CHEMICAL INDUSTRIES/130

Fundamentals of Petroleum and Petrochemical Engineering

Uttam Ray Chaudhuri

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Fundamentals of Petroleum and Petrochemical Engineering

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Dedication

This book is dedicated to the memory of my parents

Inspired by wife Sampa, daughter Aratrika, and brother Utpal

Contents

Preface

Modern civilisation cannot think of a day without petroleum and petrochemicals. Petroleum fuels, such a gasoline and diesel, are the major fuels for all transportation vehicles. Commodities manufactured from petrochemicals, for example, plastics, rubbers and synthetic fibres derived from petroleum, have become part and parcel of our daily life. The absence of petroleum will cause an end to our modern civilization unless alternative means are available. In fact, petroleum is a non-renewable fossilised mass, the amount of which is being exhausted with our increasing consumption. Future crude oil will be heavier and contaminated with unwanted salts and metals. Production and processing will be costlier than ever before. Therefore, it is inevitable to make use of this dwindling natural resource more judiciously and efficiently for the sustenance of our civilisation. The contents of this book have been prepared to provide a holistic working knowledge about petroleum and petrochemical technology. Chapter 1 presents the essential preliminaries for the exploration and production of crude petroleum oil and gas. This chapter is an introduction for beginners who may be entering the profession of oil and gas exploration and production. Chapter 2 is an analysis of crude oil and petroleum products. This will help scientists entering the profession as chemists in a refinery. The processing of petroleum in refineries is discussed in Chapter 3 and may be useful for apprentice engineers in a refinery. The fundamentals of lubricating oil and grease are dealt with in Chapter 4, which is useful for engineers and scientists entering the lubricants industries. Chapter 5 discusses the fundamentals of petrochemicals, their raw materials, and the end products, along with the manufacturing principles of some of the industrially important products. This chapter may be important for the engineer who is likely to follow a profession in petrochemical plants. The rest of the book, from Chapters 6 through 15, will be of common interest to engineers in refineries and petrochemical plants. Chapters 6 to 12 deal with the theories and problems of unit operations and the processes involved in refineries and petrochemical plants. The essential knowledge of automatic operations in a plant is dealt with in Chapter 13. Without this knowledge, engineers will not be successful in operating any plant. Chapter 14 deals with various miscellaneous activities, like start up, shutdown, maintenance, fire, and safety operations, which are essential to the running of any plant. Chapter 15 discusses the commercial and managerial activities that any engineer has to know for the ultimate success of refining or manufacturing businesses.

Author

Uttam Ray Chaudhuri is an associate professor in the Department of Chemical Technology, University of Calcutta. He holds a PhD in chemical engineering from the Indian Institute of Technology, Kharagpur, India. He received his graduate and postgraduate degrees in chemical engineering from Jadavpur University. He has 30 years of experience in industry, research, and teaching in the field of chemical engineering and technology. He has a number of research publications in foreign and Indian journals to his credit. He also served as a chemical engineer for more than ten years in the Indian Oil Corporation Ltd. (Refineries and Pipeline Division).

Introduction

Petroleum is a fossilised mass that has accumulated below the earth's surface from time immemorial. Raw petroleum is known as crude (petroleum) oil or mineral oil. It is a mixture of various organic substances and is the source of hydrocarbons, such as methane, ethane, propane, butane, pentane, and various other paraffinic, naphthenic, and aromatic hydrocarbons, the building blocks of today's organic industry. Various petroleum products, such as gaseous and liquid fuels, lubricating oil, solvents, asphalts, waxes, and coke, are derived from refining crude oil. Many lighter hydrocarbons and other organic chemicals are synthesised by thermal and catalytic treatments of these hydrocarbons. The hydrocarbon processing industry is basically divided into three distinct activities—petroleum production, petroleum refining, and petrochemical manufacture. Refineries produce cooking gas (liquified petroleum gas or LPG), motor spirit (also known as petrol or gasoline), naphtha, kerosene, aviation turbine fuel (ATF), high speed diesel (HSD), lubricating base oils, wax, coke, bitumen (or asphalt), etc., which are mostly a mixture of various hydrocarbons (the organic compounds made of carbon and hydrogen as the major constituent elements). In a petrochemical plant (where one or more petrochemicals are produced) or in a petrochemical complex (where many petrochemical products are produced), pure hydrocarbons or other organic chemicals with a definite number and type of constituent element or compound are produced from the products in refineries. Thus, petrochemicals are derived from petroleum products obtained from refineries. Products from a petrochemical complex are plastics, rubbers, synthetic fibres, raw materials for soap and detergents, alcohols, paints, pharmaceuticals, etc. Since petroleum is the mixture of hundreds of thousands of hydrocarbon compounds, there is a possibility of synthesising many new compounds. In fact, due to the advancement of new technology, new petrochemicals are being invented and will continue to be added to this industry in the near future. Hence, the petrochemical industry is still a growing industry. The manufacture of valuable petrochemicals from low-valued petroleum products has been the main attractive option for the refining industry investing in the petrochemical industry. Thus, modern refineries are, in fact, refinery cum petrochemical complexes.

1 Crude Petroleum Oil

1.1 COMPOSITION OF CRUDE OIL

The compounds in crude petroleum oil are essentially hydrocarbons or substituted hydrocarbons in which the major elements are carbon at 85%–90% and hydrogen at 10%–14%, and the rest with non-hydrocarbon elements—sulfur (0.2%–3%), nitrogen (< 0.1–2%), oxygen (1%–1.5%), and organo-metallic compounds of nickel, vanadium, arsenic, lead, and other metals in traces (in parts per million or parts per billion concentration). Inorganic salts of magnesium chloride, sodium chlorides, and other mineral salts are also accompanied with crude oil from the well either because of water from *formation* or water and chemicals injected during drilling and production.

1.1.1 Hydrocarbon Groups

Compounds solely made of carbon and hydrogen are called hydrocarbons. These hydrocarbons are grouped as paraffins, naphthenes, aromatics, and olefins. Crude oil contains these hydrocarbons in different proportions, except olefins, which are produced during processing.

Paraffins are saturated hydrocarbons. A saturated hydrocarbon is a compound where all four bonds of a carbon atom are linked to four separate atoms. Examples are methane, ethane, propane, butane, pentane, hexane, with the generic molecular formula of C_nH_{2n+2}, where n is the number of carbon atoms in that compound. The homologous series of these hydrocarbons are called alkanes (Figure 1.1).

The series starts with methane, which has the chemical formula CH_4. Alkanes are relatively unreactive as compared to aromatics and olefins. At room temperature, alkanes are not affected by concentrated fuming sulfuric acid, concentrated alkalies, or powerful oxidising agents such as chromic acid. They carry out substitution reactions slowly with chlorine in sunlight and with bromine in the presence of a catalyst. Paraffins are available both as normal and iso-paraffins. Normal paraffins are straight chain compounds and iso-paraffins are branched compounds. Normal and iso-paraffins have the same formula (i.e., same number of carbon and hydrogen atoms), but they differ widely in their physical and chemical properties because of isomerism. The number of isomers of normal paraffins increases with the number of carbon atoms in the paraffin. For example, paraffins with carbon numbers of five, six, and eight will have iso-paraffins of three, five, and eighteen, respectively. Iso-paraffins are more reactive than normal paraffins and are desirable in motor spirit. Normal paraffins can be converted to iso-paraffins by thermal or catalytic processes. This is known as the isomerisation reaction.

Olefins are unsaturated hydrocarbons, i.e., the double bond is present between the two carbon atoms in the formula. The generic formula is C_nH_{2n}, and the lowest

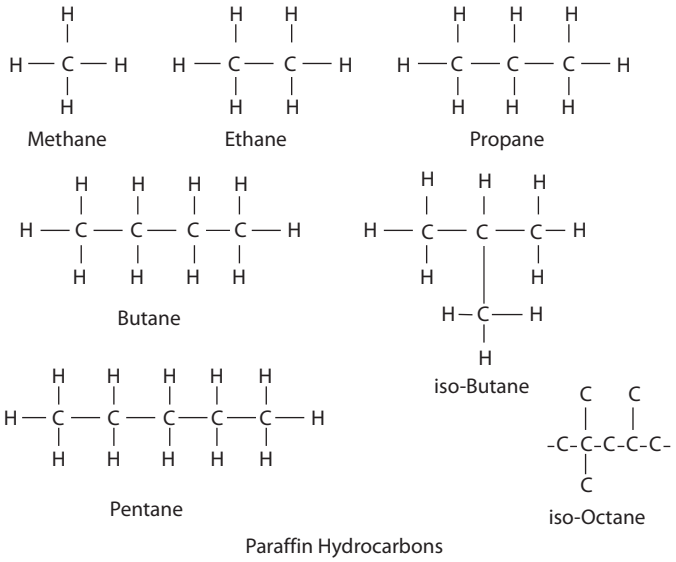


FIGURE 1.1 Common saturated hydrocarbons or paraffins.

member of this homologous series is ethylene, C_2H_4. This series is known as alkenes. These are highly reactive and can react to themselves to mono olefins (Figure 1.2).

Olefins react readily with acids, alkalies, halogens, oxidizing agents, etc. Olefins are not present in crude oil, but they are produced by thermal and catalytic decomposition or dehydrogenation of normal paraffins. Like paraffins, olefins may be straight (normal) chain or branched chain (iso-) hydrocarbons. Olefins can be determined by the bromine or iodine number in reaction with bromine or iodine. They are readily converted to

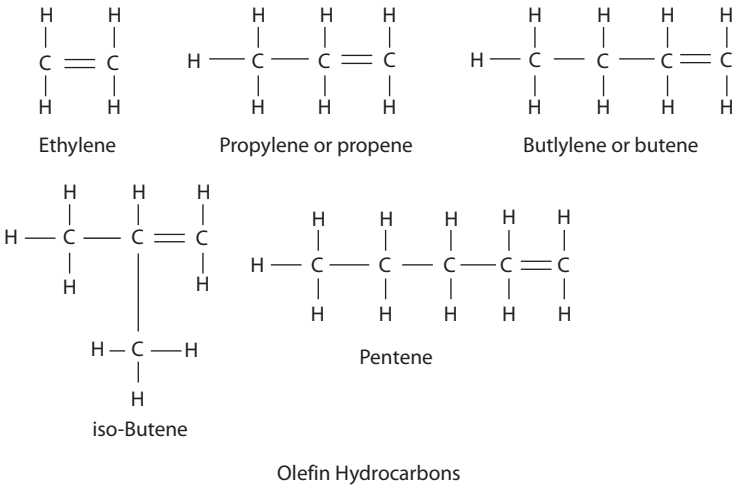


FIGURE 1.2 Common unsaturated hydrocarbons or alkenes.

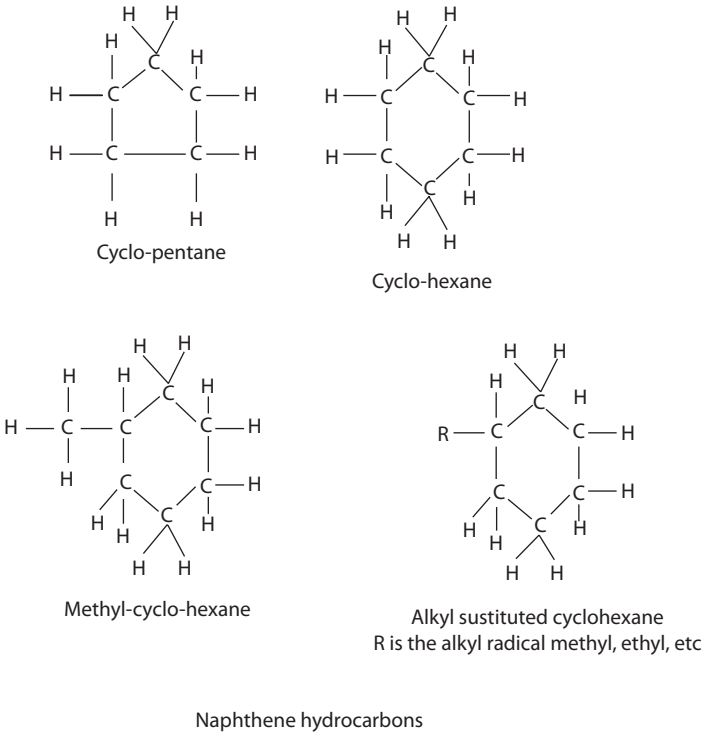


FIGURE 1.3 Common cyclic saturated hydrocarbons or cyclo alkanes.

diolefins in the presence of oxygen and form a gum-like substance. Olefins present in petroleum products can be removed by absorption in sulfuric acid.

Naphthenes are cyclic saturated hydrocarbons with the general formula, like olefins, of C_nH_{2n}, also known as cyclo-alkanes. Since they are saturated, they are relatively inactive, like paraffins. Naphthenes are desirable compounds for the production of aromatics and good quality lube oil base stocks. Some of these are shown in (Figure 1.3).

Aromatics, often called benzenes, are chemically very active as compared to other groups of hydrocarbons. Their general formula is C_nH_{2n-6}. These hydrocarbons in particular are attacked by oxygen to form organic acids. Naphthenes can be dehydrogenated to aromatics in the presence of a platinum catalyst. Lower aromatics, such as benzene, toluene, and xylenes, are good solvents and precursors for many petrochemicals. Aromatics from petroleum products can be separated by extraction with solvents such as phenol, furfurol, and diethylene glycol. Some of these are presented in (Figure 1.4).

1.1.1.1 Complex Hydrocarbons

Crude oil also contains a large number of hydrocarbons that do not fall into the category of paraffins, olefins, naphthenes, or aromatics, but may be the combined group of any two or more groups of paraffins, naphthenes, or aromatic hydrocarbons. By joining two or more naphthene rings or combining naphthene and aromatic rings, paraffin chains with aromatic rings (alkyl-aromatics), etc., a vast array of complex

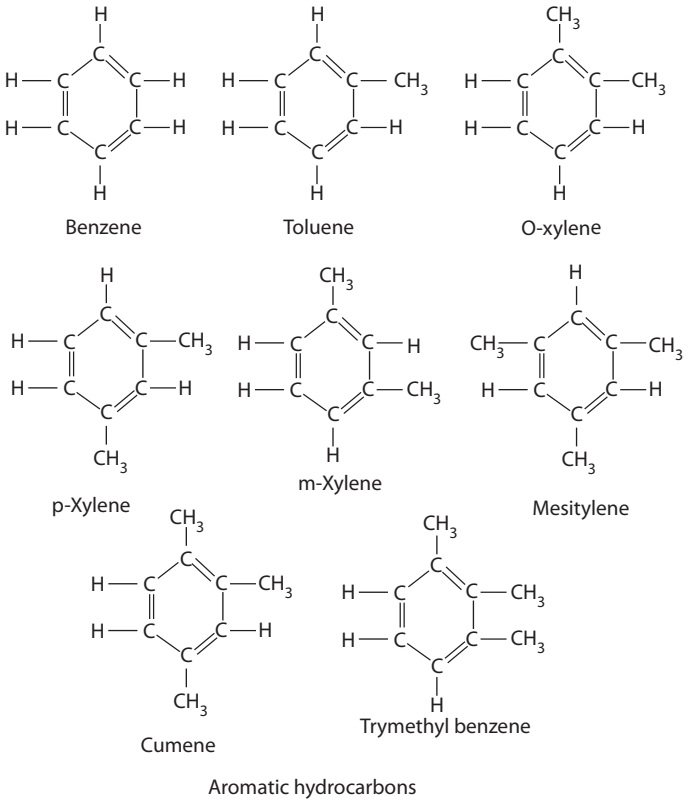
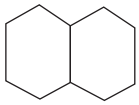


FIGURE 1.4 Common cyclic unsaturated hydrocarbons or aromatics.

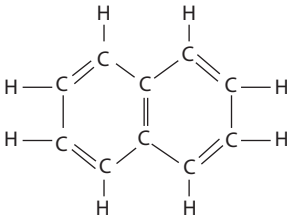
hydrocarbons may be formed. Examples of these compounds are decalin, naphthalene, and diphenyl. Heavier fractions of crude oil contain these types of hydrocarbons. Multinuclear (multi ring) aromatics or polynuclear aromatics (PNA) are well known in crude oil and its residual products. PNAs are the precursors of coke, which forms due to thermal effect. These cannot be decomposed easily even by severe hydro-cracking (Figure 1.5).

1.1.1.2 Non-Hydrocarbons or Hetero-Atomic Compounds

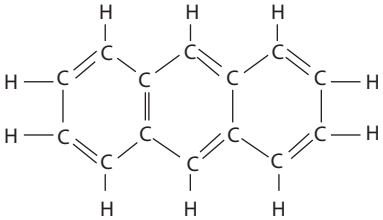
Common hetero atoms in hydrocarbons are sulfur, oxygen, nitrogen, and metallic atoms. Sulfur compounds are present in crude oil as mercaptans, mono- and disulfides with the general formula R-SH, R-S-R1, R-S-S-R1, where R and R1 are the alkyl radicals. Mercaptans are very corrosive whereas mono- and disulfides are not. Examples of cyclic sulfur compounds are thiophenes and benzothiophene. *Hydrogen sulfide* (H_2S) gas is associated with crude oil in dissolved form and is released when heated. H_2S is corrosive at high temperatures and in the presence of moisture. Crude oil that contains large amounts of H_2S is called sour crude. Sulfur present in petroleum fuel products also forms various oxides of sulfur (SO_x) during combustion, which are strong environmental pollutants. H_2S can be removed from gases by



Decalin



Naphthalene



Anthracene

Polynuclear hydrocarbons

FIGURE 1.5 Structural examples of polynuclear aromatics.

absorption in an amine solution. In the light distillates, sulfur may be present as H_2S, mercaptans, and thiophenes, but in the heavier fractions of crude oil, 80%–90% of the sulfur is usually present in the complex ring structure of hydrocarbons. In this combination, the sulfur atom is very stable and non-reactive. As a result, sulfur from heavier petroleum cannot be removed without a destructive reaction, such as severe thermal or catalytic reactions. Nowadays, sulfur is recovered during refining and sold as a product. Sulfur also has a poisoning effect on various catalysts.

Nitrogen compounds in hydrocarbons are usually found in the heavier parts of the crude oil. These are responsible for colour and colour instability and poisoning of certain catalysts. Nitrogen in petroleum fuels causes the generation of oxides of nitrogen (NO_x), which are also strong pollutants of the atmosphere. Nitrogen can be eliminated from petroleum products by catalytic hydrogenation. Like sulfur, nitrogen in the heavier parts of petroleum cannot be removed without severe cracking or hydrogenation reactions.

Oxygen compounds: crude oil may contain oxygen containing compounds, such as naphthenic acids, phenols, and cresols, which are responsible for corrosive activities. Oxygen also acts as a poison for many catalysts. This can be removed by catalytic hydrogenation. Excess oxygen compounds may even lead to explosion.

Metallic compounds of vanadium, nickel, lead, arsenic, etc., are also found in crude oil. Vanadium and nickel are found in the form of organo-metallic compounds mostly in the heavier fractions of crude oil where the metal atoms are distributed within the compound in a complex form called porphyrins. Petroleum fuels containing these metallic compounds may damage the burners, lines, and

walls of the combustion chambers. Some of the hetero-atomic hydrocarbons are shown in Figure 1.6.

1.2 PHYSICAL PROPERTIES OF CRUDE OIL

Crude oil is sometimes classified as paraffinic base, naphthenic base, or asphaltic base, according to the prevalence of the hydrocarbon groups. But various physical properties are required in addition to these classification in order to characterise a crude oil.

API gravity is expressed as the relation developed by the American Petroleum Institute, as

$$\text{API} = 141.5/s - 131.5, \tag{1.1}$$

where "s" is the specific gravity of oil measured with respect to water, both at 60°F (15.5°C). Since oil is lighter than water, API gravity is always greater than 10. The lighter the oil, the larger the API gravity. However, gravity is not the only measurement of crude oil, but a mere indicator of lightness. Since crude oil is, in fact, a mixture of various hydrocarbons varying from gases to semi-solid asphalts, it is convenient to separate these into various boiling fractions rather than as individual chemical species. Crude is distilled in a laboratory distillation apparatus and the boiling fractions are collected. Boiling fractions are a mixture of hydrocarbons

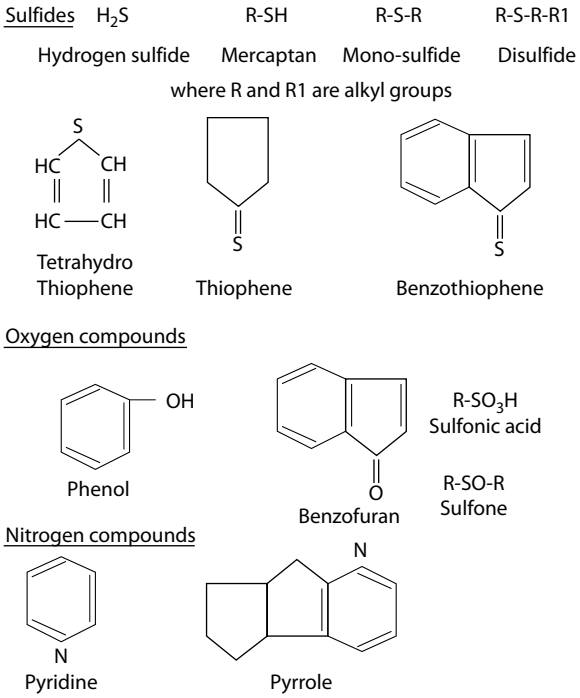


FIGURE 1.6 Some of the hetero-atomic hydrocarbons.

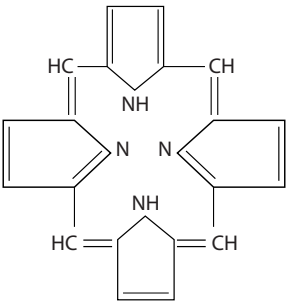
boiling in a certain range of temperatures. For a particular crude oil, each boiling fraction separated has a certain average boiling point. A *characterisation factor* of crude oil has been related with the average (molal average) boiling point (T_B in Rankine) of all the fractions separated and its specific gravity "s", as

$$C_F = (T_B)^{1/3} /s. \tag{1.2}$$

Characterisation factor (C_F) is universally accepted as the identity of a crude oil and its products. Various other properties, such as molecular weight, density, viscosity, and thermodynamic properties, are available for any oil product if its characterisation factor is determined. Since crude oil is always associated with water and settleable solids, it is essential to determine the relative amount of bottom sludge and water (BSW) after the necessary settling period. Water is separated by the solvent extraction method in the laboratory. *Ultimate analysis* of crude oil is a method to determine the amount of carbon, hydrogen, and other constituent elements in it. Combustion of crude oil yields ashes of metallic oxides that are analysed for the metallic components present in crude oil.

1.3 ORIGIN OF HYDROCARBONS

The word *petroleum* is derived from the Latin words for rock (petra) and oleum (oil). It is found in the form of gas and/or liquid phases in porous rock structures. Both gases and liquids are rich mixtures of organic components consisting of carbon and hydrogen and hence are known as hydrocarbons in general. Usually, these are available in the sub-surface of Earth in the porous rocks known as sedimentary basins. In the majority of the basins, gas, oil, and water coexist under pressure with methane gas at the cap and oil is sandwiched between the gas and water. Dissolved and liquified gases are usually present in liquid petroleum oil. Heavy, carbon-rich or bituminous hydrocarbons are also available in the shallow depth in the shales (oil shales) or on the surface sands (tar sands). The most abundant hydrocarbon gas in nature, methane, is also available in large quantities from the coal bed (known as coal bed methane). Large quantities of methane are also available as hydrates under the sea bed in the Arctic region and are known as gas hydrates. There are many hypotheses about the origin of



Porphyrine

FIGURE 1.7 Complex structure of porphyrins present in asphalt.

the formation of crude oil. To date, it is generally agreed that crude petroleum oil was formed from decaying plants and vegetables and dead animals and converted to oil by the action of high pressure and high temperature under the earth's surface, and by the action of the biological activities of micro-organisms. Organic materials of plant or animal origin accumulate in the lowest places, usually in the crevices, low-lying land, sea bed, coral reefs, etc., and are gradually buried under the surface of Earth. Thus, huge amounts of organic matter are trapped layer after layer in the earth's crust and rock. Rocks that bear these organic layers are called sedimentary rocks. Several kilometres below the earth's surface, organic sediments are decayed biologically to a mass, known as *kerogen*, which has a very high mass of organic-to-inorganic ratio favourable for conversion to hydrocarbon. The temperature of Earth increases with depth (geothermal gradient) at the rate of approximately 30°C per kilometre. Thus, at a depth of 4–5 km, called *kitchen* by geologists, temperatures of 120°C–150°C exist where kerogen is converted to hydrocarbon oil under very high pressure of rocks and soil. But this conversion takes millions of years (geological time period) to complete. Methane is also formed thermogenically (i.e., thermal conversion of kerogen) along with biogenic methane already present before the formation of crude oil. Migration of oil with gas occurs within the rock layers by the pressure gradient from high to low pressure zones. The formation of crude (or crude deposit) oil has been found in the sedimentary porous rock layers trapped under the hard and impervious igneous rock layers. Crude oil and gas accumulate in the pores of the sedimentary rocky layer as shown in Figure 1.8. This formation may be found from a few kilometers (as deep as 2 km and as deep as 7 km) below the earth's surface. The first oil deposit is known as the Drake Well, discovered in the United States (near Titusville) in 1859.

Some of the common terms used in petroleum exploration and production are *source rock*, *migration*, and *reservoir*. Sedimentary rocks are the rocky layer where organics are converted to oil and gas due to high temperature and pressure over

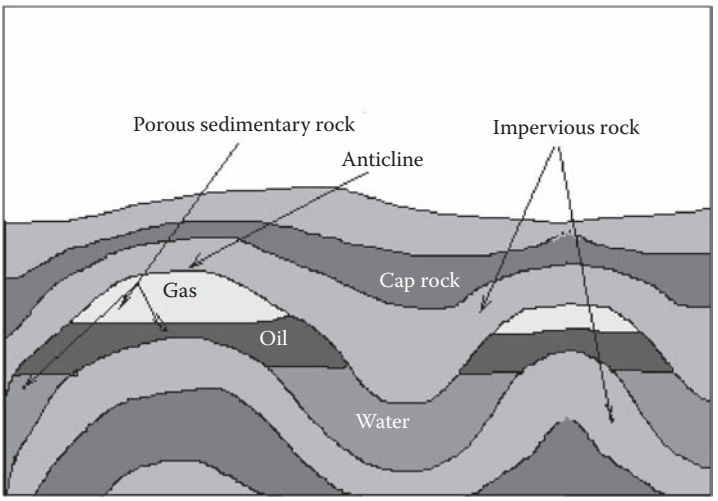


FIGURE 1.8 A typical anticline oil and gas reservoir.

millions of years. From the source rock, oil and gas then migrate to areas or traps that have a structure favourable for storing oil and gas. Traps are usually anticline or domed or faulted areas having oil and gas trapped in a porous rocky area covered by impermeable rock (seal or cap rocks) layers that do not allow further migration or escape to another area. Such an area that traps oil and gas is known as a *reservoir* or *basin*.

A *prospect* of hydrocarbon deposits is declared by the geologist when the area under study satisfies the above geological structure and conditions. The area where oil and gas are stored is known as *formation*. Drilling is started only in the *prospect* area as declared by the geologists. Oil reserves are classified into three categories, namely, *proven*, *probable*, and *possible* reserves. Proven reserves are worth for economic exploitation. Probable reserve has a certain degree of probability (about 50%) for economic exploitation. Possible reserve has very little probability (about <10%) for economic exploitation with current technology. Commercially viable formation is also known as *pay* or *pay zone*.

1.4 EXPLORATION TECHNIQUES

The selection of a drilling site is a tricky and costly affair. Though some visible evidence of a hydrocarbon source, like seepage of oil and gas from the surface, the visual appearance of surface and vegetation, the presence of oil or gas in fountains or rivers, etc., are sometimes used in locating oil and gas reserves, and many ancient oil fields were discovered by these events. But, today, such fortunate events are very rare and sometimes may not always be suitable for commercial exploitation. Modern exploration techniques use geophysical, geochemical, and geotechnical methods. Exploration of the surface of Earth can be useful for imaging or mapping sub-surface structures favourable for oil and gas accumulation. In the geophysical methods, gravimetric, magnetometric, seismic, radioactive, and stratigraphic studies of the surface are gathered. Chemical analysis of the surface soil and rocks are carried out by geochemical methods. Geotechnical methods, such as the mechanical properties of rocks and surface, are measured. Remote sensing from satellite is the most recent development for a low cost geological survey. Usual geophysical methods include gravimetric, magnetometric, and seismic methods. Geochemical methods employ chemical analysis of the cuttings (rock samples cut by drilling bit) and core (a narrow column of rock taken from the wall of a drilled hole) of the drilled site.

1.4.1 Gravimetric Method

Gravity of the earth's surface varies with distance from the surface of Earth and the type of material, such as salt, water, oil, gas, or mineral matter. The measurement of a small variation of gravity or acceleration due to gravity is recorded with accuracy and the data are converted to retrieve a geological structure of the sub-surface of Earth. A gravimeter is a very sensitive instrument, usually a spring-type balance with high resolution and accuracy capable of detecting a minute variation in gravity. Porous and oil-containing rock layers and salt have lower density compared to the

surrounding non-porous and hard rock layers. Thus, a gravimetric curve is acquired and analysed for the location of deposit.

1.4.2 Magnetometric Method

Earth has its own magnetic field that varies from one location to another owing to the different structural materials of rocks and also the presence of solar-charged particles received by Earth. A variation of magnetic field strength is recorded by a sensitive instrument, called a magnetometer. Igneous non-porous rocks are found to be magnetic as compared to sedimentary rocks containing organic deposits. Thus, a magnetometric survey can also be used to locate oil deposits. Both the gravimetric and magnetometric methods are done simultaneously to predict a reproducible sub-surface structure. After the zone is confirmed by gravimetric and magnetometric surveys, a seismic survey is carried out for a clear image of the sub-surface structure.

1.4.3 Seismic Survey

This technique uses a sonic instrument over a desired site to correctly locate the prospective basin structure. In this method, a sound signal generated by the explosion method (explorers call them mini-earthquakes, which are artificially created by explosives) is transmitted through the earth's surface under study and reflected signals are detected by geophones located at specified positions. The frequency and time of the reflected signal varies with the density, porosity, and the type of reflecting surface. Various rock deposits at different depths vary with density and porosity. Seismic reflection can measure this change as it travels below the surface. Computer simulation software is used for imaging the sub-surface structure. This is applied to all the surveys for fast and accurate prediction about the oil and gas reserve location, well before a site is finally selected for drilling operations. It is to be noted that exploration has to be deterministic, but the availability of oil and gas is estimated based on probability.

1.4.4 Remote Sensing Method

Solar radiation from the Earth's surface varies in intensity and frequency depending on the sub-surface property. This observation is collected via satellite to predict the sub-surface structure. In order to image the sub-surface structure, historical geological data collected previously by gravimetric, magnetometric, and seismic surveys are used. The final image is obtained by geological imaging software (GIS). However, the remote sensing method is not applicable during nighttime or places incapable of reflecting solar radiation, like the ocean surface, which absorbs substantial amounts of solar radiation. However, extrapolation from the land surface in the vicinity of the sea can be accurately predicted, but is not applicable for the deep sea area. A radioactive or gamma-ray survey is also used in the exploration.

1.4.5 Geochemical Methods

Inorganic contents of surface or shallow cuttings or core are sampled and analysed for inorganic materials, such as salts and carbonates, which are frequently associated with hydrocarbons. *Organic contents* or the presence of organic matter is detected by heating a sample in a crucible and the loss of mass of the sample is an indication of the presence of organic matter. The ratio of organic mass to inorganic matter in a sample is used to ascertain the presence of hydrocarbons. *Total organic carbon* is defined as the carbon present in the organic matter in the sample which is different in inorganic carbon from carbonates. Core samples are examined for porosity, permeability, salt content, organic content, and many other physical and chemical properties.

1.4.6 Stratigraphy

Correlations are established between wells, fossils, rock and mud properties, before and during drilling operations for the final prediction, and this technique is known as stratigraphy. But it is important to remember that prediction from exploration may not be correct as far as the location and amount of deposit are concerned. It may happen that the drilling operation may not yield oil or the yield may not be sufficient at the explored site and that the expenditure borne by this work is irrecoverable. Hence, a more accurate determination of the location and economic deposit should be done before investing money in well construction. After confirmation from the test drilled hole, final construction is carried out.

1.5 RESOURCE ESTIMATION

The oil potential of a deposit depends on the pressure and temperature of the formation, the surface tension, the density and viscosity of the oil, the porosity and permeability of the rock, and so forth. The quantum of oil and/or gas present in the reservoir pores is called oil and/or gas *in place*. The amount of hydrocarbon oil that can be economically produced and marketed is called reserve. The oil and gas volume/quantities can be estimated by the volumetric method.

Volumetric oil *in place* in million metric tons is given by the relation:

$$AH\,\theta(1 - s_w)\rho_0 / b_0, \tag{1.3}$$

where:

A: area of oil pool in square kilometres
H: oil pay thickness in metres
θ: porosity of the reservoir rocks
ρ_0: density of oil
b_0: volume fraction of oil in the formation
s_w: fraction saturated by water in the pores

For gas *in place*, the following relation is used:

$$AH\,\theta(1 - s_w)\, p_r T_r / (Z p_s T_s), \tag{1.4}$$

where:

A: area of oil pool in square kilometres
H: oil pay thickness in metres
θ: porosity of the reservoir rocks
s_w: fraction saturated by water in the pores
p_r: reservoir pressure in the formation
p_s: pressure at the surface of earth
T_r: absolute temperature in the formation
T_s: absolute temperature at the surface

1.5.1 Effect of Pressure

At high reservoir pressure, the gas density is high and is dissolved in the liquid oil, and is thus amenable for the production of oil and gas without the aid of additional means of power for external pressurisation. In many reservoirs, methane is the major constituent of gas, which has a tendency to form hydrates with water at high pressure. Once formed, methane hydrates are difficult to disperse in the well and may damage the well piping due to abrasion. The formation of methane hydrates is also responsible for a reduction in the oil pressure of the reservoir. Methanol may be injected into such wells to disperse methane hydrates. With the production of oil and gas, the pressure of the well falls with time (years), and to maintain production, water or high pressure inert gas is injected into the surrounding wells to maintain the pressure of the producing well. Pressure in the bottom of the well at the formation can be measured with a remote access pressure gauge lowered through the well piping. Figure 1.9 presents a pressure profile, rate of production, and water injection rate with age of the producing well. There are four stages of production with ages. Stage 1 is the *baby well*, in which production is gradually rising and reaches its maximum. Stage 2 is the *young well*, which produces the oil at the maximum rate. Stage 3 is the *middle-aged* well when production starts decreasing, and finally stage 4 is the *old*

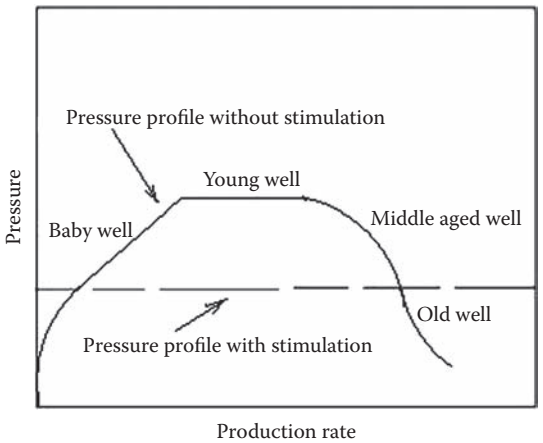


FIGURE 1.9 Pressure profiles for a producing well.

well, while production is very low and water cut is more than oil cut, it will continue until it becomes uneconomic to continue production. However, external pressurisation with water or inert gas should be planned from the beginning of stage 2 to maintain maximum pressure with controlled production. Water injection should be gradually raised to maintain the same pressure up to stage 4 to compensate for the fall in well pressure.

1.5.2 Connate Water

Oil, gas, and water are distributed in the reservoir according to their densities. Gas is also dissolved in the oil phase. Gas occupies the upper space, followed by oil in the next layer, and water in the lower part. Water occupies the major space of the reservoir. Oil, gas, and water in the reservoir are also present in the interstices of the porous rocks simultaneously. This water in the pores is called connate or interstitial water. It is important to take account of this connate water in estimating crude oil in the reserve. The greater the amount of this water, the lower the permeability for oil. Water in the reservoir usually contains mineral salts. Improper selection of sites in the surrounding wells for injection of external water or gas to pressurise the producing well may result in more water cut in the production.

1.5.3 Effect of Temperature

The temperature under the surface of Earth increases with depth. The rate of increase in temperature per 34 m of depth is called the *geothermal gradient*, which may be less than or greater than 1°C per 34 m. This may vary from well to well. The greater the thermal gradient, the more permeability of oil. Recently, attempts have been made to increase the bottom hole pressure by partial combustion of oil or injection of steam or hot gas into the surrounding wells.

1.5.4 Effect of Viscosity

Reservoir crude oil is classified as a viscoelastic fluid that exerts normal stress in addition to tangential stress developed while in the flowing condition. Thus, the flow behaviour of this type of fluid cannot be directly expressed in terms of Newtonian viscosity. However, for steady state flow, the relation for pseudoplastic fluid may be more applicable.

$$\tau = k\,(-\,du\,/\,dx)^n, \tag{1.5}$$

where τ is the shear stress, u and x are the velocity and distance, du/dx is the corresponding shear rate, k is the consistency factor (but not Newton's viscosity), and $n < 1$. However, k can be related with Newton's viscosity and can be used for the effect of temperature and other factors affecting viscosity. Production rate is inversely proportional to the viscosity of oil and directly to the pressure of the reservoir. In the well, recoverability of oil with respect to water is measured by the ratio (ξ) of viscosities of oil to water, which is

$$\xi = \mu_{oil}\,/\,\mu_{water}, \tag{1.6}$$

where μ_{oil} and μ_{water} are the viscosities of oil and water, respectively. The lower the value of ξ, the greater the oil cut and vice versa. This value increases with the age of the well and thus increases the water cut in the production. Attempts are made to inject polymer or high viscous compounds, which is readily soluble in water and increases the viscosity of water in the well. It is common to maintain a ξ value below 3 to have a greater oil cut in the production.

1.6 OIL FIELD DEVELOPMENT

Drilling is done to fracture and penetrate the rocky layers to reach the oil formation below the Earth's surface. A hollow steel pipe containing the drill bit with perforations at its mouth is used for drilling. Mud fluid is pumped through the top end of the drill pipe through a hose which moves down with the pipe as the drilling progresses. The drill pipe and the hose are suspended from the crown of a pyramidal structure called a rig. Figure 1.10 depicts a typical rig for drilling operations. A high pressure pump is employed to pump the mud solution from the mud pit through the hose such that the cuttings at the drill bit are washed out through the mouth of the drill bit and returned to the top surface through the annular space between the drill pipe and the hole developed. Cuttings with the mud solution are collected and separated from each other. Clarified mud along with fresh mud are pumped back to the drill pipe continuously. Mud is consumed due to absorption and seepage through the pores and crevices of the layers. Monitoring of the level in the mud pit is essential to assess the consumption and generation pattern of cuttings and water. An alarming decrease in the level indicates leakage through the layers due to seepage in crevices or channels. While an increase in the level indicates ingress of

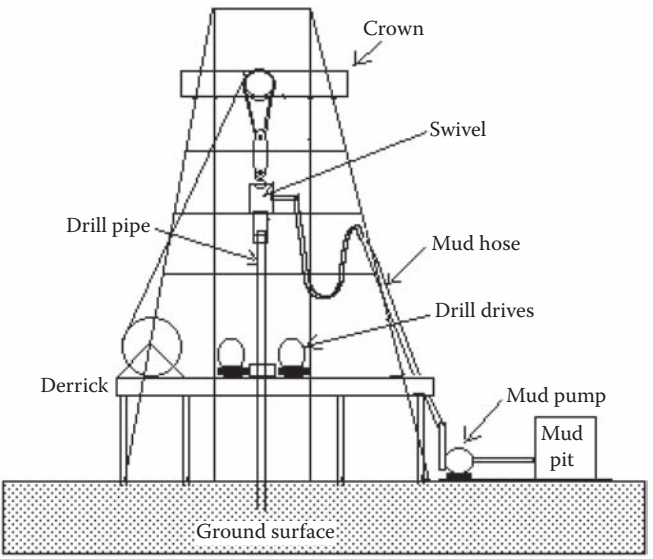


FIGURE 1.10 Schematic diagram of an oil rig for exploration.

underground water. Samples of drill cuttings are useful for surveying and assessing the direction of the drilling operation as they carry valuable information about the layers and formation. Continuous well logging is then carried out using a modern system of data acquisition and analysis. After drilling to a depth of 30–40 ft, a steel pipe is introduced into the hole to protect the wall of the hole formed. This is called the *casing string*, which is then cemented to the wall of the hole by pumping a fast-setting cement solution (usually Portland cement without sand) to the annular space between the pipe casing and the wall of the hole. This casing helps prevent caving of the wall and seepage of water from the layers. The drilling arrangement with a casing pipe is shown in Figure 1.11. An additional drill pipe is then joined of sufficient strength to withstand the various static and dynamic stresses for the increasing dead weight of piping, torsional stresses due to rotation, for upward and downward movement, abrasion from sand, fluid friction from mud fluid with cutting and corrosion, etc. The drilling operation is then continued and an additional casing pipe of a reduced diameter from the previous one is inserted and cemented at strategically located positions (for easy recovery of casing pipes after the well life is exhausted) until the target depth is reached. The final casing diameter may reach as small as 5–8 in.

At this stage, the top of the well (well head) along with the casing hanger are fitted with the necessary piping and collection headers. A pipe riser is inserted in the well to lift the oil and is connected to the well-head piping and valves. The diameter and design of the pipe riser (tubing) may differ depending on the facility of the oil lifting mechanism. The well-head connection consists of a tubing header and a Christmas tree header for collection of oil, gas, and water to the respective storage tanks. Such a complete well is presented in Figure 1.12. The surface of the casing pipe at the desired target depth is punctured by bullet or missile firing by experts. The hydrostatic pressure of the mud fluid in the well hole balances the reservoir pressure, thereby preventing spouting of the well from the formation.

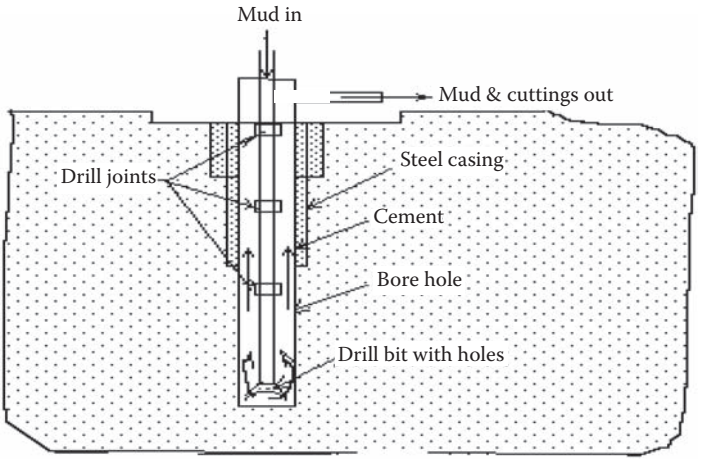


FIGURE 1.11 Drilling operation in a well.