KLM Technology Group **Practical Engineering Guidelines for Processing Plant Solutions**	**KLM** **Technology** **Group** **ENGINEERING SOLUTIONS** **www.klmtechgroup.com**	**Rev: 01** **Rev 01 – February 2016**
KLM Technology Group **P. O. Box 281** **Bandar Johor Bahru,** **80000 Johor Bahru,** **Johor, West Malaysia**	**Kolmetz Handbook of Process Equipment Design** **REFINERY ATMOSPHERIC CRUDE TOWER SELECTION, SIZING AND TROUBLESHOOTING** **(ENGINEERING DESIGN GUIDELINES)**	**Co Author** **Rev 01 – Reni Mutiara Sari** **Editor / Author** **Karl Kolmetz**

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INTRODUCTION

Scope

Crude distillation unit (CDU) is at the front-end of the refinery, also known as topping unit, or atmospheric distillation unit. It receives high flow rates hence its size and operating cost are some of the largest in the refinery. Many crude distillation units are designed to handle a variety of crude oil types.

In most refineries, this process is carried out in two stages. The oil is first heated to the maximum temperature allowable for the crude being processed and for the operation being practiced and then fed to a fractionating tower which operates at slightly above atmospheric pressure. It yields several distillate products and a bottoms product. This tower is usually called the atmospheric tower.

In fact, industrial distillation columns do not provide perfectly sharp separations. There are several causal factors such as, initial calculations using crude oil assays assume that all materials at a certain boiling point goes to one product or another, imperfect separations result in light ends & heavy ends "tails" in adjacent products and presence of tails complicate the definition of "cut point".

The key to understanding crude columns is to understand that the atmospheric crude tower is a type of main fractionator. The important characteristics that distinguish main fractionators from other types of towers include all the heat available for the distillation enters the tower with the feed. Feed heat usually comes from a fired heater or a preheat train. The tower has multiple heat removal zones using either pump arounds or pump downs. Multiple side draw products leave the towers. All these characteristics make main fractionators different from classical distillation towers. Main fractionators have intimately linked heat and material balances. Understanding their operation requires tracking how heat and material balances affect each other.

There are many available guidelines developed to aid engineers in selecting and sizing the refinery atmospheric crude tower, but mostly these guidelines are developed by certain companies and might only be suitable for the application of the refinery atmospheric crude tower provided by their own companies. Hence, it is important to obtain a general understanding of refinery atmospheric crude tower sizing and selection and whenever changes are needed in a process system, this basic knowledge is still applicable. This

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guideline is made to provide that fundamental knowledge and a step by step guideline; which is applicable to properly select and size refinery atmospheric crude tower in an independent manner.

Selection of refinery atmospheric crude tower is based on the method used for heat removal. The processes are typically composed of series of flash drums, type U, type A and type R. Whereas, in sizing the tower, there are several aspects that should be considered that are described in this guideline.

The theory for the tower consists of the properties of oils, fractionation and separation criteria and the mass and heat balances. The procedures to design refinery atmospheric tower are also summarized in this guideline.

In the application section of this guideline, there are several cases are shown and discussed in detail, highlighting the way to apply the theory for the calculation. Example Calculation Spreadsheets are part of this guideline. This Example Calculation Spreadsheets are based on case studies in the application section to make an engineer easy to follow the step by step calculation for different application industries.

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General Consideration

A. Processes in Atmospheric Crude Distillation Units

Crude units are the first units that process petroleum in any refinery. The objective is to separate the mixture into several fractions like naphtha, kerosene, diesel and gas oil. These streams will either be subject to further treating downstream or become feed stock for conversion units that may be in the Refinery Configuration. Atmospheric crude distillation unit can be shown in figure 1.
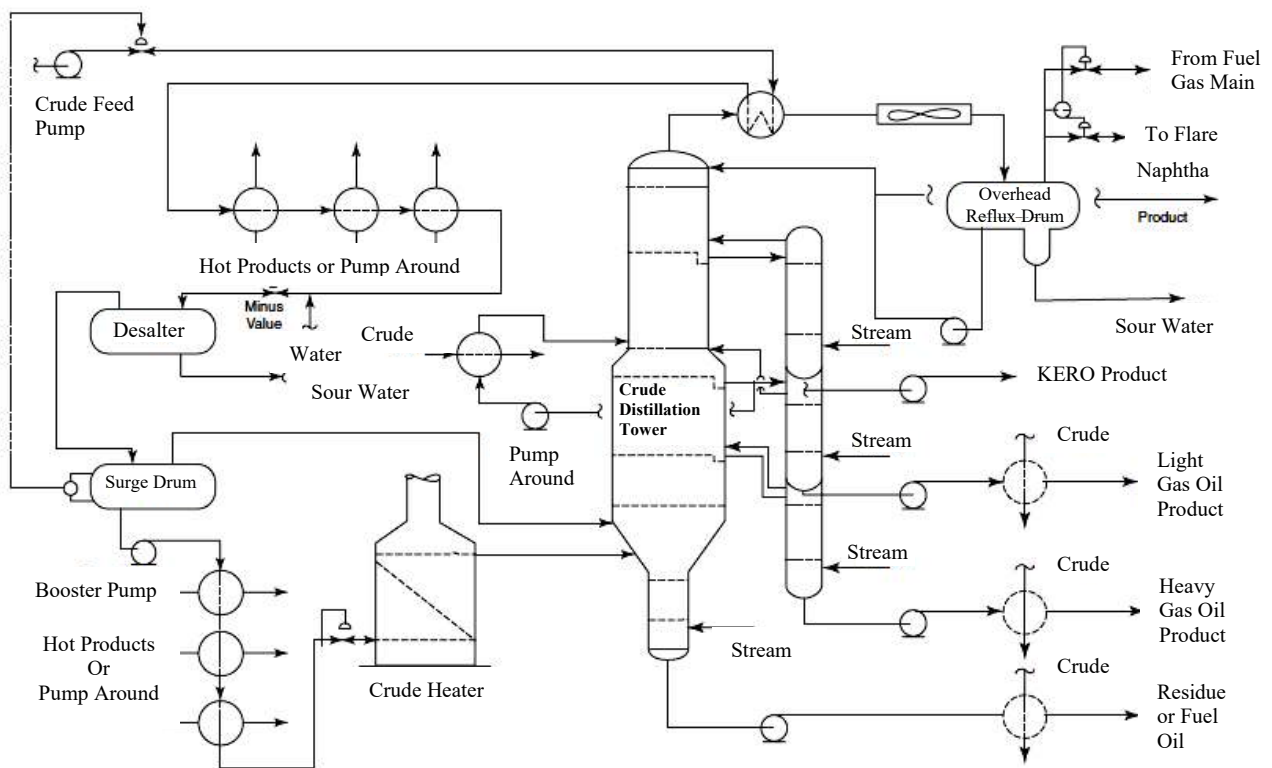
Figure 1: a typical atmospheric crude distillation unit

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Crude oil is pumped from storage to be heated by exchange against hot overhead and product side streams in the Crude Unit. At a preheat temperature of about 200–250∘F water is injected into the crude to dissolve salt that is usually present. The mixture enters a desalter drum usually containing an electrostatic precipitator. The salt water contained in the crude is separated by means of this electrostatic precipitation. A portion of the water phase from the drum is sent to a sourwater stripper to be cleaned before disposal to the oily water sewer.

The crude oil leaves the desalter drum and enters a surge drum. Some of the light ends and any entrained water are flashed off in this drum and routed directly to the distillation tower flash zone (they do not pass through to the heater). The crude distillation booster pump takes suction from this drum and delivers the desalted crude under flow control to the fired heater via the remaining heat exchange train.

On leaving heat exchanger train, the crude oil is heated in a fired heater to a temperature that will vaporize the distillate products in the crude tower. The heated crude enters the fractionation tower in a lower section called the flash zone[4].

The partially vaporized crude is fed into the feed region (called flash zone) of the atmospheric column, where the vapor and liquid separate. The vapor includes all the components that comprise the products, while the liquid is the residue with a small amount of components in the range of gas oil. These components are removed from the residue by steam stripping at the bottom of the column. Products are withdrawn from the side of the column and side strippers are used to help controlling the composition of light components[10]. The side stream distillates that are arranged according to the highest boiling point, are :

- Heavy gas oil
- Light gas oil (Diesel)
- Kerosene (Jet Fuel)

The lightest distillate fraction is not always completely condensible at the conditions of temperature and pressure in the reflux drum and, thus, may be yielded as two distillate fractions, one vapor and one liquid. A small amount of extra vaporization, called overflash, will be employed to provide adequate reflux in the section between the flash zone and the first (lowest) sidestream product draw tray.

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B. Analysis of Crude Petroleum and Its Fractions

A complete component-by-component analysis of a crude oil sample is not practically realizable. Therefore, the boiling range of petroleum liquid is of primary importance. For this reason, the composition of any given oil is approximated by various distillation methods as follows:

a. TBP (True Boiling Point) Distillation

A true boiling point distillation, commonly called TBP distillation. This method is basically a batch distillation using a large number of stages and a high reflux-to-distillate ratio so that the temperature at any point on the temperature-volumetric yield curve represents the actual (true) boiling point of the hydrocarbon material present at the volume percentage point. TBP distillations are normally run only on crude oils and not on petroleum fractions. Instead, a rapid distillation procedure is used for analysis of petroleum products and intermediate fractions.

b. ASTM (American Society for Testing Materials) Distillations

For petroleum products, a more rapid distillation procedure is used. This procedure was developed by the American Society for Testing Materials (ASTM distillations) which employs no trays or reflux between the still-pot and the condenser, like TBP, and as a result the separation is not as good as it could be in TBP distillation[2]. The only reflux available is that generated by heat losses from the apparatus. These test methods are used in control laboratories throughout the world.

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ASTM distillation test is illustrated in figure 2.
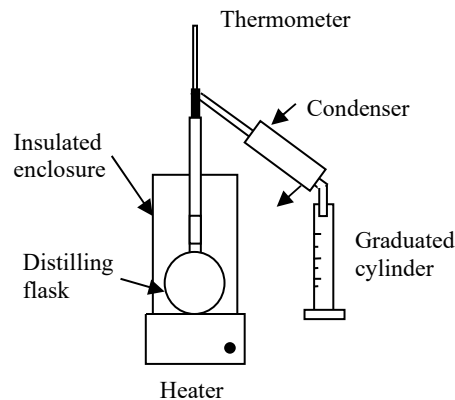
Figure 2: ASTM distillation test

At the beginning of distillation, the vapor temperature is reported as the IBP (initial boiling point) while the first drop is collected. Then, distillation is continued and the temperature of the vapor and the cumulative volume percent collected are simultaneously reported. The maximum vapor temperature at which the distillate collection is negligible, it is reported as the FBP (final boiling point).

Products from the atmospheric tower are usually drawn to meet a compositional specification that is represented by a distillation. Typically light product streams such as naphtha, kerosene, and diesel use a protocol called a ASTM D-86 to determine the product stream distillation. For heavier fractions an ASTM D-1160 test at reduced pressure is employed [3].

c. EFV (Equilibrium Flash Vaporization) Distillation

This distillation method uses a heater to heat up the liquid and then a flash drum to separate the liquid and vapor phases. This provides data that is useful for determining proper flashing operations in a refinery. By looking at the distillation curve for this method it can be noted that this gives the lowest degree of separation [8].

This distillation can be run at pressures above atmospheric as well as under vacuum, whereas the TBP and ASTM distillations are run either at atmospheric pressure or under vacuum. EFV curves are almost exclusively limited either to crude oil or to reduced crude

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samples (atmospheric tower bottoms liquid) which are being evaluated as vacuum tower charge stocks. The ASTM, TBP and atmospheric EFV distillation curves for a typical petroleum fraction can be showed in figure 3.
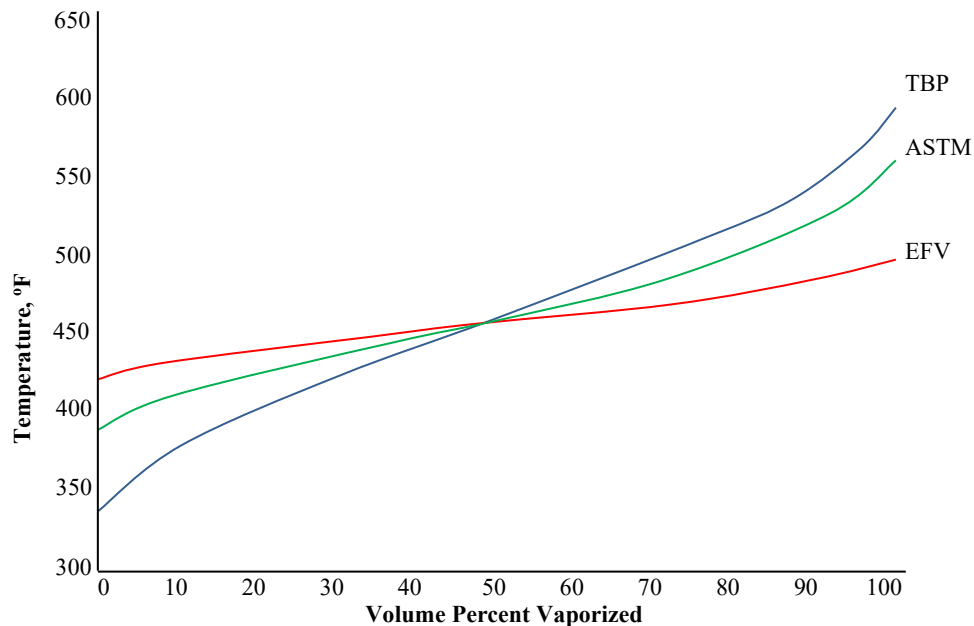
Figure 3 : ASTM, TBP and EFV curves for 39.7 degrees API light distillate

C. Crude Assay

Crude oil assay is a compilation of laboratory and pilot plant data that define the properties of the specific crude oil [4]. A complete crude assay will contain some or all of the following [7]:

1. Whole crude gravity, viscosity, sulfur content, pour point, etc.
2. TBP curve, mid-volume plot of gravity, viscosity, sulfur, etc.
3. Light-ends analysis up through C8, or C9.
4. Properties of fractions (naphtha, middle distillates, gas oils and residua)-yield as volume percent, gravity, sulfur, viscosity, octane number diesel index, flash and fire point, freeze point, smoke point, pour point, vapor pressure, etc.

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5. Properties of lube distillates (only if the crude is suitable for the manufacture of lube base stocks).
6. Properties of asphalts (only if the residua have suitable characteristics for preparation of asphalts).
7. Detailed studies of fractions for various properties, e.g., octane number versus yield for naphtha or viscosity versus yield for lube stocks.
8. EFV curve run at atmospheric pressure and/or phase diagram, although this is rarely done.

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DEFINITION

Aniline point - the minimum temperature for complete miscibility of equal volumes of aniline and a test sample. This test is an indication of paraffinicity and the ignition quality of diesel.

API gravity - an arbitrary scale expressing the density of petroleum products.

ASTM distillation - standardized laboratory batch distillation for naphtha and middle distillate at atmospheric pressure.

ASTM gap - the difference between the ASTM 5% boiling point of the heavier product and the 95% point of the lighter product.

Atmospheric tower - distillation unit operated at atmospheric pressure.

Characterization factor - a systematic way of classifying a crude oil according to is paraffinic, naphthenic, intermediate or aromatic nature.

Cetane number - related to ignition quality and defined as the time period between the start of injection and start of combustion (ignition) of the fuel.

Cloud point - temperature at which the oil becomes cloudy or hazy.

Crude assay - a procedure for determining the general distillation and quality characteristics of crude oil.

Cut point - temperature on the whole crude TBP curve that represents the limits (upper and lower) of a fraction to be produced (yield of a fraction).

Distillate - the products of distillation formed by condensing vapors.

End points - the actual terminal temperatures of a fraction produced commercially.

F-Factor - the ratio of the hot gallons per hour (GPH) of the lightest product from draw off tray to the total vapor product (cold GPH) leaving the lightest product draw off tray.

Flash point - the temperature at which the vapor above the oil will momentarily flash or explode.

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Fractionation criteria - a correlation between Reflux Ratio, N, G and ΔT50% TBP between the adjacent cuts.

Fractionating tower - process unit that separates various fractions of petroleum by simple distillation, with the column tapped at various levels to separate and remove fractions according to their boiling ranges.

Pour point - the temperature at which the oil ceases to flow.

Octane number - a measure of a gasoline's resistance to knock or detonation in a cylinder of a gasoline engine.

Overflash - to provide additional heat (over and above that set by the product vaporization required) required by the process to generate the internal reflux required by the process.

Reboiler - an auxiliary unit of a fractionating tower designed to supply additional heat to the lower portion of the tower.

Reflux - the portion of the distillate returned to the fractionating column to assist in attaining better separation into desired fractions

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NOMENCLATURE

Ad = downcomer area, ft^2

API = API gravity, (dimensionless)

At = total area, ft^2

Av = bubble area, ft^2

Aw = waste area, ft^2

C = specific heat of stripped product, Btu/lb.^{o}F

D = diameter of tray, ft

DN = total distillates (vapor and liquid) to top tray, measured as 60 ^{o}F liquid,gal/hr

F = crude feed, gal/hr or bbl hr

G$_f$ = Mass velocity of vapor at flood in lbs/hr. sqft of bubble area

h$_F$ = enthalpy of feed, Btu/lb

h$_w$ = enthalpy of bottom (waste), Btu/lb

K = characterization factor, (dimensionless)

LM = reflux from the upper draw tray measured as 60 ^{o}F liquid, gal/hr

LN = reflux from the top tray measured as 60 ^{o}F liquid, gal/hr

Lo = overflash, gal/hr

MeABP = mean average boiling points, ^{o}R

NT = number of actual trays in the section
i.e., trays M through N inclusive = N - (M - 1) = N - M + 1

P = pressure. psia

PN = total product vapors, measured as 60 ^{o}F liquids, to the upper draw tray
i.e., stream DN plus all lighter products, gal/hr

PP = partial pressure, psia

Q = heat flux, Btu/hr

SDRL = slope of the distillation reference line, (dimensionless)

SF = volume of stripper feed revaporized (stripout), %

SG = specific gravity, (dimensionless)

T = temperature, ^{o}F

V' = vol. percent crude feed flash, gal/hr or bbl hr

v$_L$ = downcomer liquid velocity, ft/s

V$_{SO}$ = stripout, gal/hr

W = volume of total bottom products, gal/hr or bbl hr

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Greek Letter

$\sum D$ = total distillate products exclusive of overflash, gal/hr

ρ_{HL} = heavy liquid density, lb/ft^3

ρ_L = liquid density, lb/ft^3

ρ_V = vapor density, lb/ft^3

v = kinematic viscosity (cSt)

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THEORY

A. Crude Oils and Oil Products Properties

Crude oils and oil products are measured by several properties. The several important properties can be described as follows.

a. API gravity

The main classification of crude is by referring to their density. The gravity of crude oil determines its price commercially. It is generally expressed as API gravity defined as

$$API = \frac{141.5}{SG} - 131.5 \qquad\qquad \text{Eq (1)}$$

where SG is the specific gravity defined as the density of the crude oil relative to the density of water both at 60 °F. Generally low API gravity means lots of dense aromatic compounds, high gravity means lots of short chain paraffinic compounds. The API gravity can range from 8.5 for very heavy crudes to 44 for light crudes.

b. Viscosity

Viscosity indicates the relative mobility of various crude oils. Temperature has a marked effect on viscosity. The viscosity is typically determined in kinematic viscosity.

c. Vapor Pressure

Vapor pressure for crude as well as petroleum fractions can be obtained by using the correlation presented by Maxwell (1950) to relate vapor pressure in atmospheric with temperature and normal boiling point of the hydrocarbon. The normal boiling point is estimated as the volume average boiling point (VABP)[6]. The correlation is presented in table 1. Normal boiling point is considered from left to right, whereas oil temperature is from top to bottom.

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Table 1: vapor pressure data for hydrocarbons

T(°F)	C_4H_{10}	C_5H_{12}	100	150	200	250	300	350	400	450	500	550	600	700	800	900	1000	1100	1200
50	1.47	0.38	0.36	0.12	0.04	0.10													
75	2.32	0.65	0.61	0.22	0.07	0.23	0.01												
100	3.51	1.07	1.00	0.39	0.14	0.47	0.01												
125	5.20	1.64	1.53	0.65	0.25	0.90	0.03	0.01											
150	7.25	2.46	2.32	0.99	0.42	0.16	0.06	0.02	0.01										
175	9.85	3.51	3.35	1.50	0.66	0.27	0.10	0.04	0.01										
200	13.10	4.96	4.56	2.22	0.99	0.44	0.17	0.07	0.02	0.01									
225	17.15	6.78	6.50	3.15	1.48	0.67	0.29	0.12	0.04	0.02	0.01								
250	21.95	9.01	8.56	4.34	2.11	1.01	0.45	0.19	0.08	0.03	0.01								
275	27.91	12.02	11.40	5.82	3.02	1.47	0.68	0.31	0.13	0.05	0.02	0.01							
300	34.90	15.20	14.40	7.78	4.05	2.08	1.0	0.47	0.21	0.09	0.04	0.01							
325	42.40	19.30	18.80	10.05	5.45	2.81	1.43	0.70	0.33	0.14	0.06	0.02	0.01						
350	51.80	24.30	23.20	13.10	7.41	3.80	2.02	1.02	0.48	0.23	0.10	0.04	0.02						
375	60.50	30.20	28.90	16.40	9.42	5.15	2.81	1.45	0.71	0.35	0.16	0.07	0.03						
400	72.10	37.10	35.02	20.70	12.02	6.76	3.68	1.94	1.01	0.51	0.25	0.11	0.05	0.01					
425	83.20	43.60	41.80	25.20	14.90	8.55	4.76	2.66	1.39	0.74	0.36	0.17	0.08	0.01					
450	95.30	51.20	49.10	30.80	18.30	10.7	6.22	3.48	1.86	1.01	0.51	0.25	0.12	0.02					
475		60.00	57.90	36.50	22.20	13.2	7.83	4.51	2.44	1.41	0.72	0.36	0.18	0.04	0.01				
500		70.10	67.40	43.20	27.30	16.3	9.80	5.77	3.21	1.84	1.02	0.52	0.26	0.06	0.01				
525		80.20	77.50	50.10	32.50	19.9	12.4	7.42	4.24	2.48	1.23	0.74	0.38	0.09	0.02				
550		92.00	88.70	59.10	39.10	24.1	15.2	9.23	5.42	3.24	1.81	1.01	0.53	0.14	0.03	0.01			
575			100	69.20	45.20	29.2	18.6	11.6	6.97	4.20	2.42	1.35	0.74	0.2	0.05	0.01			
600				79.70	52.70	34.1	22.3	14.0	8.48	5.22	3.11	1.79	1.01	0.29	0.08	0.02			
650			100	71.20	47.6	31.6	20.6	13.0	8.20	5.04	3.05	1.72	0.56	0.17	0.05	0.01			
700				90.00	62.2	42.1	28.4	18.7	12.2	7.65	4.68	2.83	0.98	0.33	0.10	0.03	0.01		
750					79.1	55.2	38.1	25.9	17.6	11.2	7.15	4.24	1.62	0.61	0.20	0.06	0.01		
800						96.7	70.0	49.7	33.5	23.5	15.3	10.7	6.48	2.52	1.02	0.37	0.11	0.03	0.01
850							86.3	63.8	44.1	31.8	20.8	14.8	9.25	3.76	1.61	0.62	0.20	0.06	0.02
900								78.5	57.2	41.7	28.1	19.1	12.6	5.58	2.43	1.02	0.36	0.12	0.03
950								96.1	71.9	53.5	37.1	26.2	17.9	8.05	3.69	1.59	0.62	0.22	0.07
1000									87.4	68.1	47.9	34.8	23.2	11.3	5.36	2.45	1.02	0.39	0.15
1050										83.9	59.6	44.5	30.8	15.2	7.70	3.63	1.59	0.64	0.24
1100										100	73.8	56.1	39.1	20.4	10.8	5.22	2.32	0.99	0.42
1150											89.9	68.5	50.2	26.3	14.1	7.36	3.43	1.52	0.65
1200												82.0	62.4	32.4	18.4	9.90	4.86	2.21	1.01

d. Flash Point

Flash point, which is defined as the temperature at which the vapor above the oil will momentarily flash or explode. It is expressed as:

$$\text{Flash Point (°F)} = 0.77\left(ASTM\,5\%(^{o}F) - 150(^{o}F)\right) \qquad \text{Eq (2)}$$

e. Pour Point

Pour point, defined as the temperature at which the oil ceases to flow. The relation of this is the lower the pour point then, the lower the alkane content and the greater the aromatics content.

f. Reid Vapor Pressure

Reid vapor pressure indicates the relative percentage of gaseous and lighter hydrocarbons. This specific test is to measure volatility at 100°F. It is determined by ASTM method D 323.

g. Cloud Point

This is defined as the temperature at which a haze appears in a sample which is attributed to the formation of wax crystals. Cloud point data is used to determine the tendency of small orifices to plug in cold operating temperatures, normally measured on middle distillate cuts.

h. Aniline Point

Aniline point indicates the lowest temperature at which the oil is completely mixed with an equal volume of aniline. High aniline point indicates that the fuel is Paraffinic and hence has a high diesel index and very good ignition quality [9].

i. Octane Number

Octane number, is a measure of a gasoline's resistance to knock or detonation in a cylinder of a gasoline engine. The higher this resistance is the higher will be the efficiency of the fuel to produce work.

j. Cetane Number

Cetane number, or Diesel Index, is related to ignition quality and defined as the time period between the start of injection and start of combustion (ignition) of the fuel. The fluids of reference are: n-hexadecane (Cetane Number = 100) and alpha methyl naphthalene (Cetane Number = 0). Higher cetane fuels will have shorter ignition delay periods than lower cetane fuels. Diesel Index is also related by the aniline point that is given as[2]

$$\text{Diesel Index } = \text{API x aniline point, °F} / 100 \qquad \text{Eq (3)}$$