrogen. Water vapor is a by-product of burning hydrogen. This removes heat from the flue gases, which would otherwise be available for more heat transfer.

Natural gas contains more hydrogen and less carbon per kg than fuel oils and as such produces more water vapor. Consequently, more heat will be carried away by exhaust while firing natural gas.

Too much, or too little fuel with the available combustion air may potentially result in unburned fuel and carbon monoxide generation. A very specific amount of O₂ is needed for perfect combustion and some additional (excess) air is required for ensuring complete combustion. However, too much excess air will result in heat and efficiency losses.

Not all of the fuel is converted to heat and absorbed by the steam generation equipment. Usually all of the hydrogen in the fuel is burned and most boiler fuels, allowable with today's air pollution standards, contain little or no sulfur. So the main challenge in combustion efficiency is directed toward unburned carbon (in the ash or incompletely burned gas), which forms CO instead of CO₂.

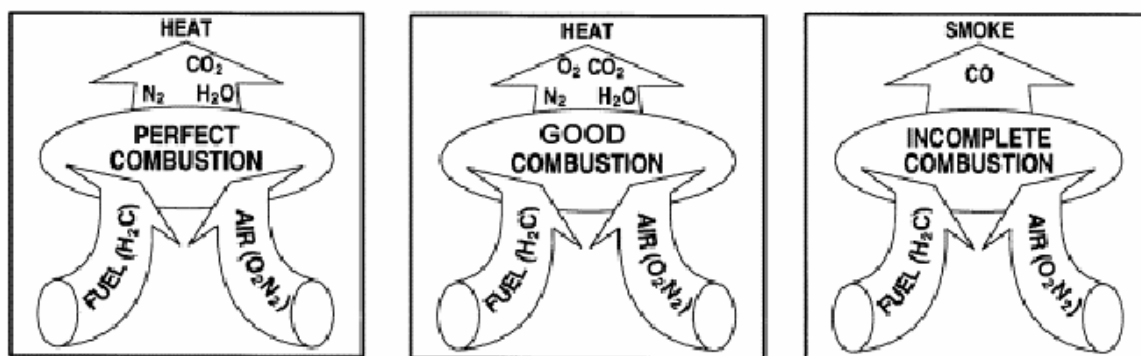


Figure 1. Perfect, good and incomplete combustion
(Bureau of Energy Efficiency, 2004)

3.2 Stoichiometric Calculation of Air Requirement

3.2.1 Calculation of stoichiometric air needed for combustion of furnace oil

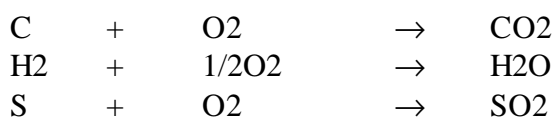
For combustion air is needed. The amount of air needed can be calculated using the method given below.

The first step is to determine the composition of the furnace oil. Typical specifications of furnace oil from lab analysis is given below:

Constituents	% By weight
Carbon	85.9
Hydrogen	12
Oxygen	0.7
Nitrogen	0.5
Sulphur	0.5
H ₂ O	0.35
Ash	0.05
GCV of fuel	10880 kcal/kg

If we take these analysis data, and considering a sample of 100 kg of furnace oil, then the chemical reactions are as follows:

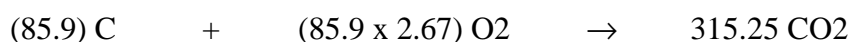
Element	Molecular Weight (kg / kg mole)
C	12
O ₂	32
H ₂	2
S	32
N ₂	28
CO ₂	44
SO ₂	64
H ₂ O	18



Constituents of fuel

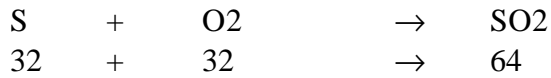
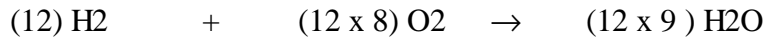


12 kg of carbon requires 32 kg of oxygen to form 44 kg of carbon dioxide therefore 1 kg of carbon requires 32/12 kg i.e 2.67 kg of oxygen

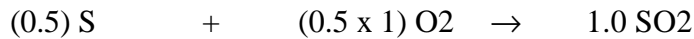


4 kg of hydrogen requires 32 kg of oxygen to form 36 kg of water, therefore 1 kg of hydrogen requires 32/4 kg i.e. 8 kg of oxygen.

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32 kg of sulphur requires 32 kg of oxygen to form 64 kg of sulphur dioxide, therefore 1 kg of sulphur requires 32/32 kg i.e. 1 kg of oxygen



$$\begin{array}{rcl} \text{Total oxygen required} & = & 325.57 \text{ kg} \\ (229.07+96+0.5) & & \end{array}$$

$$\begin{array}{rcl} \text{Oxygen already present in} & & \\ 100 \text{ kg fuel (given)} & = & 0.7 \text{ kg} \end{array}$$

$$\begin{array}{rcl} \text{Additional oxygen required} & = & 325.57 - 0.7 \\ & = & 324.87 \text{ kg} \end{array}$$

$$\begin{array}{rcl} \text{Therefore quantity of dry air needed} & = & (324.87) / 0.23 \\ (\text{air contains 23\% oxygen by weight}) & & \\ & = & 1412.45 \text{ kg of air} \end{array}$$

$$\begin{array}{rcl} \text{Theoretical air required} & = & (1412.45) / 100 \\ & = & 14.12 \text{ kg of air / kg of fuel} \end{array}$$

Therefore, in this example, for each kg of furnace oil burnt, 14.12 kg of air is required.

3.2.2 Calculation of theoretical CO₂ content in the flue gases

It is necessary to also calculate the CO₂ content in the flue gases, which then can be used to calculate the excess air in the flue gases. A certain amount of excess air is needed for complete combustion of furnace oils. However, too much excess air points to heat losses and too little excess air points to incomplete combustion. The CO₂ in flue gases can be calculated as follows:

$$\begin{array}{rcl} \text{Nitrogen in flue gas} & = & 1412.45 - 324.87 \\ & = & 1087.58 \text{ kg} \end{array}$$

Theoretical CO₂% in dry flue gas by volume is calculated as below:

$$\begin{array}{rclcl} \text{Moles of CO}_2 \text{ in flue gas} & = & (314.97) / 44 & = & 7.16 \\ \text{Moles of N}_2 \text{ in flue gas} & = & (1087.58) / 28 & = & 38.84 \\ \text{Moles of SO}_2 \text{ in flue gas} & = & 1/64 & = & 0.016 \end{array}$$

$$\begin{array}{rcl} \text{Theoretical CO}_2 \text{ \% by Volume} & = & (\text{Moles of CO}_2 \times 100) / \text{Total Moles (Dry)} \\ & = & (7.16 \times 100) / (7.16 + 38.84 + 0.016) \\ & = & 15.5\% \end{array}$$

3.2.3 Calculation of constituents of flue gas with excess air

Now we know the theoretical air requirements and the theoretical CO₂ content of flue gases. The next step is to measure the actual CO₂ percentage in the flue gases. In the calculation below it is assumed that the measured %CO₂ in the flue gas is 10%.

$$\begin{aligned} \text{\% Excess air} &= \frac{[(\text{Theoretical CO}_2\% / \text{Actual CO}_2) - 1] \times 100}{1} \\ &= \frac{[(15.5/10) - 1] \times 100}{1} \\ &= 55\% \end{aligned}$$

$$\begin{aligned} \text{Theoretical air required for 100kg of fuel burnt} &= 1412.45 \text{ kg} \\ \text{Total quantity of air supply required with 55\% excess air} &= 1412.45 \times 1.55 \\ &= 2189.30 \text{ kg} \end{aligned}$$

$$\begin{aligned} \text{Excess air quantity (actual - theoretical excess air)} &= 2189.30 - 1412.45 \\ &= 776.85 \\ \text{O}_2 \text{ (23\%)} &= 776.85 \times 0.23 \\ &= 178.68 \text{ kg} \\ \text{N}_2 \text{ (77\%)} &= 776.85 - 178.68 \\ &= 598.17 \text{ kg} \end{aligned}$$

The final constituents of flue gas with 55% excess air for every 100 kg fuel is as follows:

$$\begin{aligned} \text{CO}_2 &= 314.97 \text{ kg} \\ \text{H}_2\text{O} &= 108.00 \text{ kg} \\ \text{SO}_2 &= 1 \text{ kg} \\ \text{O}_2 &= 178.68 \text{ kg} \\ \text{N}_2 &= 1685.75 \text{ kg} (= 1087.58 \text{ in air} + 598.17 \text{ in excess air}) \end{aligned}$$

3.2.4 Calculation of theoretical CO₂% in dry flue gas by volume

Now that we have the constituents by weight, we can calculate the constituents on a volume basis as follows:

$$\begin{aligned} \text{Moles of CO}_2 \text{ in flue gas} &= 314.97 / 44 = 7.16 \\ \text{Moles of SO}_2 \text{ in flue gas} &= 1/64 = 0.016 \\ \text{Moles of O}_2 \text{ in flue gas} &= 178.68 / 32 = 5.58 \\ \text{Moles of N}_2 \text{ in flue gas} &= 1685.75 / 28 = 60.20 \end{aligned}$$

$$\begin{aligned} \text{Theoretical CO}_2\% \text{ by volume} &= (\text{Moles of CO}_2 \times 100) / \text{Total moles (dry)} \\ &= (7.16 \times 100) / (7.16 + 0.016 + 5.58 + 60.20) \\ &= 10\% \\ \text{Theoretical O}_2\% \text{ by volume} &= (5.58 \times 100) / 72.956 \\ &= 7.5\% \end{aligned}$$

3.3 Concept of Excess Air

For optimum combustion, the real amount of combustion air must be greater than that required theoretically. Part of the stack gas consists of pure air, i.e. air that is simply heated to stack gas temperature and leaves the boiler through the stack. Chemical analysis of the gases is an objective method that helps to achieve finer air control. By measuring CO₂ or O₂ in flue gases (by continuous recording instruments or Orsat apparatus or some cheaper portable instruments) the excess air level and stack losses can be estimated. The excess air to be supplied depends on the type of fuel and the firing system.

A faster way to calculate the excess air is by using the figures 2 and 3, provided the percentage of CO₂ or O₂ in the flue gases have been measured.

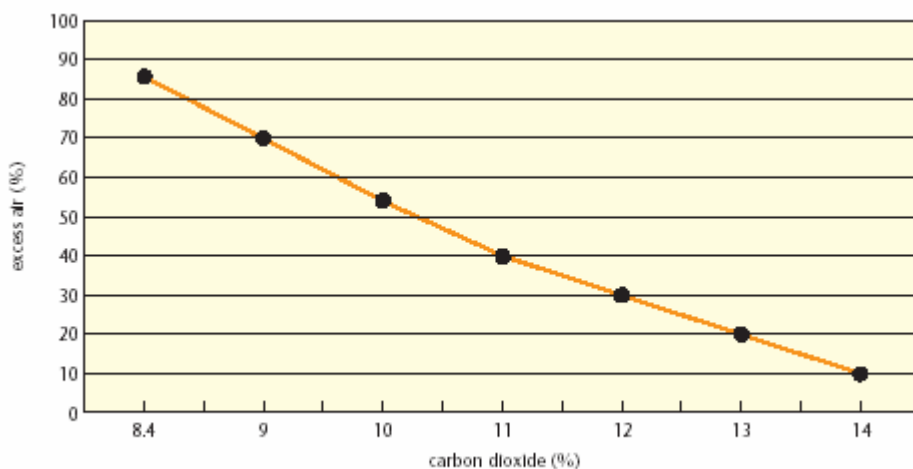


Figure 2. Relation between CO₂ & Excess Air
(Bureau of Energy Efficiency, 2004)

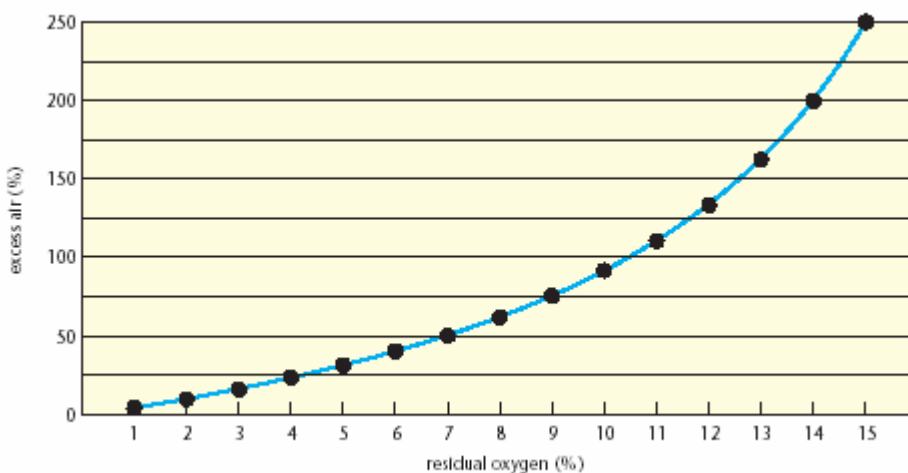


Figure 3. Relationship between residual oxygen and excess air
(Bureau of Energy Efficiency, 2004)

For optimum combustion of fuel oil the CO₂ or O₂ in flue gases should be maintained as follows:

CO ₂	=	14.5–15 %
O ₂	=	2–3 %

3.4 Draft System

The function of draft in a combustion system is to exhaust the products of combustion, i.e. flue gases, into the atmosphere. The draft can be classified into two types namely natural draft and mechanical draft.

3.4.1 Natural draft

Natural draft is the draft produced by a chimney alone. It is caused by the difference in weight between the column of hot gas inside the chimney and column of outside air of the same height and cross section. Being much lighter than outside air, chimney flue gas tends to rise, and the heavier outside air flows in through the ash pit to take its place. Draft is usually controlled by hand-operated dampers in the chimney and breeching connecting the boiler to the chimney. Here no fans or blowers are used. The products of combustion are discharged at such a height that it will not be a nuisance to the surrounding community.

3.4.2 Mechanical draft

It is draft artificially produced by fans. Three basic types of drafts that are applied are:

- **Balanced draft:** Forced-draft (F-D) fan (blower) pushes air into the furnace and an induced draft (I-D) fan draws gases into the chimney thereby providing draft to remove the gases from the boiler. Here the pressure is maintained between 0.05 to 0.10 in. of water gauge below atmospheric pressure in the case of boilers and slightly positive for reheating and heat treatment furnaces.
- **Induced draft:** An induced-draft fan draws enough draft for flow into the furnace, causing the products of combustion to discharge to atmosphere. Here the furnace is kept at a slight negative pressure below the atmospheric pressure so that combustion air flows through the system.
- **Forced draft:** The Forced draft system uses a fan to deliver the air to the furnace, forcing combustion products to flow through the unit and up the stack.

4. ENERGY EFFICIENCY OPPORTUNITIES

This section includes energy efficiency opportunities in Fuel Combustion

4.1 Pre-heating of the Combustion Oil

The viscosity of furnace oil and LSHS (Low Sulphur Heavy Stock) increases with decreasing temperature, which makes it difficult to pump the oil. At low ambient temperatures (below 25 °C), furnace oil cannot be pumped easily. To circumvent this, preheating of oil is accomplished in two ways:

- The entire tank may be preheated. In this form of bulk heating, steam coils are placed at the bottom of the tank, which is fully insulated;

- The oil can be heated as it flows out with an outflow heater. To reduce steam requirements, it is advisable to insulate tanks where bulk heating is used.

Bulk heating may be necessary if flow rates are high enough to make outflow heaters of adequate capacity impractical, or when a fuel such as LSHS is used. In the case of outflow heating, only the oil, which leaves the tank, is heated to the pumping temperature. The outflow heater is essentially a heat exchanger with steam or electricity as the heating medium.

4.2 Temperature control of Combustion Oil

Thermostatic temperature control of the oil is necessary to prevent overheating, especially when oil flow is reduced or stopped. This is particularly important for electric heaters, since oil may get carbonized when there is no flow and the heater is on. Thermostats should be provided at a region where the oil flows freely into the suction pipe. The temperature at which oil can readily be pumped depends on the grade of oil being handled. Oil should never be stored at a temperature above that necessary for pumping as this leads to higher energy consumption.

4.3 Preparation of Solid Fuels

4.3.1 Sizing of coal

Proper coal sizing is one of the key measures to ensure efficient combustion. Proper coal sizing, with specific relevance to the type of firing system, helps towards even burning, reduced ash losses and better combustion efficiency.

Coal is reduced in size by crushing and pulverizing. Pre-crushed coal can be economical for smaller units, especially stoker-fired units. In a coal handling system, crushing is limited to an upper size of 6 or 4mm. The devices most commonly used for crushing are the rotary breaker, the roll crusher and the hammer mill.

It is necessary to screen the coal before crushing, so that only oversized coal is fed to the crusher. This helps to reduce power consumption in the crusher. Recommended practices in coal crushing are:

- Incorporation of a screen to separate fines and small particles to avoid extra fine generation in crushing.
- Incorporation of a magnetic separator to separate iron pieces in coal, which may damage the crusher.

Table 11 gives the proper size of coal for various types of firing systems.

Table 11. Proper size of coal for various types of firing system

No.	Types of Firing System	Size (in mm)
1.	Hand Firing (a) Natural draft (b) Forced draft	25-75 25-40

2.	Stoker Firing (a) Chain grate i) Natural draft ii) Forced draft (b) Spreader Stoker	25-40 15-25 15-25
3.	Pulverized Fuel Fired	75% below 75 micron*
4	Fluidized bed boiler	< 10 mm

*1 Micron = 1/1000 mm

4.3.2 Conditioning of coal

The fines in coal present problems in combustion on account of segregation effects. Segregation of fines from larger coal pieces can be reduced to a great extent by conditioning coal with water. Water helps fine particles to stick to the bigger lumps due to surface tension of the moisture, thus stopping fines from falling through grate bars or being carried away by the furnace draft. While tempering the coal, care should be taken to ensure that moisture addition is uniform and preferably done in a moving or falling stream of coal.

If the percentage of fines in the coal is very high, wetting of coal can decrease the percentage of unburnt carbon and the excess air level required for combustion. The table below shows the extent of wetting, depending on the percentage of fines in coal.

Table 12. Extent of wetting: fines vs surface moisture in coal

Fines (%)	Surface Moisture (%)
10 - 15	4 - 5
15 - 20	5 - 6
20 - 25	6 - 7
25 - 30	7 - 8

4.3.3 Blending of coal

In the case of coal containing excessive fines, it is advisable to blend the predominantly lumped coal with lot of coal that contains excessive fines. Coal blending may thus help to limit the extent of fines in coal being fired to not more than 25%. Blending of different qualities of coal may also help to supply a uniform coal feed to the boiler.

4.4 Combustion Controls

Combustion controls assist the burner in regulation of fuel supply, air supply, (fuel to air ratio), and removal of gases of combustion to achieve optimum boiler efficiency. The amount of fuel supplied to the burner must be in proportion to the steam pressure and the quantity of steam required. The combustion controls are also necessary as safety device to ensure that the boiler operates safely.

Various types of combustion controls in use are:

- **On/Off control:** The simplest control, ON/OFF control means that either the burner is firing at full rate or it is OFF. This type of control is limited to small boilers.
- **High/low/off control:** Slightly more complex is HIGH/LOW/OFF system where the burner has two firing rates. The burner operates at slower firing rate and then switches to

full firing as needed. Burners can also revert to the low firing position at reduced load. This control is fitted to medium sized boilers.

- **Modulating control:** The modulating control operates on the principle of matching the steam pressure demand by altering the firing rate over the entire operating range of the boiler. Modulating motors use conventional mechanical linkage or electric valves to regulate the primary air, secondary air, and fuel supplied to the burner. Full modulation means that boiler keeps firing, and fuel and air are carefully matched over the whole firing range to maximize thermal efficiency.

5. OPTION CHECKLIST

This section includes most important options to improve energy efficiency of fuel use and in combustion processes.

Fuel Checklist

- Daily check: Oil temperature at the burner and oil/steam leakages
- Weekly task: Cleaning of all filters and draining of water from all tanks
- Yearly task: Cleaning of all tanks

Troubleshooting for fuels

1. Oil not pumpable
 - Viscosity too high
 - Blocked lines and filters
 - Sludge in oil
 - Leak in oil suction
 - Vent pipe choked
2. Blocking of strainers
 - Sludge or wax in oil
 - Heavy precipitated compounds in oil
 - Rust or scale in tank
 - Carbonization of oil due to excessive heating
3. Excess water in oil
 - Water delivered along with oil
 - Leaking manhole
 - Seepage from underground tank
 - Ingress of moisture from vent pipe
 - Leaking heater steam coils
4. Pipeline plugged
 - Sludge in oil
 - High viscosity oil
 - Foreign materials such as rags, scale and wood splinters in line
 - Carbonization of oil

Combustion Checklist

1. Start up

- Check for correct sized burner/nozzle.
- Establish air supply first (start blower). Ensure no vapour/gases are present before light up.
- Ensure a flame from a torch or other source is placed in front of the nozzle.
- Turn ON the (preheated) oil supply (before start-up, drain off cold oil).

2. Operations

- Check for correct temperature of oil at the burner tip (consult viscosity vs. temperature chart).
- Check air pressure for LAP burners (63.5 cm to 76.2 cm w.c. air pressure is commonly adopted).
- Check for oil drips near burner.
- Check for flame fading/flame pulsation.
- Check positioning of burner (ensure no flame impingement on refractory walls or charge).
- Adjust flame length to suit the conditions (ensure flame does not extend beyond the furnace).

3. Load changes

- Operate both air and oil valves simultaneously (For self-proportioned burner, operate the self-proportioning lever. Do not adjust valve only in oil line).
- Adjust burners and damper for a light brown (hazy) smoke from chimney and at least 12 percent CO₂.

4. Shut down

- Close oil line first.
- Shut the blower after a few seconds (ensure gases are purged from combustion chamber).
- Do not expose the burner nozzle to the radiant heat of the furnace. (When oil is shut off, remove burner/nozzle or interpose a thin refractory between nozzle and furnace).

Troubleshooting for combustion

The checklist in the Table below can help find the causes and solutions for typical problems found with fuel combustion.

TROUBLESHOOTING CHART FOR COMBUSTION		
No	Problems	Causes & solutions
1.	Starting difficult	<ol style="list-style-type: none"> 1. No oil in the tank. 2. Excess sludge and water in storage tanks. 3. Oil not flowing due to high viscosity/low temperature. 4. Choked burner tip. 5. No air. 6. Strainers choked.
2.	Flame goes out or splutters	<ol style="list-style-type: none"> 1. Sludge or water in oil. 2. Unsteady oil and air pressures. 3. Too high a pressure for atomizing medium which tends to blow out flame. 4. Presence of air in oil line. Look for leakages in suction line of pump. 5. Broken burner block, or burner without block.
3.	Flame flashes back	<ol style="list-style-type: none"> 1. Oil supply left in 'ON' position after air supply cut off during earlier shut off. 2. Too high a positive pressure in combustion chamber. 3. Furnace too cold during starting to complete combustion (when temperature rises, unburned oil particles burn). 4. Oil pressure too low.
4	Smoke and soot	<ol style="list-style-type: none"> 1. Insufficient draft or blower of inadequate 2. Oil flow excessive. 3. Oil too heavy and not preheated to 4. Suction air holes in blower plugged. 5. Chimney clogged with soot/damper 6. Blower operating speed too low.
5.	Clinker on refractory	<ol style="list-style-type: none"> 1. Flame hits refractory because combustion chamber is too small or 2. is not correctly aligned. 3. Oil dripping from nozzle. 4. Oil supply not 'cut off' before the air supply during shut-offs.
6.	Cooking of fuel in burner	<ol style="list-style-type: none"> 1. Nozzle exposed to furnace radiation after shut- 2. Burner fed with atomizing air over 300 °C. 3. Burner block too short or too wide. 4. Oil not drained from nozzle after shut off.
7.	Excessive fuel oil consumption	<ol style="list-style-type: none"> 1. Improper ratio of oil and air. 2. Burner nozzle oversized. 3. Excessive draft. 4. Improper oil/air mixing by burner. 5. Air and oil pressure not correct 6. Oil not preheated properly. 7. Oil viscosity too low for the type of burner used. 8. Oil leaks in oil pipelines/preheater. 9. Bad maintenance (too high or rising stack gas temperature).

6. WORKSHEETS

Worksheet 1: Excess Air Calculation

No	Parameters	Formula	Units	Value
1	Carbon (C)		% by Weight	
2	Hydrogen (H)		% by Weight	
3	Oxygen (O ₄)		% by Weight	
4	Nitrogen		% by Weight	
5	Sulphur		% by Weight	
6	H ₂ O		% by Weight	
7	Ash		% by Weight	
8	GCV of Fuel		kCal/kg	
9	Oxygen Required for burning of Carbon (O ₁)	$C \times (32/12)$	kg/100 kg of Fuel	
10	Oxygen Required for burning of Hydrogen (O ₂)	$H \times (32/4)$	kg/100 kg of Fuel	
11	Oxygen Required for burning of Sulphur (O ₃)	$S \times (32/32)$	kg/100 kg of Fuel	
12	Total Oxygen Required (O)	$O_1 + O_2 + O_3 - O_4$	kg/100 kg of Fuel	
13	Stoichiometric Amount of Air Required (S.A)	$O / 0.23$	kg/100 kg of Fuel	
14	Excess Air (EA)		%	
15	Actual Amount of Air Required	$S.A \times (1 + EA/100)$	kg/100 kg of Fuel	

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