Atmospheric distillation involves operating with atmospheric column inlet temperatures no greater than 370-380°C in order to avoid the formation of cracking gases and to prevent coke being deposited in the coils of the heater.

Vacuum distillation is carried out at reduced pressures, down to 10-15 absolute mmHg at the top of the column. Generally the outlet temperatures from the heater are higher in comparison with those used in atmospheric distillation; moreover, in order to maximize the recovery of the distillates, the partial pressure of the hydrocarbons is lowered in the flash zone, injecting steam into the coils of the heater and using appropriate quantities of stripping steam in the bottom of the column itself.

### 2.3.1 Vacuum distillation purposes

The purpose of the vacuum distillation unit is to recover higher quantities of distillates (vacuum gas oils) from the residue of the atmospheric distillation.

In addition to vacuum gas oils, the other products which are obtained are the vacuum residue, which comes out from the bottom of the vacuum column, a waxy-like fraction (called *slop wax*), which is generally extracted from a chimney tray positioned above the flash zone, and incondensable gases which exit through the top of the column. The incondensable gases consist of cracking gases which are formed in the heater and of air which seeps into the column through the flanged nozzles. The vacuum residue can be sent to subsequent conversion plants or can be used as a component in fuel oil or in the production of lubricating oils and bitumens. A scheme showing the main pieces of equipment of a vacuum plant is reproduced in Fig. 1.

After being preheated in the exchangers which recover heat from the vacuum column’s products and from the intermediate refluxes (commonly referred to as *circulating refluxes* or *pumparound*), the atmospheric residue is sent to the vacuum heater, in which its temperature is raised to between 380 and 420°C in order to vaporize the required amount of distillates; it is then sent to the flash zone of the vacuum column. This temperature limit is imposed by the necessity to minimize thermal cracking reactions which lead to the formation of gas and carbonaceous materials which tend to be deposited on the coils of the heater and on the hottest internal parts of the column, in particular in the flash zone and in the sections immediately above.

A vacuum column normally contains the following sections (Fig. 2):

- **A Light Vacuum Gas Oil (LVGO) section.** This is the upper section where the lightest part of the vapours flowing upward from the flash zone of the column are condensed. The incondensable hydrocarbons and the air which seeps in, exit from the top of the column and are removed by a system of ejectors.
- **A Heavy Vacuum Gas Oil (HVGO) section.** The heavier vapours condense in this section. In some instances, in order to obtain greater homogeneity in the distribution of the column’s liquid and vapour load and hence reduce its maximum diameter, it can be useful to include the extraction of a Medium Vacuum Gas Oil fraction (MVGO).
- **A washing (wash oil) section.** The vapours coming out of the flash zone, where the feedstock is fed in, are ‘washed’ and partially condensed in order to reduce the entrainment into the distillate above (HVGO) of the heavier fraction, which contains metals, particles of coke and asphaltene components. Slop wax, which
can be re-circulated back into the heater or mixed with the vacuum residue, is obtained from the chimney tray, which is normally installed under the wash oil section.

- A vacuum residue section. This collects the heavier hydrocarbons from the feedstock which descend from the flash zone and from the wash oil section.

### 2.3.2 Operating variables

It is essential to consider the effect that changes to the principal operating variables can have on the column’s operation in order to ensure the correct operation of the vacuum distillation unit.

**Level of vacuum in the column**

The level of vacuum in the column, which is maintained by ejectors, has a positive effect on the fractionating allowing, among other things, the heater outlet temperature to be lowered and the depositing of carbon material on the heater’s coils to be minimized. Operating at higher levels of vacuum, hence at lower absolute pressure levels, the boiling temperatures of the hydrocarbons are reduced to the point at which it is possible to recover the heaviest components of the heavy vacuum gas oil fractions which are present in the atmospheric residue fed into the plant, thus avoiding the need to reach temperature levels that could lead to the formation of cracking gas and carbon particles that could be transported towards the higher zones of the column. In summary, all other operating parameters being equal, increasing the
Vacuum level increases the recovery of distillates of the quality required for downstream processing. The optimization of a vacuum distillation plant calls for maximizing the recovery of the distillates and minimizing the quantity of vacuum residue which is used for the production of fuel oil or bitumen, or which must be processed in a thermal or catalytic cracking plant. In general, vacuum gas oils feed catalytic plants, for example Fluid Catalytic Cracking (FCC) units or hydrocrackers. To obtain good catalytic plant performance, and in particular for hydrocracking units, it is advisable to minimize the content of Conradson carbon residue and of metals (nickel, vanadium, etc.), especially for heavy vacuum gas oil. A high carbon residue content is obtained when, as a result of high temperatures, cracking takes place leading to the formation of carbon particles which are transported into the heavy vacuum gas oil fraction. In fact, the formation of large quantities of carbon particles reduces the efficiency of the wash oil section, worsening the fractionating and hence increasing the content of vacuum residue components, with high contents of Conradson carbon residue and metals, in the heavy vacuum gas oil. Naturally a reduction of pressure in the column leads to an increase in the volume of vapour that rise from the flash zone towards the top of the column; it is therefore necessary to choose the appropriate diameter of the column that will prevent excessively high vapour velocities from transporting heavy products into the distillates. Conversely, given the same heater outlet temperature, an increase in overhead pressure reduces the vaporization in the flash zone and hence reduces the yield of the distillates and lowers the initial distillation point of the vacuum residue. A typical temperature and pressure profile for a vacuum column in relation to its theoretical stages can be seen in Table 1. Stages 15 and 16 simulate the vacuum residue stripping trays. Higher vacuum levels (30-40 mmHg) can also be reached in the flash zone, provided that installation of a booster ejector is foreseen on the overhead vapours at the vacuum outlet.

Outlet temperature of the vacuum heater

Any variation in the heater outlet temperature alters the equilibrium within the vacuum column, changing the temperature profile and the quality and yield of the distillates. An increase will lead to greater vaporization and the distillates will become heavier, while the opposite effects will result from a reduction in the temperature. An excessively high temperature leads to cracking reactions with the formation of carbon deposits, particularly on the coils of the heater, making it necessary to shutdown the plant more frequently in order to clean the heater (decoking). To limit the heater outlet temperature steam can be injected into the coils. These injections enable the partial pressure of the hydrocarbons to be reduced and therefore, while maintaining the same quantity of vaporized material, the temperature to be reduced. Moreover, the injection of steam increases the velocity to a value that is ideal for minimizing the residence time of the hydrocarbons in the heater coils in the area which is subject to the highest flue gas temperature.

Flow rate of stripping steam to the vacuum column

Superheated steam is usually injected into the bottom of the column to remove the part of the heavy distillates which have remained dissolved in the liquid fraction coming from the heater. A typical flow rate value for stripping steam would be 2-3% by weight with respect to the flow rate of vacuum residue exiting from the bottom of the column. A flow rate which is too low tends to leave some of the components of the heavy vacuum gas oil in the vacuum residue, while an excessive flow rate can cause upward transport of the heavy product, with a consequent decrease in the recovery of the distillates.

### Table 1. Pressure and temperature profiles for a distillation column operating under (not excessively high) vacuum

<table>
<thead>
<tr>
<th>TRAY</th>
<th>TEMPERATURE (°C)</th>
<th>PRESSURE (absolute bar)</th>
<th>PRESSURE (absolute mmHg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80</td>
<td>0.112</td>
<td>84.0</td>
</tr>
<tr>
<td>2</td>
<td>135</td>
<td>0.114</td>
<td>85.5</td>
</tr>
<tr>
<td>3</td>
<td>185</td>
<td>0.115</td>
<td>86.2</td>
</tr>
<tr>
<td>4</td>
<td>229</td>
<td>0.117</td>
<td>87.7</td>
</tr>
<tr>
<td>5</td>
<td>245</td>
<td>0.119</td>
<td>89.5</td>
</tr>
<tr>
<td>6</td>
<td>256</td>
<td>0.120</td>
<td>90.0</td>
</tr>
<tr>
<td>7</td>
<td>273</td>
<td>0.122</td>
<td>91.5</td>
</tr>
<tr>
<td>8</td>
<td>293</td>
<td>0.124</td>
<td>93.0</td>
</tr>
<tr>
<td>9</td>
<td>318</td>
<td>0.126</td>
<td>94.5</td>
</tr>
<tr>
<td>10</td>
<td>338</td>
<td>0.127</td>
<td>95.3</td>
</tr>
<tr>
<td>11</td>
<td>359</td>
<td>0.129</td>
<td>96.8</td>
</tr>
<tr>
<td>12</td>
<td>369</td>
<td>0.131</td>
<td>98.3</td>
</tr>
<tr>
<td>13</td>
<td>376</td>
<td>0.132</td>
<td>99.0</td>
</tr>
<tr>
<td>14</td>
<td>380</td>
<td>0.134</td>
<td>100.5</td>
</tr>
<tr>
<td>15</td>
<td>386</td>
<td>0.136</td>
<td>102.0</td>
</tr>
<tr>
<td>16</td>
<td>380</td>
<td>0.154</td>
<td>115.5</td>
</tr>
</tbody>
</table>
contamination of the distillates withdrawn from the column in the area above the flash zone. The stripping steam also allows the partial pressure of the hydrocarbons to be reduced and hence the flash zone temperature to be lowered, while maintaining the same yield of distillates.

In some instances it is possible to carry out ‘dry’ vacuum distillation, hence without the injection of steam into the coils of the furnace and without stripping steam. In this latter case the yield of distillates is generally lower, but it has the advantage that the diameter of the vacuum column can be reduced; in fact, the flow rate of the vapours is much lower because there is no steam present in the vapour phase which rises towards the top of the column. In the case of ‘dry’ operations the absolute operating pressure should be minimized in order to maximize the recovery of the distillates.

**Flow rates and temperatures of refluxes in the column**

All of the heat which is not removed by the products leaving the vacuum column must be removed by circulating refluxes, that is by extracting the liquid from the column at a suitable section and, after having cooled it, returning it to the column. The amount of heat extracted by each circulating reflux is dependent on the temperature at which it is withdrawn, the temperature at which it is returned and its flow rate. Moreover, the amount of the heat is determined by the heat balance of the column and by the profiles of the liquid and vapour flow rates in the various sections of the column. The distribution of the heat extracted along the column is dependent on the desired yield of the various fractions (LVGO, MVGO and HVGO), on the degree of fractionation required between the adjacent fractions extracted from the column and on the thermal level at which the heat is removed.

**Bottom temperature of a vacuum column**

A higher temperature in the stripping section of a vacuum column results in a higher recovery of distillates but can cause cracking reactions to take place, with a consequent increase in the flow rate of incondensable gases and a greater formation of carbon material on the trays of the vacuum column. To avoid these problems, the vacuum residue must be kept at a predefined temperature, by means of cooling (quenching) with recirculation of part of the cold vacuum residue. Furthermore, the residence time in the bottom section of the column should be kept to a minimum.

**Flow rate of side cuts from the distillation column**

The final point of the side cuts can be adjusted in a way similar to that described in the atmospheric distillation section, whereas the initial point cannot be modified because normally no provision is made for side stripping columns (stripers). These stripers are provided only in those cases in which the lateral fractions of the vacuum column are used for the production of lubricant bases.

### 2.3.3 Vacuum generation

The operating pressure is maintained by means of a system of ejectors which use steam as their motive fluid, normally at a medium pressure. The size and number of ejectors and condensers are determined by the degree of vacuum required and the characteristics of the vapour exiting from the top of the vacuum column. In the case of a flash zone pressure of about 30 mmHg, normally a three stage vacuum generation system (vacuum system) is used.

The first stage of ejectors compresses the overhead vapours to a sufficient pressure in order to obtain, in the immediately downstream condenser, condensation of the hydrocarbons and of most of the steam present, including the motive steam. On the other hand, the second and third stages, are used to increase the pressure of the incondensable gases up to a pressure slightly above atmospheric pressure, so that they can be used as fuel gases in special burners or discharged to the flare. A condenser is installed between two successive stages. The degree of vacuum attainable is limited by the flow rate of the cooling water which is available and its inlet temperature.

The flow to the vacuum system is made up of:

1. **a)** incondensable gases, i.e. cracking gas generated in the heater and air that has entered the system through the flanged nozzles of the equipment and the piping which operate under vacuum;
2. **b)** condensable hydrocarbons coming from the column’s overhead tray (corresponding to the temperature and pressure of the tray) including also any possible entrainment;

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**Fig. 3. Cross section of an ejector.**
c) injection steam introduced into the coils of the vacuum heater; and d) stripping steam sent to the bottom of the vacuum column.

The incondensable gases are generated in the coils of the heater as a result of cracking reactions. The flow rate to the vacuum system can be affected by poor fractionating in the atmospheric distillation section, by instances of entrainment of light products due to inadequate removal of heat in the overhead section of the column and hence insufficient condensation of the LVGO fraction.

The principle on which the operation of an ejector is based (Fig. 3) is that of converting the energy of the steam used as a motive fluid into kinetic energy by adiabatic expansion. In the nozzle, once the cross section reduces, then an increase in velocity and a reduction of pressure of the motive fluid will occur. Conversely, in the subsequent diffuser the velocity of the fluid is reduced and the pressure increased until it reaches the counter-pressure existing at the outlet of the ejector. The point with the lowest static pressure is between the nozzle and the diffuser; this pressure is roughly equal to that of the process fluid arriving from the vacuum column. At this point the fluid sucked in is mixed with the motive steam which passes through the nozzle with an exit velocity of 3-4 times the sonic velocity. The mixture of steam and gas coming out of the vacuum column then enters the diffuser, where in the convergent part (supersonic regime) the velocity is converted into pressure as the cross section reduces; in the divergent part (subsonic regime) the velocity is reduced further, with a consequent increase in pressure. The temperature and pressure of the vapour are critical parameters for the determination of the size of a vacuum system; normally superheated steam has to be used because the presence of entrained water droplets can cause erosion of the internal parts of the ejector due to the high velocity.

As an alternative to the exclusive use of ejectors, a mixed system, consisting of ejectors and liquid ring pumps deployed in series, could be used. Normally ejectors are used to obtain absolute pressures of about 150-200 mmHg, while liquid ring pumps enable the required discharge pressure to be attained. This solution is adopted whenever it is intended to reduce the consumption of steam at medium pressure, thus increasing in electric power consumption.

### 2.3.4 Processes

The basic structure of a vacuum distillation plant has already been described. Below are listed different configurations of the typologies of the process scheme.

**Vacuum columns operating with (wet) or without (dry) stripping steam**

In a column operating under wet conditions, the steam is normally injected in the heater coils of the radiant section and into the stripper foreseen below the flash zone of the column itself, with the result that vaporization of the liquid is increased. In a wet column there is always a pre-condenser upstream of the ejector system in order to condense the steam injected into the heater and/or the vacuum residue stripper, with the aim of reducing the inlet flow into the first ejector stage and hence to lower the consumption of motive steam. A wet column operates at higher pressures than a dry column: the pressure must be high enough to permit condensation of the steam in the pre-condenser.

In a column operating under dry conditions there is no injection of steam, either into the coils of the heater or into the column. Using this configuration it is possible to achieve almost the same degree of vaporization as with the wet configuration, provided that the column operates at a lower pressure in the flash zone (typically 25-30 mmHg); the equivalent wet configuration would require a pressure of about 80-85 mmHg.

For fractionating under very high vacuum (initial TBP, True Boiling Point, temperature of the vacuum residue in excess of 535°C) wet conditions are normally employed since, for a given level of distillate production, this allows lower temperature profiles to be maintained compared with dry operation and hence reduces cracking.

**Vacuum unit for the production of lubricants**

This unit (Fig. 4) is designed for the production of high quality distillate fractions used for the production of lubricating oils. Each distillate has a specific viscosity corresponding to a category of lube oil. To prevent any thermal deterioration of the distillates, the column operates under wet conditions and at high levels of vacuum. Moreover, it is necessary to obtain a high degree of fractionating between the adjacent fractions extracted from the column.

**Vacuum unit for the production of bitumens**

The residue from vacuum distillation can be used as feedstock for a bitumen production plant. The operation of the vacuum column must be such as to produce a vacuum residue that makes it possible to obtain suitable rheologic characteristics in the bitumen (for example, penetration index and softening point). An increase in the degree of vacuum in the column will result in the production of a bitumen which is ‘harder’, and is characterized by higher softening points and lower penetration indexes.
2.3.5 Features of the contact devices

In general, a vacuum column uses similar contact devices to those described in Chapter 2.2 with reference to atmospheric distillation. Nevertheless it can be seen that the column, operating under conditions of high vacuum and, in the case of a wet vacuum plant, in the presence of significant quantities of steam, involves high flow rates of vapours (hydrocarbon vapours and steam). Furthermore, given the nature of the feedstock and the temperature at which the bottom section of the column operates, there can be entrainment of carbon material which has a tendency to be deposited on the contact devices. Hence, the use of structured packings is preferred, due to the fact that they lead to lower pressure drop and higher capacity.

Deposits of carbon material on the inside of the column must be avoided, especially in the washing section and the section for the recovery of heavy vacuum gas oil, because obstructing the areas where the vapours flow upward tends to reduce their flow rate and hence, at the same heater outlet temperature, to increase the pressure in the flash zone, with a consequent reduction in the yield of the distillates and a deterioration in their quality.

Moreover, it is important to ensure a continuous flow of clean liquid within each layer of the packing, in particular in the critical layers, in order to avoid the deposit of carbon material. To achieve this goal filters are installed on the discharge of the intermediate reflux pumps, to remove any solid particles, and spray nozzles are installed on special distributors above each packing with the purpose of ensuring the “wettability” of the entire layer (see again Fig. 2).

2.3.6 Problems of corrosion and materials

Corrosion phenomena in a vacuum distillation plant are principally caused by a high sulphur content in the feedstock and products, by the presence of naphthenic acids and by the acid condensates in the overhead ejector and condensation system.

Sulphur corrosion

Sulphurous products with a high boiling point are made up essentially of organic sulphur present in the polycyclic aromatic-ring components contained in the atmospheric residue. Some of these decompose in the heater leading to production of hydrogen sulphide, which is removed from the top of the column together with the incondensable gases, while others are distributed in the side cuts and in the bottoms product. It is therefore necessary to choose appropriate materials (typically martensitic steels with a chrome content varying between 5 and 13%, depending on the type of equipment) in order to avoid serious corrosion.
problems. The corrosive action of the hydrogen sulphide produced by the decomposition of the heavy products takes place throughout the overhead zone (ejectors, condensers and related equipment), where steam condensation occurs.

Naphthenic acids

As with atmospheric distillation plants, also in the case of vacuum distillation plants it is important to assess the neutralization number of the individual products and the amount of naphthenic components in the initial crude in order to get an indication of the degree of corrosiveness of the different fractions obtained by the plant. The naphthenic acids are concentrated essentially in the HVGO and hence affect the zone in the column in which this product is separated and its related circuit, until the temperature is reduced to values below 250°C. The heater, the transfer line, the flash zone and the heavy vacuum gas oil section are also areas vulnerable to corrosive attack, for which reason it is necessary to choose appropriate materials. Typically austenitic steels are used (types AISI 316L or AISI 317).

Choice of materials

From the above discussion it can be seen that in vacuum plants the problems of corrosion are in part similar to those in atmospheric distillation and occur mainly in the sections or the equipment described below.

Feedstock pre-heating section. In the hottest part (above 250°C) in particular the material can be attacked because of the presence of sulphur (sulfiding). For this reason steels with high chrome contents are used. The heater coils (high internal temperature and velocity) are usually made of 5Cr-0.5Mo or else 9Cr-1Mo, depending on the sulphur content of the feedstock and the heater outlet temperature level. When naphthenic acids are present AISI 316L type stainless steel is used for the coils.

Vacuum column. It is normally made of carbon steel, internally clad with 3 mm of 13 Cr (steel type 405, 410 or 410S); in the event that naphthenic acids are present in the crude oil feed, AISI 316L type stainless steel is used for the internal cladding.

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