



Fundamentals of Petroleum Refining

An Online Continuing Education Course for Engineers

Course Number: O-3001

Credit: 3 Hours / 3 PDH / 3 CPD

FUNDAMENTALS OF PETROLEUM REFINING

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Introduction

Imagine, for just a moment, how your lifestyle would be changed if you had no access to transportation via automobiles, trucks, motorcycles, planes, or any other equipment powered by internal combustion engines. How would you commute to work or to shop for consumer goods? Would you walk, ride a bicycle—or ride a horse? Imagine how the selection of goods available to you at local retailers would be negatively impacted by similar constraints. For example, you would have limited or no access to fresh fruits and vegetables except during the local growing season. The costs of goods produced other than locally would be appreciably higher. The lifestyle that we take for granted is made possible through the usage of the fuels (i.e., motor gasolines, diesel fuels, jet fuels, aviation gasolines, heating oils, heavy fuel oils, etc.) and specialty products (i.e., lubricants, waxes, asphalts and solvents), as well as the petrochemical industry feedstocks produced by the petroleum refining industry from crude oils.

The modern petroleum refinery is a very sophisticated, capital-intensive industrial complex. To the casual observer, the typical petroleum refinery appears to be a maze of piping, with scattered, process units containing very tall equipment, and massive storage tanks too numerous to count taking up most of the refinery real estate.

Economy of scale has a very significant relevance to the economics of refinery operations. More than two-thirds of the 146 petroleum refineries in the United States (see Appendix 1) have crude oil processing capacities exceeding 50,000 barrels/day (b/d, one barrel is 42 U.S. standard gallons), with the largest exceeding 500,000 b/d! In most cases, due to logistics economics, the primary consideration in deciding where to build a petroleum refinery is proximity to the product end-users or a product pipeline hub rather than the proximity to the area of crude oil production. This enables crude oils to be received by a few large pipelines and minimizes the length of the scores of product pipelines emanating from the refinery. The larger petroleum refineries are located near coastlines or navigable rivers, enabling crude oils to be received and product to be shipped via ships and barges.

No two major petroleum refineries are identical. This uniqueness stems predominantly from the geographical location of the refinery, which in conjunction with the refinery process configuration, determines how efficiently crude oils can be delivered to the refinery and products to the markets served by the refinery. An overview of the fuels processes typically incorporated into a modern petroleum refinery is provided in this short course. A simplified flow diagram of a typical fuels refinery is shown below.

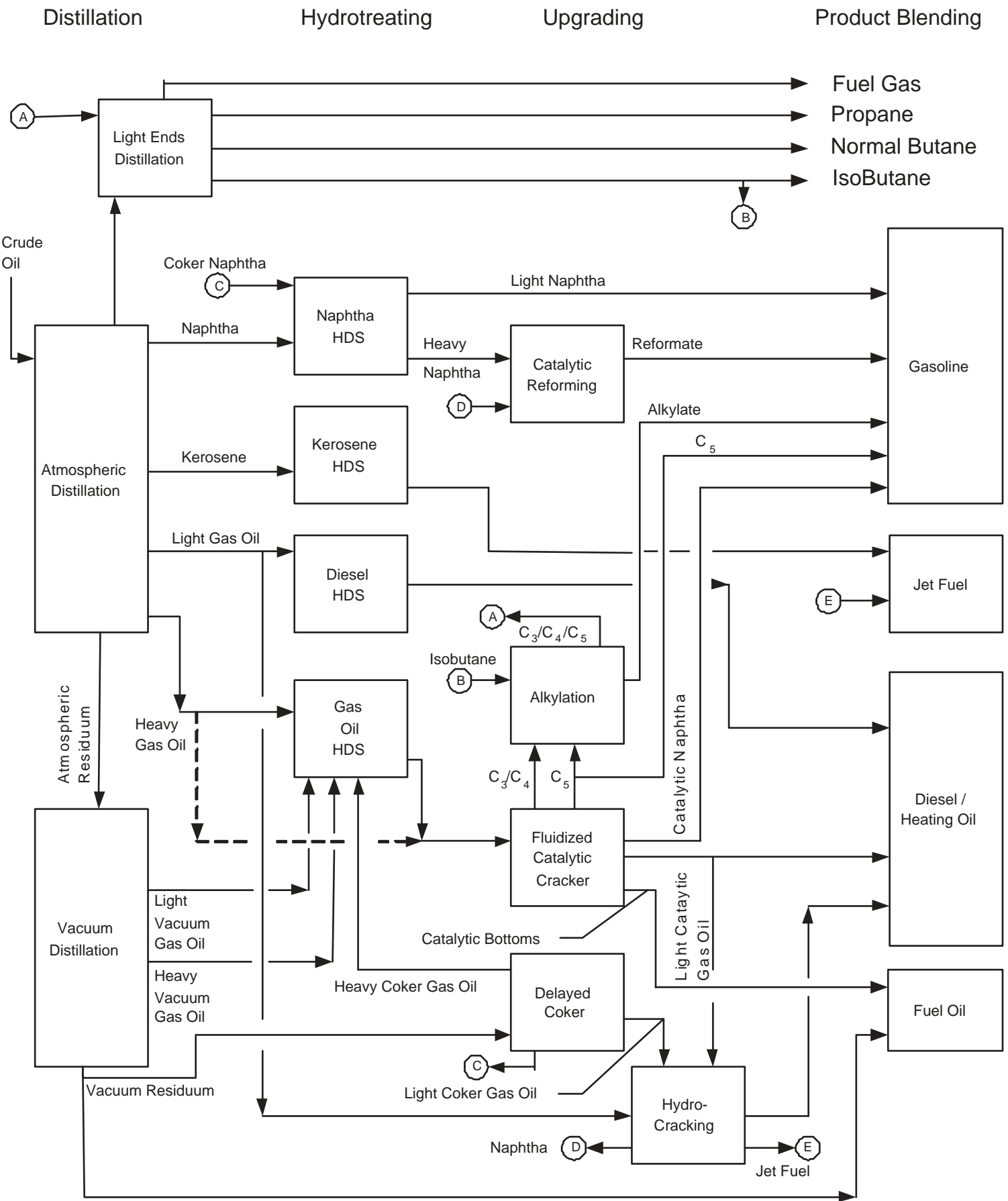


Figure 1 - Simplified Refinery Process Flow Diagram

The key function of most refinery processes is to effect chemical reactions on the hydrocarbons being processed. Generally, the reactions are carried out at elevated temperatures in the 600-1,000°F range depending on the process, and in most cases at elevated pressures, from 200 pounds per square inch (psi) to as high as 3,000 psi. Those processes involving reactions will typically incorporate a fractionator to distill the reactor effluent into various product streams. The primary function of some refinery processes, such as Crude Distillation, for example, is fractionation only.

A general description of a refinery processing unit is that the unit feedstocks are pumped and/or compressed up to the required pressures, pre-heated via heat exchange with reactor effluent and/or product streams, and finally heated via heat exchange in a direct-fired furnace before entering the reactor(s) or distillation tower (if no reaction is intended). The reactor effluent is then cooled via heat exchange with unit feedstocks, fractionated into the desired product streams via distillation, which are then further cooled via heat exchange with unit feedstocks. As the individual refinery processes are described in the subsequent sections, simplified process flow diagrams will be provided to illustrate the specific process flow sequence for the applicable process.

The process units that constitute a refinery are continuous operations that run 24 hours per day, 365 days per year. Refinery process operations personnel typically work 12-hour shifts around-the-clock to operate the process equipment. A process unit run-length is usually 1 to 5 years before it is shutdown for several weeks of turnaround maintenance. As a result, a refinery process unit's service factor (i.e., availability) is well above 90%. The turnaround timing is scheduled based upon catalyst activity requiring a catalyst change out (if applicable) or based on predictive maintenance techniques applied to the critical process equipment.

Crude Oils

In almost all cases, crude oils have no inherent value without a petroleum refining industry to process them into usable specification products. The rare exceptions are very light crude oils or condensates that may be burned as low quality fuels in locations with very loose or non-existent environmental restrictions. However, as a result of the refining industry, crude oil is one of the most significant categories among the commodities in the world.

Petroleum crude oils are composed of numerous hydrocarbons. Hydrocarbons are chemical compounds made up of predominantly carbon and hydrogen. Hydrocarbons found in crude oils generally also contain the elements sulfur and nitrogen. Many crude oils also contain absorbed levels of the toxic gas hydrogen sulfide (H₂S). Additionally, crude oils may contain trace amounts of metals such as nickel and vanadium, as well as salts. Most of the non-

hydrogen, non-carbon elements found in crude oils are undesirable and are removed from the hydrocarbons in total or in part during refinery processing.

One of the key attributes for characterizing the hydrocarbons composing crude oils is by “boiling point”. This attribute is determined through laboratory test methods by measuring the temperature at which the components of the crude oil will evaporate at a given pressure (typically atmospheric pressure unless stated to be a different pressure basis). A “True Boiling Point” (TBP) curve is developed as a part of the Crude Assay to plot or tabulate the liquid volume percent of the crude oil that evaporates relative to temperature at atmospheric pressure. The numerous hydrocarbon components constituting crude oil will generally have individual boiling points ranging from less than 60°F to greater than 1200°F.

Crude oils are named and grouped into broad categories typically based on the geographic location of origin, along with the level of sulfur contained in the crude and/or density of the crude oil. For example, West Texas Intermediate (WTI) and West Texas Sour (WTS) are two families of crude oils produced in the oilfields of West Texas—WTI is a light, sweet (i.e., low levels of sulfur relative to high sulfur “sour” crude oils) crude oil when compared to the heavier, higher sulfur content WTS. Higher sulfur crude oils are more corrosive than lower sulfur crude oils. To ensure a reasonable life expectancy for equipment processing the higher sulfur crude oils, refiners specify that such equipment be built from more expensive alloys with a higher corrosion resistance.

The American Petroleum Institute (API) has developed the term Degrees API Gravity (°API) which is widely used as another general characterization of the density of crude oils. The relationship is as follows:

$$^{\circ}\text{API} = (141.5/\text{Specific Gravity at 60 degrees Fahrenheit}) - 131.5$$

“Specific Gravity at 60 degrees Fahrenheit” is the density of the crude oil measured at 60°F divided by the density of water at 60°F.

Therefore, when comparing two crude oils, the higher density crude (i.e., the one with the highest specific gravity) will have a correspondingly lower °API. For example, the 34.5°API West African crude oil Bonny Light is heavier than the 40.4°API North Sea crude oil Forties.

Crude oil assays are a compilation of the results of numerous laboratory analyses conducted on the whole crude oil or fractions of the crude oil. These tests characterize a crude oil and enable refiners to evaluate the feasibility and economics of processing a given crude in their refinery or competitor’s refineries. Crude oil assays vary widely in the degree of detail. However, qualities of interest with respect to the whole crude, as well as various fractions of the crude

are presented in the assay.

Unfortunately, the boiling point curve for most crude oils does not match that of the products demanded. The United States demand for the lighter petroleum products boiling below 650°F (motor gasolines, diesel fuels, and jet fuels) represents roughly 85% by volume of the crude oil processed in the U.S. However, an average crude mix (as exemplified by the Strategic Petroleum Reserve crude oil assays showing only 54-62% by volume of the crude oil boiling below 650°F) has a much lower yield of hydrocarbons in the desired boiling range. Crude oils are split into the desired fractions by boiling. The low demand for these products.

Fractionation

Fractionation is a process in which the feedstock is separated into individual components by imposing a temperature gradient. This is accomplished by imposing a temperature gradient across the equilibrium compositions through the tower. The hydrocarbons at the top of the tower which vaporizes at the bottom of the tower exchange in an overhead condenser. The condensed hydrocarbons flow down the bottom and heat is removed. This heat addition at the bottom of the tower establishes the temperature profile across the tower. In some applications, additional heat is removed by heat exchange with circulating liquid "pumparound" streams which are withdrawn and returned at intermediate levels of the tower. Perforated tray decks or packed bed sections allow intimate contacting of the liquid and vapor phases followed by separation.

Distillation concentrates the lower boiling point material towards the top of the tower. The lowest boiling point product is the tower overhead vapors which are condensed as distillate. Progressively higher boiling point material is present further down the tower. Gravity forces the liquid phase to flow down the tower. Additional intermediate boiling range streams may be withdrawn at various levels from the tower as side-stream products. The highest boiling range material is the liquid product withdrawn from the bottom of the tower.

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