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Crude Distillation Unit (CDU)

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Abstract

The chapter considers the technology of the crude distillation unit in general. The crude distillation unit is at the front-end of the oil refinery. The desalting process and distillation of crude oil are included in the crude distillation unit (CDU). The desalting process of crude oil is imperative to ensure the good quality of crude oil, that is, to remove impurities before its transfer to refining. This procedure minimizes or eliminates harmful substances such as sulfur, water, salts, and even mechanical impurities, which ensures a long operation of pipelines. However, the desalting process is only part of the distillation unit. The other phase of this unit is as already mentioned above is: distillation. Distillation is a more physical than a chemical process. The distillation process is characterised by mass-thermal transfer of materials, which leads to the obtaining of fractions. The distillation in the crude distillation unit is carried out consecutively in two ways: atmospheric and vacuum. In the Russian Federation, we classify oil refining plants in general as follows: fuel, fuel-oil, fuel-petrochemical, and fuel-oil-petrochemical. Also, regardless of the profile of the refinery, great importance is given to the crude distillation unit. The crude distillation unit, if well modeled and organized, makes it possible to obtain already more light products at this stage; therefore, there is a reduction of heavy residues, the refinement of which requires more expensive processes such as hydrocracking or catalytic cracking. The oil topping column K-1, within this framework, has been adopted in several oil refining plants in addition to the main column commonly referred to as K-2. The principal purpose of column K-1 is the separation of light gasoline and the major part of dissolved gases from crude oil. This first step of distillation at K-1 has the effect of normalizing the amount of gasoline hydrocarbons and stabilizing the operation of the main column K-2 despite possible fluctuations in the composition of crude oil. Besides, the CDU equipped with column K-1 demonstrates an increase in some valuable products such as methane, ethane, naphtha, etc.

Keywords: demulsifiers, crude oil, desalting process, desalter, electrostatic desalter, sump, separator, crude distillation units, atmospheric distillation units, vacuum distillation units, K-1 oil topping column, K-2 main atmospheric column

1. Introduction

Many crude oils usually contain besides the basic elements of its chemical composition hydrocarbons such as sulfur, oxygen, nitrogen, and mechanical impurities [1]. Oil also contains the gaseous phase as methane, ethane, and liquid phase. Gas typically dissolves in the liquid, whereas in the balance's case remains strong. It is noticed with the experience that natural gas fields are close to oil fields [2]. In general, there are four or three oil: aromatic, paraffin, naphthenic. But there is also a

mixed type [1]. The classification of crude oil is carried out for various reasons. The criteria for classifying crude oil refer more or less to its quality [3]. For a better understanding of classificatory at the quality (quality/price), the Petroleum world has adopted a benchmark called stallion as Brent Blend produced in the North Sea, West Texas Intermediate (WTI) from the USA, Dubai Crude from Dubai... However, there are other possibilities to classify oil by density, sulfur content, and viscosity. Crude oil supplied to refineries must meet requirements [4]. The pre-treatment of oil from harmful impurities occupies an important place among the main processes associated with the production, collection, and transportation of oil to refineries or export [5]. The harmful impurities of oil can be divided into two groups: hydrophilic (lipophobic) and hydrophobic (lipophilic). The hydrophobic impurities are soluble in oil. These hydrophobic impurities are organometallic compounds (metalloporphyrin complexes), organic acids, among which the most undesirable organochlorine compounds. The Hydrophilic impurities include impurities that are inherently insoluble in oil, these impurities are water and inorganic salts dissolved in it, as well as solid salts, mechanical impurities (sand, clay), hydrogen sulphide, etc. These hydrophilic impurities are in another phase (water), which are dispersed in the oil in the form of drops of water [6, 7]. Therefore, the degree of pre-treatment oil in production areas is an imperative and significantly affects the efficiency and reliability of transportation by pipeline, tanker, rail, and even road transportation [2]. These requirements should facilitate the transportation and future processing of Petroleum. The requirements are summarized as follows: water content, the content of mechanical impurities, saturated steam pressure, the content of chloride salts, and organochlorine compounds [5]. Usually, the degree of pre-treatment of oil for transportation does not consider the content of chloride salts and the content of organochlorine compounds [8], literally because all salts are large in water and not in oil [9], in connection with the decision of the Russian Federation to join the world trade organization (WTO), the requirements for oil are unified following the requirements for prepared oil according to ASTM D1250-97 [4] and EN 224 [3]. However, countries such as Russia use the GOST R 51858-2002 standard for oil, established by oil and gas companies for transportation by oil pipeline [5] for delivery to oil refining plants in the Russian Federation and export. In Russia, the pipeline transport takes into account the above-mentioned points [3, 10]: salt content (100–900 mg/l), water content from 0.5 to 1.0% of mass, impurity content (not over 0.05% of mass).

1.1 Pre-treatment of crude oil

The crude distillation unit is the first phase of oil refining. That's what we usually hear. However, if we are very careful, we can notice that oil refining began at the level of oil wells with its pre-treatment; the first pre-treatment of crude oil. However, additional pre-treatment is essential before the first separation (fractions our cups) are obtained. This additional pre-treatment and the manufacturing of these first fractions are carried out at the crude distillation unit as shown in **Figure 1**. As well, in our humble opinion for a better understanding of this unit, before getting into the thick of the topic, it is important to make the list of the main devices that make up it: The desalination plant, furnaces, distillation columns (atmospheric and under vacuum). Furthermore, in this process, there are also auxiliary equipment that is also very important, such as pumps, valves, heat exchangers, coolers, automatic process control systems, etc. The Russian Federation, as a major participant in the world oil industry alongside the United States of America, Saudi Arabia, Canada, Argentina, and other countries, has developed its own standards incorporating international standards. In a similar approach, ordinarily, in Russia, they
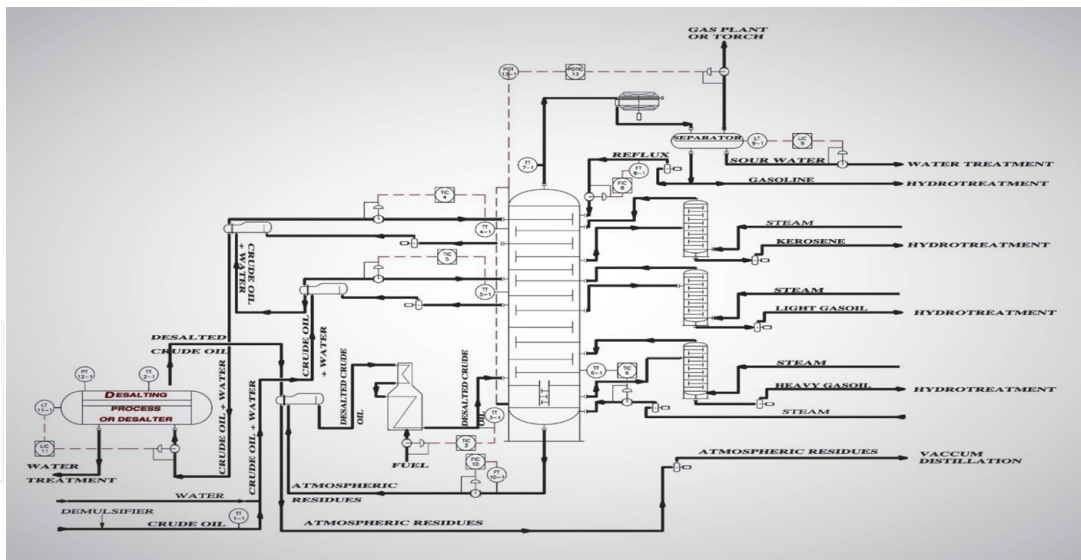
Figure 1.
P& ID diagram flow process of crude distillation unit without vacuum distillation. We would like to emphasize that reboilers were used in this scheme in this way, just for esthetics. Less flow to the reboilers is done differently.

appoint the distillation unit: Atmospheric-vacuum distillation unit (AVDU). AVDU is itself subdivided into two other units which are: Atmospheric distillations unit (ADU) and vacuum distillation unit (VDU). As a result, in this chapter, we tried to explain the operation of the atmospheric distillation crude, to model it, and to compare the usual model of the crude distillation unit with the model of the Russian Federation.

1.2 Description of the crude oil and demulsifier

1.2.1 Oil emulsion

An emulsion is a suspension of small droplets of a liquid (water) in a second liquid (oil crude) [11]. The liquids, in a stable emulsion, can only be separated by a treatment process which calls the desalting process [10]. The electrical conductivity of oil emulsions in the literature note that it has an ionic nature. A detailed theory of ionic conductivity of liquid dielectrics. Despite the low dielectric constant, the polar components of crude oil dissociate into ions and create a fairly significant amount of electrical conductivity. The reason of this manifestation is asphalt-resinous substances in oil [12]. Oil emulsion is illustrated in **Figure 2**.

1.2.2 The demulsifier (surfactant)

The demulsifier is a chemical additive to break the crude oil emulsion. The emulsifier destroys the emulsion by reducing the mechanical resistance of the protective shells formed on the surface of the water droplets. By maintaining a strict hydrophilic-lipophilic balance [6]. These emulsions are destroyed using synthetic surfactants (demulsifiers) added to the oil emulsion [13]. The criteria for selecting and evaluating the demulsifier in terms of technology, that is, yield, are as follows [8, 12, 14]:

• The velocity of separation of water from oil;

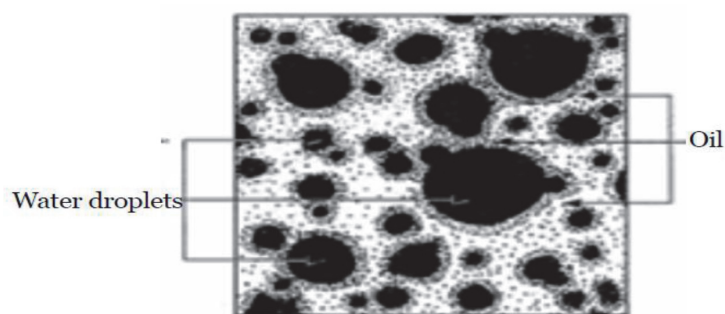• Quality of destruction of emulsions (fullness of water separation);

Figure 2.
Oil emulsion.

- Reliability in changing production conditions;

- The demulsifier must have a good quality/price or cost/efficiency ratio.

1.3 Mechanisms and devices of process of dehydration-desalination (pre-treatment) of oil crude

The process of dewatering of crude oil enters the oil production process. At the initial production period of a fresh field, wells often produce either anhydrous or low-water oil. However, over time, the water content of the oil produced increases at different rates and sometimes reaches 80–90% in old fields [1, 14]. The desalting (dewatering) processes depend on the type of oils and its content, any of the following typical processes of desalting of crude oil are combined a lot of methods like thermal, chemical, electrical and mechanical Often, a combination of Thermal and chemical methods with the mechanical or the electrical method is used to achieve effective Dehydration of crude oil [11]. The chemical treatment presents itself as a good option. It consists to use a demulsifier. The demulsifier must be introduced as early as possible (at the bottom of the well). This is an increased contact time and the interaction capacity of the demulsifier with emulsion for maximum destruction of the system [15, 16]. The injection of the demulsifying agent before the pump ensures proper contact with the crude oil and minimizes the formation of an emulsion [15]. The Industrial application of demulsifiers is not based on non-electrolytes, as their use is associated with excessive consumption or high price, as well as complex separation from oil after the deposition of the water layer. Preference is given to colloidal surface-active substances, among which are anionic, cationic, and nonionic types [13]. The number of steps (one, two or three) during oil desalination is determined by the characteristics of the initial oil emulsion and the salts contained therein For the desalination of oil emulsion independently of the stage: At the well or the refinery, the main types of equipment used for oil dewatering are electrostatics disasters, sumps, and separators [7], and they are detailed in **Figure 3** [7, 17]:

- thermo-chemical dehydrator;

- sump;

- ultrasonic;

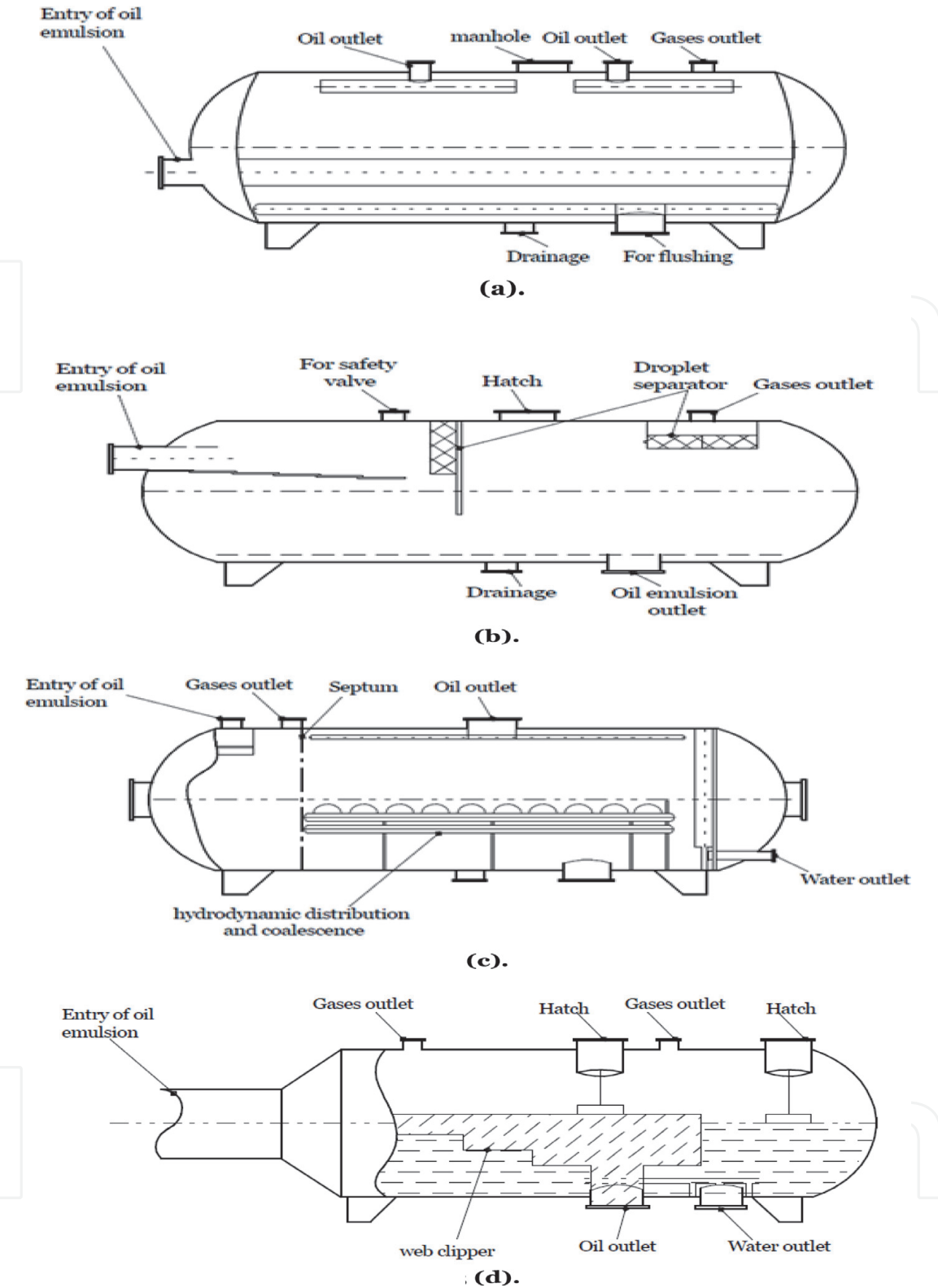- centrifugal;

- electrostatic desalter.

Figure 3.
Some examples of devices for crude oil dewatering, degassing, and desalting. (a) Sump. (b) Separator.
(c) Three-phases separator. (d) Hydrodynamic phase separator.

Each of the above-mentioned apparatus has its own peculiarities and its own derivatives, according to the precise tasks to be accomplished:

- Advanced separators-vertical flow, horizontal unit with advanced electrostatic oil dehydration capabilities.

- Desalting device-vertical flow, horizontal device with improved capabilities of electrostatic dehydration and desalting of oil. The process can occur in one or two stages.

- Field separator-electrostatic coagulator, horizontal apparatus of electrostatic coagulator. It contains the initial section of the chimney of the heating section for preheating.

- Electromechanical separators-a horizontal device that is characterized by a combination of electrostatic grids, coalescing blocks, and the initial section of the chimney heating section for preheating.

The selection criterion of devices, it is recommended to consider the following parameters when choosing the equipment [8, 12, 18]:

- properties of formation fluid and its quantity;

- stream type;

- the resistance of emulsion;

- pressure into the device;

- temperature regime.

In the separators, they usually separate gas is usually from the oil in two or three steps under slight pressure or dilution. The separators of the first stage simultaneously play the role of buffer reservoirs and are usually located on the deposit. The separators of the second and third stages are mostly on the territory of central collection and distribution points (the sites of pre-treatment and pumping of oil) [7, 17]. The vertical separators are more productive in comparison with horizontal ones, but also the vertical separators have a higher price. They are suitable for enterprises with high production capacities, as well as if the emulsion contains many solid particles [18]. The horizontal separators are the best option for processing small volumes of material, as well as liquids with a high content of dissolved gas. They are in the greatest demand, as they are quite productive and affordable. To achieve maximum efficiency when using horizontal oil and gas separators, the oil is mixed in the separation process; the temperature is increased, and the pressure is reduced. To increase the depth and improve the quality of separation in Russia, introducing hot drainage water before separation with a three-phase separator is often used. Thus, they use heat, which increases the selection of gas, intensifies the process of demulsification of oil, improves the quality of spilled formation water, reduces investments, energy costs of processes, and significantly improves the conditions of Environmental protection. The three-phase separator can split oil, gas, and water at once. However, separators have limits. Even with a three-stage separation, complete separation of gas from oil is not achieved [8]. Besides, it should be noted that, despite the improvement in oil and gas separation techniques and technologies, field separators remain cumbersome and expensive devices [19]. Their operation is based on an inefficient gravitational principle and they are unproductive; the separators cease to function when the oil and gas mixture forms foam. The loss of energy contained in the flow of oil and gas, with a decrease in the pressure in the degassing in stages, leads to the need to use more pumping and compressor units for the collection and transportation of oil and gas through the pipeline [7, 8].

The final processes of dewatering and desalting are carried out at oil refineries with electrostatic desalter [20]. At the refinery, three types of electrostatic desalter

are mainly operated as oil pre-treatment equipment: vertical, horizontal, and ball electrostatic desalter [1].

1.4 The salts in crude oil

The salts and minerals often present in the oil are mainly magnesium, calcium, and sodium chlorides with sodium chloride being the abundant type. These salts cause corrosion of equipment. For example, hydrogen chloride (HCl). Hydrogen chloride dissolves in the emulsion's water producing hydrochloric acid, an extremely corrosive acid. However, $NaCl = Na^+ + Cl^-$. Water, though slight, but dissociates into ions, and the equilibrium is established: $H_2O = H^+ + OH^-$, thus, in the salt solution, there is a mixture of Na^+ cations and OH^-, Cl^- anions. Ions in the solution move randomly and constantly collide with each other [21]. But these collisions of Na^+ and OH^- ions, H^+ and Cl^- ions do not lead to the formation of compounds, since NaOH is a strong base, and HCl is a strong acid. Since weak electrolytes are not formed when sodium chloride is dissolved in water, sodium chloride is not hydrolyzed. The concentration of H^+ ions is equal to the concentration of OH^- ions, so the color of the indicators does not change [13, 20]. All chemical compounds based on chlorine hydrolyze, except for NaCl, hydrolyze at high temperature to hydrogen chloride:

$$CaCl_2 + 2H_2O \rightarrow Ca(OH)_2 + 2HCl \tag{1}$$

$$MgCl_2 + 2H_2O \rightarrow Mg(OH)_2 + 2HCl \tag{2}$$
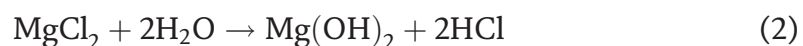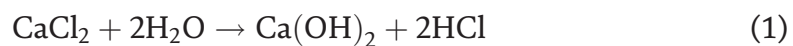
Any remaining salts are neutralized by the injection of sodium hydroxide which reacts with the calcium and magnesium chloride to produce sodium chloride because NaCl does not hydrolyze to the corrosive hydrogen chloride.

$$CaCl_2 + 2NaOH \rightarrow Ca(OH)_2 + 2NaCl \tag{3}$$
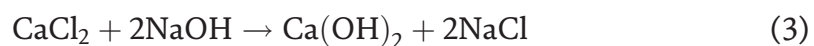
1.5 Description of dewatering of oil emulsions with electrostatic desalter

The electrical conductivity of oil emulsions is due to the ionic conductivity of oil, the conductivity of dispersed water droplets in oil. Under certain conditions, droplets of emulsified water in oil form conductive structures in the form of "chains", located along the field lines [12, 22]. The electrical conductivity of the system in such cases increases sharply (hundreds and thousands of times) in comparison with the electrical conductivity of anhydrous oil. Electrical Conductivity of hydrocarbons (oil), the hydrocarbons have three types of conductivity regimes in general [23]:

- The stable insulating regime, this regime is characterized by very high resistance. In this state, conduction is related to traces of dissolved water in the hydrocarbon.

- The semiconductor, this regime is independent of the presence of water in the hydrocarbon.

- Conductor, relatively stable. The regime, however, it disappears by sufficient removal or reduction of the applied electric field and reappears when it is restored to its initial value.

1.5.1 Description of electrostatic desalter and its process

The modern desalting units are designed with electric dehydrators only horizontal execution and are part of the equipment for preparing oil: both atmospheric and atmospheric-vacuum installations. The horizontal design of electrostatic desalter has several advantages, such as a large area of the electrodes and, accordingly, a greater amount of oil per unit of section of the device, a lower vertical speed of the moving flow of oil, which provides favorable conditions for settling water, as well as implementing processes with higher pressure and temperature [22, 24]. The dominant types of electrostatic desalter are shown in **Figure 4**. The increases of the electrical conductivity are related to traces of dissolved water in the oil; it has the effect of slowly eliminating this water, correlative elimination of an indefinite increase in resistivity. The work and efficiency of the electrostatic desalter are based on the Stokes formula [25] for the time of deposition of water droplets and the specific electrical conductivity (γ, Om m^{-1}) is the electrical conductivity of a substance measured between flat electrodes of the same area, located at a distance (L) in meter, and divided by the electrode area [12]. The principle of operation of the electrostatic desalter is quite simple. We have one inside two electrodes that have two opposite charges. The oil is supplied to the lower stage of the device, which provides its additional washing and passing through two (2) electric fields: weak and strong as shown in **Figure 5**. The charges of these electrodes change alternately, resulting in a separation of the different phases: oil, water, and gas [11, 26]. The water has a higher density than the oil and by the gravitational force, so the water is concentrated at the bottom of the electrostatic desalter. The oil and the gas without water, so without salts, come out from the upper part of the electrostatic desalter by manifold as shown in **Figure 6** [20]. In the literature, there are indications that the electrical conductivity of oil and petroleum products is largely determined by the content of polar surfactants (asphalt-resins) in them [25].

1.5.2 Desalting processes at a refinery

They can be one and two-stage (respectively, with one or two electrostatics desalters) [20]. To increase the efficiency of the operation, the demulsifiers are added to the crude oil. Two-stage installations are used to reduce the flow of freshwater when washing crude oil [13]. The desalter of this design achieves 90% salt removal. However, 99% salt removal is possible with two-stage desalters [7, 20] as shown in **Figure 7**. A second stage is also essential since desalter maintenance requires a lengthy amount of time to remove the dirt and sediment which settle at the bottom. Therefore, the crude unit can be operated with a one stage desalter while the other is cleaned.

1.6 Example of modeling of electrostatic desalter at refinery

The electrostatic desalter volume 96 m^3, which length-10 m, diameter –3 m. U (voltage of the electrodes) = 22000 v. Maximum emulsion pre-treatment capacity
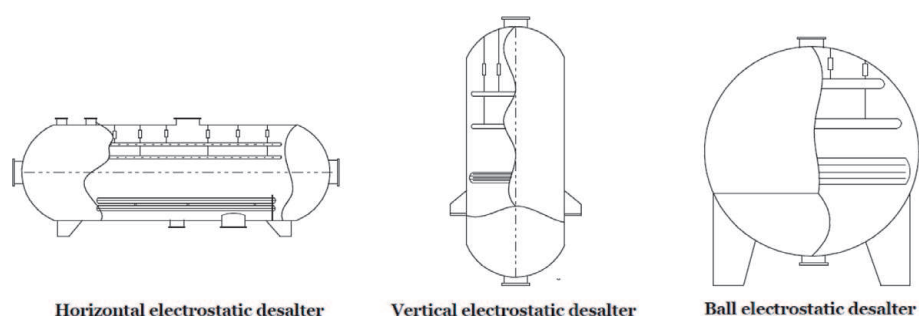

Horizontal electrostatic desalter   Vertical electrostatic desalter   Ball electrostatic desalter

Figure 4.
The major types of electrostatic desalter.

| Designation	denomination
1	Pressure, temperature indicator
2	safety valve
3	For to remove sludge
4	outlett desalted crude oil
5	Transformer
6	Level control (level meter)
7	salt water output
8	Hatch
9	The pumping of crude oil
10	oil emulsion inlet
A	insulator
B	High voltage electrode
C	commutator
D	distributor
E	collector
F	suspension insulator
H	High voltage electrode
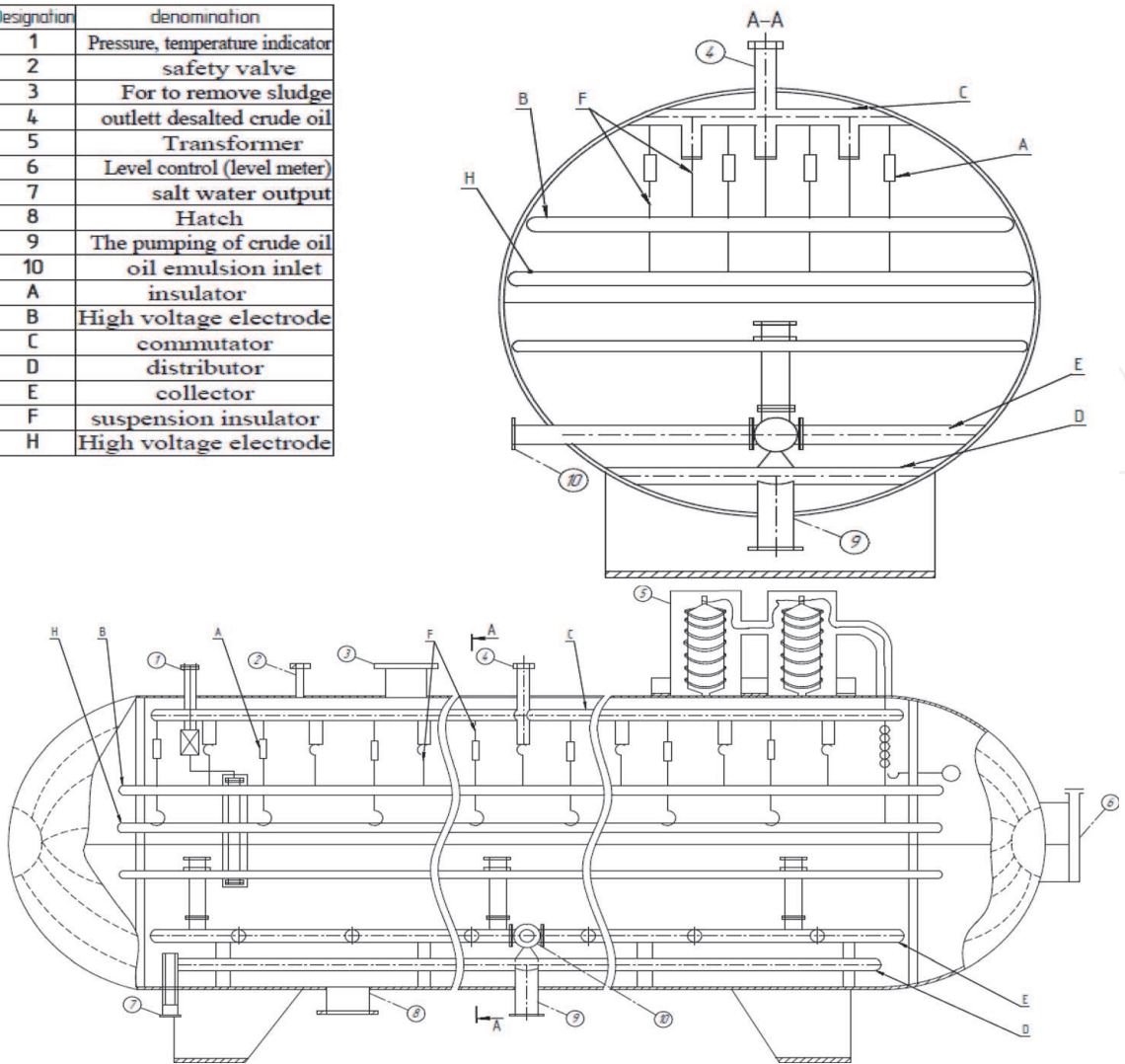
Figure 5.
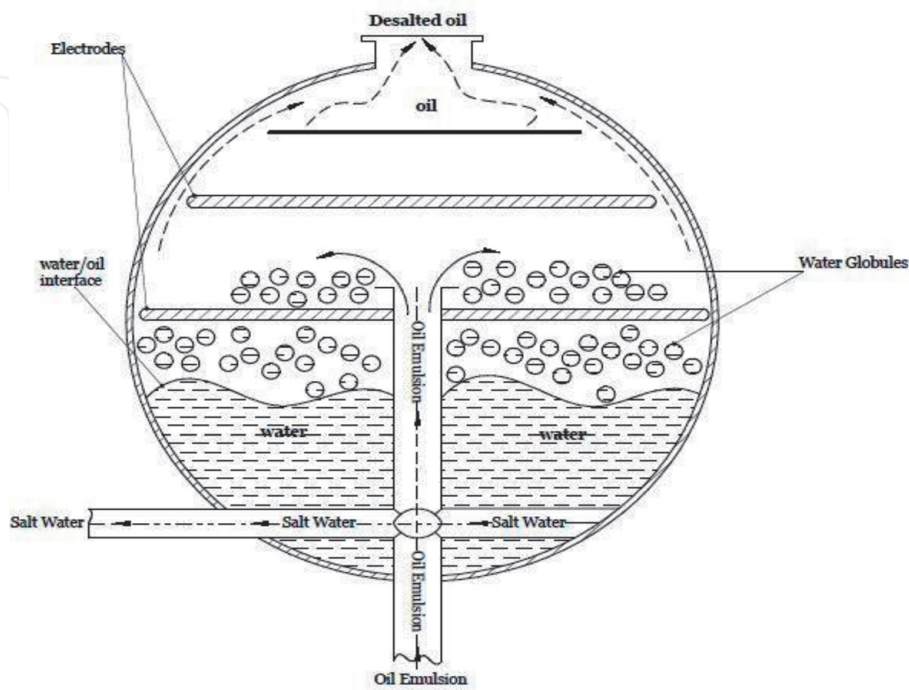*Technical schema of electrostatic desalter design.*

Figure 6.
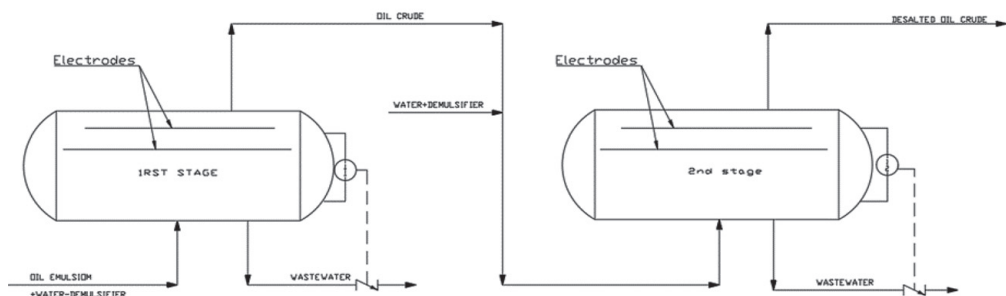*The simplified work description of electrostatic desalter.*

9

Figure 7.
Two-stage desalting flow processing of crude oil.

is 140 tons/h. The program used in our modeling is Mathcad, to calculate the material balance and mechanical calculations of electrostatic desalter. The characteristics of the feedstock are presented in **Table 1** [27, 28].

1.6.1 Materials balances of electrostatic desalter

The establishment of a material balance is necessary for modeling [7, 25, 29]. The material balance material allows us to have an idea of the results we need to get and correct some errors during the project in order to have a satisfactory performance of our facilities. To calculate the material balance of electrostatic desalter, it is necessary to know the data:

- the temperature at the entrance of feedstocks into the electrostatic desalter, $t_1 = 90°C$;

- the temperature at the outlet of feedstocks in the electrostatic desalter, $t_2 = 145°C$.

The quantity of oil emulsion chosen is 140 t/h. the water Content of the initial emulsion is 1% of the total mass. The consumption of the demulsifier (surfactant) is 30 g/t. Our work in this part is to make material balances of the pre-treatment of the oil at the refinery. Electrostatic desalter performs two procedures at the same time which are: dehydration and desalination. The descriptive diagram e of the desalting process is presented in **Figure 8**. The amount of freshwater or water processing supplied at the desalting stage is 10% of the mass. The reagent is fed only at the dehydration stage. We consider the reagent water-soluble. First, the status of "incoming" is drawn up. The

Indicators	Methods	Units of measure	Values
Density at 15°C	NF EN 12185	kg/m^3	884
Water content	NF EN 9029	% mass	1
Total acid number	ASTM D 664	mg KOH/g	0.619
Sulfur content	NF EN 8754	% m/m	0.254
API	ASTM D1298	—	29
Kinematic viscosity at 100°C	ASTM D445	cSt	1.9
Freezing point	NF EN ISO 3016	°C	−17

Table 1.
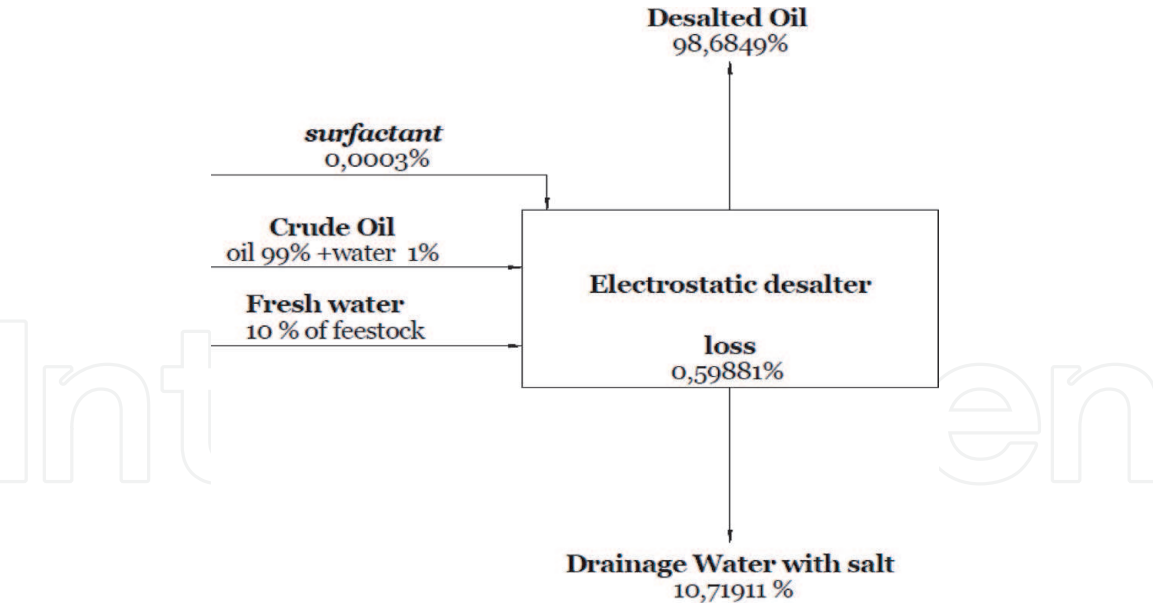*The physicochemical characteristics of Bonga crude oil.*

Figure 8.
The descriptive diagram of the desalting process.

status "Expense" is similar to the desalting- dewatering process. 140 t of emulsion −
1.4 t of water in emulsion = 138.6 t of oil. The status "Expense" is similar to the
desalting-dewatering process. Loss is equal: $\frac{(138.6 \times 0.3)}{100}$ = 0.4191 t. The amount of
dewatered oil or desalted oil will be 138.6 t – 0.4158 t = 138.0897 t. According to this
task and Russian GOST R 51828-2002, the water content in the desalted oil shall not
exceed 0.5% of the mass. Thus, the water contained in the desalted oil will be:

$$138.0897 \text{ t} - 99.95\% \text{ mass.} \tag{4}$$

$$X - 0.05\% \text{ mass.} \tag{5}$$

The amount of water X is 0.0691 t.

The water content-X is 0.0691 t in the desalted oil. The total water content phase
in the "incoming" status is 14 t + 0.14 t = 14.14 t.
Based on the previous results and by the possibility that we can really have more
losses. We arbitrarily decide to multiply our losses by 2; the total loss is:
0.4191 t + 0.4191 t = 0.8383 t. Consequently, the summary material balance of the
installation is made. The total amount of drainage water is equal to the drainage
water by oil treatment stage: 0.9332 t + 14.07 t = 15.0032 t. The material balance of
the electrostatic desalter installation is presented in **Table 2**.

1.6.2 Modeling of the desalting process with electrostatic desalter

The exercise of modeling is a variant very often useful and used in the modeling
of units and devices [7, 14, 19]. This task is interesting in case we do not have a
simulator or simulation and modeling program like Hysys Aspen to solve this
operation. In the framework of modeling the desalination unit, we use the ASTM D
341-2003 standard is based on Walter's equation and proposes the dependence of
the kinematic viscosity of crude oil (hydrocarbon):

$$lg \times lg(\nu + 0,8) = a + b \times lgT, \tag{6}$$

$$a = lg \times lg(\nu_1 + 0,8) - b \times lgT_1 \tag{7}$$

Feedstocks	ton/h	% mass	Products	ton/h	% mass
1. Oil emulsion, including:	140.0000	100.0000	1. Stable oil, including:	138.1589	98.6849
• Oil	138.6000	99.0000	• Desalted oil	138.0897	98.6355
• Water	1.4000	1	• Water	0.06916	0.0495
2. Surfactants (Demulsifiers)	0.0004	0.0003	2. Drainage water	15.0032	10.7191
3. Water processing (freshwater)	14.0000	10	3. Loss	0.8383	0.5988
Total	154.0004	110.0003	Total:	154.0004	110.0003

Table 2.
The material balance of electrostatic desalter.

$$b = \frac{lg \times \left[\frac{lg(\nu_1 + 0,8)}{lg(\nu_2 + 0,8)}\right]}{lg\frac{T_1}{T_2}}, \tag{8}$$

where ν – viscosity, cSt, T is the absolute temperature, K; a and b are the constants determined by two known values of viscosity ν_1 and ν_2 at temperatures, respectively, T_1 and T_2. The empirical formula of formula Filonov – Reynolds is more convenient for analytical solutions:

$$\mu_t = \frac{1}{C} \times \left(C \cdot \mu_{t_o}\right)^\chi \tag{9}$$

where.

$$\chi = \frac{1}{1 + \alpha(t - t_o) \times lg\left(C \cdot \mu_{t_o}\right)}; \tag{10}$$

ν_t, ν_o – Dynamic viscosity of the oil at temperatures t and to, respectively, mPa·s; α and C are empirical coefficients.

$$\text{If } \nu_o \geq 1000 \text{ mPa} \cdot \text{s, then } C = 10, 1/\text{mPa} \cdot \text{s}; \alpha = 2.52 \cdot 10^{-3} \text{ 1/°C}; \tag{11}$$

$$\text{If } 10 \leq \nu_o < 1000 \text{ mPa} \cdot \text{s, then } C = 100, 1/\text{mPa} \cdot \text{s}; \alpha = 1.44 \cdot 10^{-3} \text{ 1/°C}; \tag{12}$$

$$\text{If } \nu_o < 10 \text{ mPa} \cdot \text{s, then } C = 1000, 1/\text{mPa} \cdot \text{s}; \alpha = 0.76 \cdot 10^{-3} \text{ 1/°C}. \tag{13}$$

$$x = \frac{1}{[1 + 0.76 \times (90 - 100)] \times log\,(1000 \times 0.0014144)}$$

$\nu = \frac{1}{1000} \times (1000 \times 0.0014144)^x = 7.055 \times 10^{-4}$

In modeling of electrostatic desalter to determine his maximum performance and the required number of devices for desalting crude oil.

$$E_{Critical} = \theta \times \sqrt{\frac{2 \times \lambda}{\phi \times d}}, \text{v/cm}, \tag{14}$$

The interaction between water droplets can be increased by increasing the electric field strength, E.

$$EReal = \frac{U}{l}, \text{v/cm} \tag{15}$$

For to determine the *E-Critical* and *E-Real* for the desalter with the following data. Water content in oil – 1%; λ (interfacial surface tension) = 12 dyn/cm; d (the diameter of the droplets) = $1.5 \cdot 10^{-2.55}$ m or $4.228 \cdot 10^{-1}$ cm; φ (dielectric constant of the emulsion) = 2; l (distance between electrodes) = 20 cm; U (voltage of the electrodes) = 22000 v.

$$E_{Critical} = 382 \times \sqrt{\frac{2 \times 12}{2 \times 4.228 \cdot 10^{-1}}} = 2035.1 \text{ V/cm.}$$

$$E_{Real} = \frac{22000}{20} = 1100 \text{ V/cm.}$$

$E_{-Real} < E_{-Critical}$, consequently, the dispersion of droplets will not. The electrostatic desalter receives crude oil, the amount of Q = 162 m³/h with temperature 90⁰C (preheat). $\rho^{90}_{crude\ oil}$ = 838.4 kg/m³, ρ^{90}_{H20} = 965.3 kg/m³, the kinematic viscosity of crude oil $\mu_{oil\ crude}$ = $7.055 \cdot 10^{-4}$ m²/s, the diameter of the globules of water – $1.5 \cdot 10^{-2.55}$ meter. The residence time of the emulsion in the apparatus – 30 minutes is applied to the device volume 96 m³, which length – 10.19 m, diameter – 3 m. The maximum surface deposition: $S = D \times L = 10.19 \times 3 = 30.57$ m². The efficiency of the electric desalter depends on the values S/V, where S – the average area of the horizontal section of the device, m²; V – the volume of the device, m³. For effective sludge must be met the condition $\tau \geq \tau_W$, where τ - oil residence time in the apparatus, h; τ_W – time required for precipitation of water droplets, an hour.

$$\tau = \frac{h_{Em}}{U_{Em}}, \tag{16}$$

where h_{Em} – the height of the emulsion layer in the apparatus, m; U_{Em} – the velocity of the crude oil flow during its lower flow, m/h.

$$\tau_W = \frac{h_{Em}}{U_{Real}} = \frac{h_{Em}}{U_{water} - U_{wo}}, \tag{17}$$

where U_{water} – deposition rate of water droplets in a stationary medium, m/h; U_{wo} – real deposition rate of water droplets in the rising oil flow, m/h.

$$U_{water} - U_{wo} \geq U_{Em} \text{ or } U_{Water} \geq 2 \times U_{Em}. \tag{18}$$

The linear velocity of the oil in the electrostatic desalter must be at least 2 times less than the calculated rate of water droplet deposition. The deposition rate is calculated using the Stokes formula [7, 25]:

$$U_{Water} = \frac{d^2 \times g \times \left(\rho_{H_2O} - \rho_{crudeoil}\right)}{18 \times \mu_{crudeoil} \cdot \rho_{crudeoil}} \text{ m/s,} \tag{19}$$

where d – diameter of water drops, m; ρ_{H2O}, $\rho_{crude\ oil}$ – the density of water and oil, kg/m³.

$\mu_{crude\ oil}$ – kinematic viscosity of oil at sludge temperature, m²/s.

$$U_{Water} = \frac{\left(1.5 \cdot 10^{-2,552}\right)^2 \times 9.81 \times (965.3 - 838.4)}{18 \times 7.055 \times 10^{-4} \times 838.4} \text{m/s}$$

$$U_{water} = 0.0021 \text{ m/s}.$$

It is necessary to check the Reynolds number (Re) by the formula:

$$\Re U_{Water} \times \frac{d}{\nu_{crudeoil}}. \tag{20}$$

The condition must be met:

$$10^{-4} \leq Re \leq 0.4 \tag{21}$$

$$\Re 0.00208974 \times \frac{1.5.10^{-2,55}}{7.055 \times 10^{-4}} = 0.0125, \text{ Re} < 0.4$$

h_{Em} is the height of the emulsion level in the devices, m = meter

$$h_{Em} = 0.75 \times D - h_1, \tag{22}$$

where h_1 the distance from the bottom of the electric Hydrator to the oil-water interface. We choose h_1 = 0.75 m $\times$ U_{Em} – the velocity of the oil flow during its lower flow, m/h, $h_{Em} = 0.75 \times 3 - 0.75 = 1.69$ m

$$U_{Em} = \frac{h_{Em}}{\tau} \tag{23}$$

$$U_{Em} = \frac{1,69}{0.75} = 2.25 \text{m/h} = 6.259 \cdot 10^{-4} \text{ m/s}.$$

Knowing the U_w, determine the U_{wo} and the required cross-section of the electric dehydrator (S). The actual deposition rate of water droplets in the rising oil stream will be:

$$UReal = U_{water} - U_{Em} \tag{24}$$

$$UReal = 2.08 \times 10^{-3} - 6.259 \times 10^{-4} = 1.464 \cdot 10^{-3} \text{m/s}.$$

The performance of the desalter:

$$J = UReal \times S, \text{m}^3/\text{s} \tag{25}$$

$$J = 1.464 \cdot 10^{-3} \times 30.57 = 0.045 \text{ m}^3/\text{s} = 161.3 \text{ m}^3/\text{h}.$$

The number of devices (N):

$$N = \frac{Q}{J}, \tag{26}$$

where Q – the quantity of emulsion supplied to the unit, m^3/h; J – The performance of the desalter, m^3/h.

The required number of parallel running for the electrostatic desalter:

$$N = \frac{162}{161.3} = 1.005$$

1.6.3 Mechanical modeling of electrostatic desalter (theory)

This task is as interesting as the one already solved. In case we do not have a simulator or simulation and modeling program like Ansys to solve this vital operation [1, 18, 29, 30]. The calculation of the strength of a cylindrical shell under internal pressure. The wall thickness is determined by the formula (25).

$$S_R = \frac{P \times D}{2 \times [\sigma] \times \phi - P};$$ (27)

Permissible internal overpressure.

$$[p]_D = \frac{2 \times [\sigma] \times \phi \times (S - C)}{D + (S - C)}$$ (28)

P is the pressure in the device, mPa; S_R – the calculated value of wall thickness, mm; D- intern diameter of the shell, mm; $[\sigma]$ – permissible voltage, mPa (depends on the steel grade and operating temperature).

The steel grade is chosen depending on the properties of the processed medium. For butt and t-shaped double-sided seams performed by automatic welding, the coefficient of the strength of the weld $\phi = 1$, for the same manual stitches, $\varphi = 0.9$. Increase taking into account corrosion C is determined by the formula:

$$C = V \times T,$$ (29)

V is the rate of corrosion (usually take 0.1–0.2 mm/year); T – the service life of the device (usually take 10–12 years). For materials resistant to the processed medium, in the absence of data on permeability, it is recommended to take C = 2 mm. Condition for reliable operation $P < [P]_D$ must be observed.

The choice of corrosion resistance of materials is made concerning this environment is resistant to corrosion.

$$S \geq S_R + C$$ (30)

The wall thickness calculated using this formula is rounded up to the nearest standard sheet thickness (4, 6, 8, 10, 12, 14, 18, 20 mm). The calculation of shells loaded with external over-pressure consists in determining the permissible external pressure since the wall thickness of the shell was determined earlier. Permissible external pressure:

$$[p]_{pp} = \frac{[P]_p}{\sqrt{1 + \left(\frac{[P]_p}{[P]_E}\right)^2}},$$ (31)

$[P]_p$ durability allowable pressure corresponding to the strength condition:

$$[P]_D = \frac{2 \times [\sigma] \times \phi \times (S - C)}{D + (S - C)}.$$ (32)

i – coefficient of stability (for the operating conditions of $i = 2.4$), l_R – the estimated length of the shell.

$$l_R = l - 2 \times h_0 + \frac{H_D}{3},$$ (33)

E is the modulus of elasticity. l = length of the cylindrical part of the corpus; h_0 – the height of the bottom flanging, H_D – the height of bottom edge. Allowable pressure of conditions of stability within the limits of elastic deformation:

$$[P]_E = \frac{18 \cdot 10^{-6} \times E}{i} \times \frac{D}{l_R} \left[\frac{100 \times (S - C)}{D} \right]^2 \times \sqrt{\frac{100 \times (S - C)}{D}} \qquad (34)$$

Condition for reliable operation $[P]_E \leq [p]_{pp}$ must be observed.

1.6.4 Resolution example based on our electrostatic desalter

P – pressure in the device, mPa = 1.1; D-inner diameter of the shell, mm = 3000. The increase in corrosion C is determined by the formula (27).

$$C = 0.2 \times 20 = 4 \text{ mm}$$

V is the rate of corrosion (usually take 0.1–0.2 mm/year); T – the service life of the device (usually take 10–12 years), but we take 20 years. For materials resistant to the processed medium, in the absence of data on permeability, it is recommended to take C = 2 mm. According to the table of corrosion resistance of materials, we choose the steel grade 316Ti, S31635-USA (ASTM/AISI), or 1.4571, X6CrNiMoTi17-12-2-Germany (DIN/WNr). $[\sigma]$ = 168.6 mPa. The coefficient of the strength of the weld is assumed $\phi = 1$. The service life is 20 years. The corrosion rate is 0.2 mm/year. Increase taking into account corrosion C = 4 mm.

$$S_R = \frac{1.1 \times 3000}{2 \times 168.6 \times 1 - 1.1} = 9.819 \text{ mm.}$$

$$S = 9.819 + 4 = 13.819 \text{ mm.}$$

The wall thickness calculated using this formula is rounded up to the nearest standard sheet thickness (4, 6, 8, 10, 12, 14, 18, 20 mm). We assume S = 14 mm.

$$[p]_D = \frac{2 \times 345 \times 1 \times (14 - 4)}{3000 + (14 - 4)} = 1.12 \text{ mPa.}$$

Condition for reliable operation $P < [P]$ (1.1 mPa < 1.12 mPa) observed.

The calculation of shells loaded with external over-pressure consists in determining the permissible external pressure since the wall thickness of the shell was determined earlier.

$[P]_p$ the allowable pressure corresponding to the strong condition.

$$[P]_p = \frac{2 \times 168.6 \times 1 \times (14 - 4)}{3000 + (14 - 4)} = 1.12$$

E is the modulus of elasticity, i – coefficient of stability (for the operating conditions of i = 2.4), l_R – the estimated length of the Desalter. E = 1.86·10^5 mPa; l = 10,190 mm; H_D = 1500 mm; h_0 = 25 mm.

$$l_R = 10190 - 2 \times 25 + \frac{1500}{3} = 10640 mm$$

Allowable pressure of conditions of stability within the limits of elastic deformation:

$$[P]_E = \frac{18 \cdot 10^{-6} \cdot \times 1.86 \cdot 10^{-5}}{2.4} \times \frac{3000}{10640} \times \left[\frac{100 \times (14-4)}{3000}\right]^2 \times \sqrt{\frac{100 \times (14-4)}{3000}} = 0.0252 \text{ mPa}$$

Permissible external pressure:

$$[p]_{pp} = \frac{1.12}{\sqrt{1 + \left(\frac{1.12}{0.0252319}\right)^2}} = 0.0252 \text{ mPa.}$$

Condition for reliable operation $[P]_E \leq [p]_{pp}$ (0.0252 mPa $\leq$ 0.0252 mPa) observed.

1.7 Summary

The desalting and dewatering of crude oil take begins on the oil fields. This operation is part of the processing of crude oil, and a good pre-treatment of crude oil implies:

- degassing – removal of gases from crude oil;

- dewatering – removal of water from crude oil.

If the desalting of crude oil is carried out qualitatively, the oil has almost no harmful effect on the equipment. Most of the impurities that cause corrosion of the metal are in the remains of formation water. Therefore, the fundamental task of desalting is to remove water drops from the oil. This is a fairly complex process, because the water in crude oil is in the form of droplets with a size quantity often. The improvement and appreciation of the oil pretreatment process level are characterized by:

- providing effective sludge at high viscosity and density of oil through the use of a sump with intermediate partitions of variable height;

- increasing the degree of dehydration and desalination of oil due to effective washing with water from salts;

- improving the efficiency of the sump and improving the quality of the prepared oil due to more complete and qualitative removal of the intermediate layer from it, as well as due to a more uniform distribution of fluid flow rates when entering the sump and its cross-section;

- ensuring uniform receipt of production of wells for the installation of oil treatment and prevention of failures of its work through the use of the reservoir;

- improving the performance of the electrostatic desalter, that is, expanding the range of workloads, improving the efficiency of desalination and dehydration, as well as reducing the cost of oil pre-treatment.

The poor pre-treatment (desalting process) of crude oil can lead to considerable extra costs. We are talking about the high cost of transportation if the product is not cleared of unnecessary substances that give it extra volume and weight as well as financial investments in equipment. After all, oil, which is not derived from salt, can very quickly damage the pipeline. The requirements for the oil content of the

water and especially for chlorides more stringent on the refineries. The oil content of water before processing must be no more than 0.1% of the mass and for salts-no more than 5 mg/l [3, 31]. These related requirements using much more expensive equipment (columns, heat exchangers, reboilers, etc.). Also, these the requirements induce to reduce the energy consumption, to reduce the corrosion of the equipment, to increase the life of the catalysts, improves the quality of the petroleum products. If these requirements not performed, the oil is necessarily subjected to desalting and dehydration at the electric desalting plant (electrostatic desalter). The surfactants are added if the crude oil contains a lot of suspended solids. The crude oil is heated usually to a temperature of 50 to 90°C to reduce viscosity and surface tension for easier mixing and separation of water.

2. Atmospheric Distillation Unit (ADU)

2.1 Introduction

The distillation is heating a liquid solution or mixture of liquid stream to produce steam, and then collecting and condensing that steam. In the simplest case, the products of the distillation process are limited to the upper distillate and the bottom, the composition of which differs from the feed. Thus, the major purpose of distillation is the separation or splitting into two or more products from a feed [32]. The distillation or rectification is one of the oldest and most common methods of chemical separation [33]. Historically, one of the most famous uses is the production of spirits from wine. More simply, in other words, the target of distillation is usually to remove the light component from the heavy component mixture, or vice-versa, to separate the heavy product from the light component mixture [32]. One of the components of crude oil refining is distillation, therefore a stage of refining. Oil refining is a rather complex technological process that begins with the transportation of oil from the field to refineries. The fractionation or distillation column exists in practically all oil refining technologies through reforming, thermal cracking, hydrocracking, etc. [20]. Before receiving the petroleum products common to users, the oil goes through several stages before becoming a finished product. Some of these stages are [1, 9, 20, 21]:

- pre-treatment of crude oil;

- distillation atmospheric and vacuum;

- catalytic reforming, isomerization;

- alkylation, visbreaking, coking;

- catalytic cracking, hydrocracking;

- treatment of petroleum products (hydrotreatment, desulphurization, etc.)

2.2 Description and characteristics crude distillation unit (CDU)

The oil emulsion is a complex mixture of naphthenic, paraffin, aromatic carbohydrates, which have different molecular weight and boiling point, and sulfur, oxygen, and nitrogen organic compounds. At distillation receive a big range of oil products and semi-products. The principle of the process is based on the difference

between the initial boiling point of the components. As a result, the oil is divided into fractions up to fuel oil and tar and even base oil. The distillation of oil can be carried out [34]:

• Single evaporation or flash vaporization

• Multiple evaporations

• Gradual evaporation

The single evaporation of oil is a one-step separation technique. The single evaporation process involves heating the oil to increase the temperature and enthalpy to the true boiling point (TBP) of the vapor-liquid mixture. The process of multiple evaporations is a sequence of single evaporation with a gradual increase in the heating temperature. Distillation by gradual evaporation is a slight change in the oil's state with every single evaporation. The main devices in which the distillation of oil are distillation columns, reboilers, furnaces, etc. [1].

The difficulty of separating crude oils is mainly determined by the volatility of the key components or by the difference in the boiling point of the key components [34]. The closer the relative volatility is to one per mole, the more plates or plates are needed and more irrigation is needed to achieve the same purity of distillate and residue. For key components, two adjacent components are taken for key components, one belonging to the distillate, the other to the residual product. The relative volatility of these adjacent components and their proportion in crude oil are the main criterion determining the difficulty of sufficiently clear separation from crude oil [34]. More the tangent of the angle of inclination of the TBP increase, the easier the separation conditions are. The wider the crude oil TBP intervals, more the distillate and the residue obtained during the process are clean. As we all know, crude oil from the bowels of the Earth contains salt as dissolved salt in a tiny drop of water that forms water into an emulsion [1, 9]. This water cannot be completely separated by gravity or mechanical means. The deep separation of water from the emulsion occurs with electrostatic at the plant, before the distillation process [20].

After desalting process, the crude oil is heated in heat exchangers or reboilers (preheating of crude oil). Of course, preheating is not sufficient, since the oil must be partially evaporated to the extent that all products except atmospheric residues must be in the vapor phase when the oil enters the atmospheric column. Thus, the furnace is required to raise the temperature between 330 and 385°C depending on the components of oil [35]. The partially evaporated crude oil is transferred to the flash zone column located at a point below the distillation column and above what is called the stripping section. The main distillation column is generally up to 50 m with a 30–50 valve [34]. The size of the column is determined by the number of plates and the amount of steam. Besides, the amount of steam is determined by the content of crude oil in volatile elements or compounds. As a result, the rising steam in huge amounts and at top flow rates, requires a large diameter column above the flash zone [1, 34]. At the bottom of the section, water vapor is injected into the column to remove the atmospheric residue of any light hydrocarbon and reduce the partial pressure of hydrocarbon vapors in the flash zone [20]. This causes the true boiling point of hydrocarbons to decrease and causing more hydrocarbons to boil and raise the column to eventually thicken and removed as lateral flows. As hot vapors grow from the flash zone, they ascend into the column through the plates to the upper zone of the column [36]. A portion part of the light fraction of naphtha or gasoline returns to the column in the form of reflux. This reflux allows controlling

the quality of the distillate and the pressure in the column. The main products of atmospheric petroleum distillation are [33]:

- Gas

- Gasoline (35–200°C)

- Kerosene (220–275°C)

- Diesel or gas oil (200–400°C)

- Atmosphere residue (above 350°C).

The distillation process is carried out in columns with plates inside and it is as follows: hot vapors, rising on the column, in contact with the cooler liquid (reflux) flowing down. There is a cooling of the vapors, hence condensation; a transition from vapors to liquid. This is the process of mass transfer and heat exchange; the contact efficiency is provided by the plates. Most of the side currents (light fractions) pass through the striping section, where they are again dispersed to control their starting and ending boiling point, while the liquid is heated, the low boiling components evaporate [36]. The temperature and pressure have a great influence on the processes (movement of fluids) due to the plates inside the column [32]. The distillation plates are designed to create close contact between Steam and liquid during the grinding process. Mainly apply grid, groove, cap, s-shape, valve, and other types of plates. The design of the plates, besides the close contact between steam, and liquid must ensure sufficient performance of the column, have a low hydraulic resistance to the flow of steam. For example, the movement of vapors in distillation columns depends on the types of plates shown in **Figures 9** and **10** [32]. The materials used in the design are also of great importance because they influence the metal capacity of structures, ease of assembly, and cleaning.

2.3 Description of the distillation column and its operation

The distillation is designed to separate gas and liquid mixtures comprising two or more components or fractions. We can classify distillation columns according to various characteristics [32, 34]:

- by technological application;

- by an internal device (plates) ensuring contact between the steam and the liquid;

- columns of atmospheric vacuum.

Figure 9.
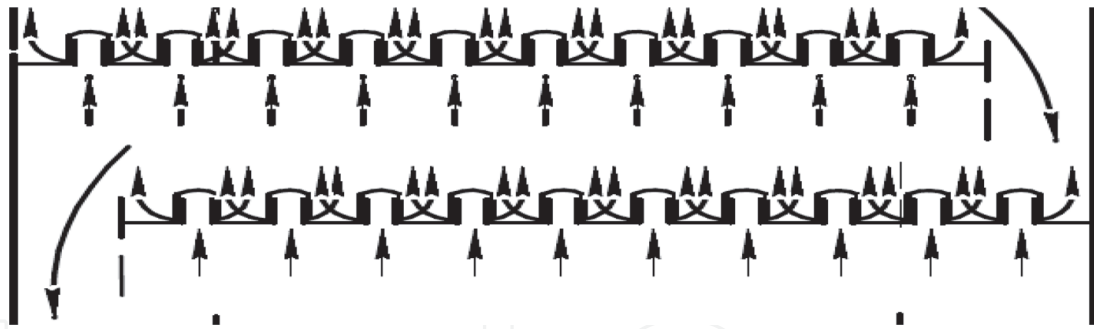*The types of plate in the column: (a) cap, (b) grid, (C) valve.*

Figure 10.
The movement of steam and liquid flows on the cap plates.

The quality of distillation depends on the number of plates in the column and the amount of irrigation. The speed of movement of vapors in the column and the distance between the plates is great significance. The design of distillation plates is important in the column's performance. Thus, under practical conditions, the heat exchange between steam and liquid on the plate does not reach the equilibrium state, so the concept of plate efficiency (energy conversion efficiency) was introduced. It depends on the design and operating conditions and usually varies between 0.4 and 0.8 [32]. The distillation column comprises three (3) zones: the separation zone, the crude supply (feeding zone), and the heating zone. The feeding zone is generally below the separation zone. However, in some columns like the stripping columns, the feeding zone is located in the upper area of the column. Also, we can say that the separation zone in this type of column is non-existent. In short, this type of column is a column stabilization.

In oil refining, the first oil separation process is very often operated with complex columns or main columns [20]. The oil is sent to the atmospheric distillation column and after the desalination process. The oil is supplied to the feeding area in the form of steam, liquid, or vapor-liquid mixture. This area is called evaporative. Above the entrance (feeding zone) to the oil is the separation zone of the column, and below-the heating zone. In the evaporation zone of the column, there is single evaporation of the oil heated long before in the furnace or the heat exchanger. The purpose of atmospheric distillation is the primary separation of various "Fractions" of hydrocarbons: fuel gases, liquefied petroleum gas, naphtha, kerosene, diesel fuel, and from the bottom of the distillation; the atmospheric residue (heavy hydrocarbon residue). The residues from the atmospheric distillation column or atmospheric residues are sent to the vacuum distillation column. The atmospheric residues in the vacuum column (under the vacuum condition) and temperatures above 400°C give new fractions (heavy gasoil) [1, 32].

2.4 The plates for distillation columns of oil plants

In oil refining, a fairly large number of plate types are widespread; new types are being developed. This situation is explained by the desire to develop more productive and economic plates than those used previously. The choice of the types of plate depends on a load of steam and liquid, the physical properties of steam and liquid [34]. In order to ensure optimal conditions for the operation of columns in various technological processes, it is necessary to use plates of different designs [32]. In atmospheric columns, steam and liquid charges are moderate. While in vacuum columns, large vapor loads and small liquid loads are observed, that is low volumetric expenditures of liquid and high linear velocities of vapors. Thus, for some varieties of columns, several types of plates are

recommended, depending on the particular conditions of operation and use of these columns. These operating conditions of the column provide a comparative assessment of the different types of plates under these operating conditions as shown in **Table 3**. The comparison is carried out on the following characteristics and indicators [34]:

- efficiency;

- operating stability range;

- hydraulic resistance;

- ability to work on contaminated raw materials;

- cost (or weight) of the column.

As already noted above, there is a multitude of types of plates. Then we will talk about the most frequent plates in oil plants.

2.4.1 The lattice or grid plates

The plates with holes, usually have holes on 3/16 inch to 1 inch. Pairs come out of the holes to get a multi-hole effect. The Steam or vapor velocity prevents liquid from passing through the holes. The number and size of the hole are based on the fall of steam in the column. The fluid flow is transported down the tower using triggers, a dam, and a bypass device on the side of the plate. The Minimum capacity sieve tray capacity is about 70% [30].

2.4.2 The cap plates

The cap plate is a "classic" plate, although it is still very widespread nowadays, it is gradually replaced by plates of other, more effective types. The dominant part of the cover plate is a steel disc (or cover plate) with holes for steam pipes. Usually provided with slots for passing steam, the steam will be in contact with the liquid bubble formed on the next tray. It can operate at low steam and liquid velocities [36] (less than 2 gallons per minute per foot of average flow width). The fittings are welded to the disc. Above the nozzles, caps with a diameter of 60 or 80 mm are installed. Caps have slots with a height of 15; 20 or 30 mm.

Types columns or application	Plates types	Restrictions on column diameter
AVDU units or CDU	C or S-shaped plates	No
Atmospheric distillation of CDU or ADU, with including stripping	C or S-shaped plates	No
	Valve plates	No less 3 m
	Jet plates	Not over 3.2 m
Vacuum distillation of CDU or VDU	Jet plates with bumpers	No
Any installation, especially if there is no reliable design data	Cap plates	No

Table 3.
Types of plates common in refining oil plants.

2.4.3 The valve plates

The valve plates are mainly used in CDU or AVDU and gas plants. The dominant element of the plate is a valve of round or rectangular shape that closes the holes at the base of the plate of appropriate shape. Structurally, the valve is made so that it cannot be raised to a certain height. The arrangement of the valves of round shape on the plane of the plate is the same as the plugs on the cap plate. The valve plate is used that rises with increasing steam velocity and then decreases as the stream velocity decreases, which stops the liquid from flowing. The valve can be round or rectangular, with or without a frame. The disk rises with an increase in the velocity of steam [30, 36].

2.4.4 The jet plates

The jet plate consists of a flat sheet, on which there are offset slots made in the form of a tongue with the cut-out part bent upwards. All slots are bent at a side angle. The plate has a drainage device of the usual design, but does not have a drain bar at the outlet of the liquid from the plate [32].

2.5 Examples of material balances of crude distillation unit and with its major blocks or units like the furnace

2.5.1 Determination of the yield (material balance) of the furnace

The role of the furnace is to heat the oil to a temperature in the range of 330–385°C in order to achieve a vapor-liquid balance before the distillation column [1, 7, 25, 29]. The most popular furnace in the Russian Federation is the tube furnace, as shown in **Figure 11**. The tube furnace is a unit designed to heat and force chemical processes inside the chamber, which are achieved by using the heat generated when fuel is burned. To calculate the heat balance of the atmospheric column, it is necessary to determine the heat of the furnace by the vapor phase and the liquid phase, therefore determine the material balance of the furnace. For example, the furnace material balance we used Bonga crude and the following data [25]:

- the temperature at the entrance of raw materials into the convection chamber t_1 = 250°C;

- the temperature at the outlet of raw materials in the convection chamber t_2 = 380°C;

- the pressure at the exit of the furnace, p = 2 bars;

- the data of the molar and mass composition of desalted crude are presented in **Table 4**.

We use the method of gradual approximation to calculate the percentage of the top product's distillate, with the Eq. (35).

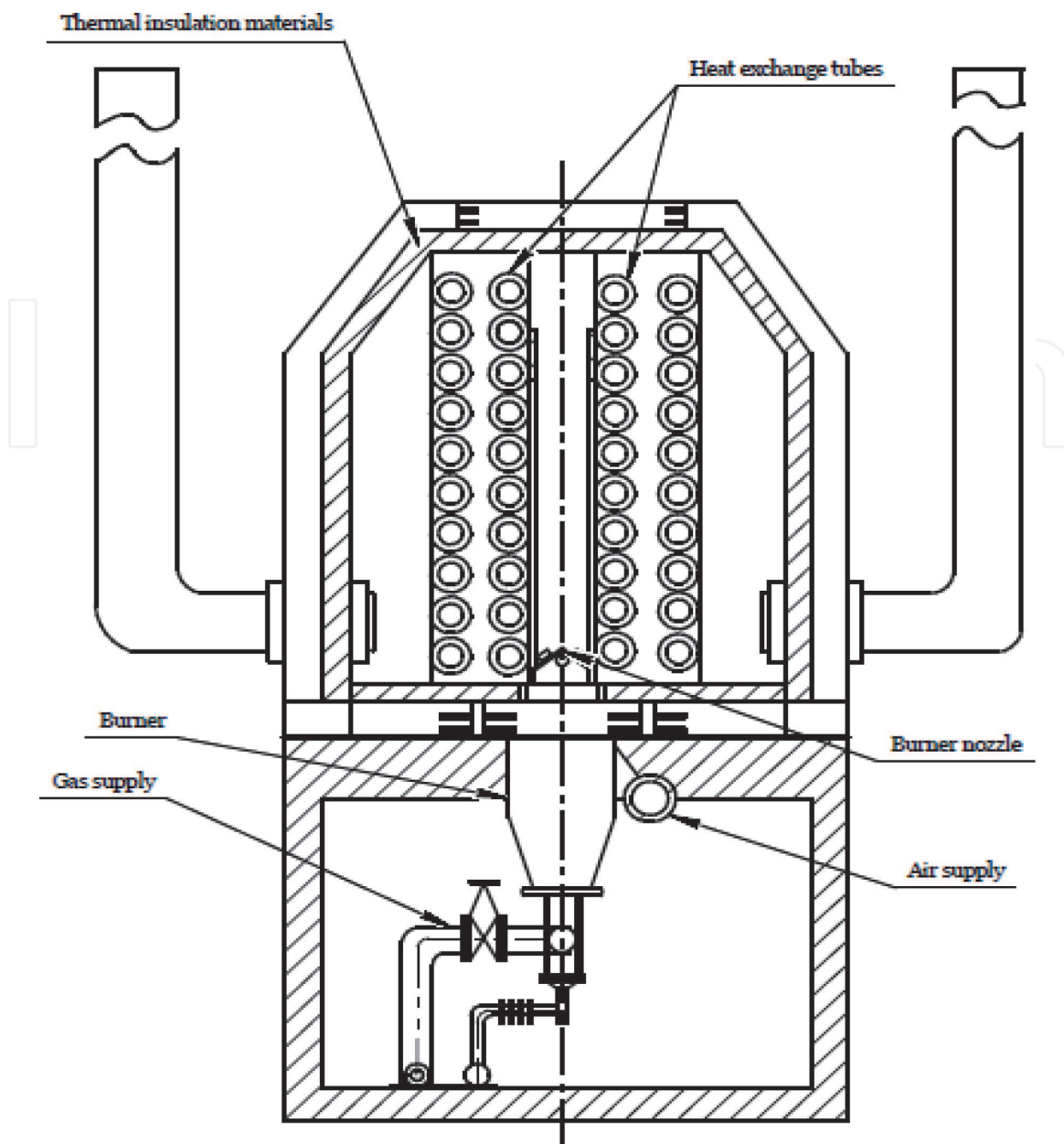$$\text{Fn (emol)} = \sum_i \frac{Cmol_i}{1 + emol \times (K_i - 1)} \qquad (35)$$

Figure 11.
Cross-sectional with heat exchange chamber of a tube furnace.

Where, Cmol-molar composition of the upper product (distillate); emol- the mole fraction of the distillate; Ki-phase equilibrium constant of components *i* under conditions. The graph or **Figure 12** shows the proportion of distillation through the formula (33) of Bonga crude – 138158.9 kg/h.

From the graph (**Figure 12**) we determine that the molar fraction of distillation is emol = 0.855. The molar composition of the liquid is also found by the formula (36).

$$Y_i = K_i \times Y_i, \tag{36}$$

The mass fraction of distillation is calculated by the formula (37):

$$emas = emol \times \frac{MsrP}{MsrC}, \tag{37}$$

where MsrP is average molecular weight of the vapor phase; MsgC is average molecular weight of feedstocks.

Components	kg/kmol	kg/h	% mass	Mole fraction	Steam
C_2H_6	30	22.11	0.02	0.00	1028.85
C_3H_8	33	388.23	0.28	0.01	404.90
Iso-C_4H_{10}	58	563.69	0.41	0.01	135.04
N-C_4H_{10}	58	886.98	0.64	0.02	126.43
Iso-C_5H_{12}	72	124.34	0.09	0.00	85.12
N-C_5H_{12}	72	31.78	0.02	0.00	84.19
75–105	95.1	4863.19	3.52	0.08	103.15
105–125	107.72	3550.68	2.57	0.05	25.25
125–145	118.72	4738.85	3.43	0.06	19.53
145–165	130.52	9035.59	6.54	0.10	15.72
165–185	143.12	2528.31	1.83	0.03	12.51
185–205	156.52	5526.36	4.00	0.05	9.84
205–225	170.72	5567.80	4.03	0.05	7.66
225–245	185.72	7046.10	5.10	0.06	5.88
245–265	201.52	4324.37	3.13	0.03	4.47
265–285	218.12	6769.79	4.90	0.05	3.35
285–305	235.52	7046.10	5.10	0.04	2.47
305–325	253.72	8469.14	6.13	0.05	1.80
325–345	272.72	15017.87	10.87	0.08	1.30
345–375	297.6	21456.08	15.53	0.11	0.92
>375	443.91	30132.46	21.81	0.10	0.58
H_2O	18	69.08	0.05	0.01	0.05

Table 4.
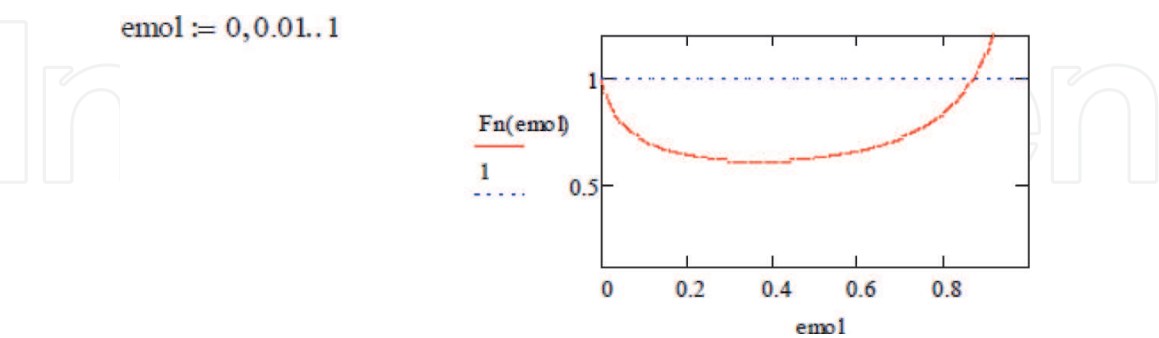*Data of the molar and mass composition of desalted crude.*

Figure 12.
Graph of the vapor-liquid state isotherm.

Molecular masses are calculated according to the rule of additivity (38):

$$\text{MsrP} = \sum M_i \times Y_i \qquad (38)$$

Accordingly, MsrP = 180.54; MsrC = 206.77. emas = 0.747.
The amount of steam and liquid mG phases is determined by the formulas (39), (40):

$$mP = F \times emas, \tag{39}$$

$$mG = F \times (1 - emas), \tag{40}$$

where F (feedstock) is the exiting flow from the electrostatic desalter, and entering the tube furnace.

The mass of the vapor phase = 103,104 kg/h, the mass of liquid phase = 35054.88 kg/h. The mass composition of crude oil, vapor, and liquid phase after furnace are presented in **Table 5**.

2.5.2 Examples of material balance of atmospheric distillation unit (ADU)

The production capacity of the atmospheric distillation unit for processing crude oils is 1,159,200 tons/year, with an initial load of 140 kg/h. This material balance as shown in **Table 6** was made based on the physicochemical characteristics of Bonga crude oil and the typical CDU model without the K-1 oil topping column.

Components	Feedstock		Products			
	Crude oil composition		Vapor phase composition		Liquid phase composition	
	kg/h	% mass	kg/h	% mass	kg/h	% mass
C_2H_6	22.11	0.02	22.10	0.02	0.05	0.00
C_3H_8	388.23	0.28	388.05	0.38	1.47	0.00
Iso-C_4H_{10}	563.69	0.41	562.91	0.55	4.85	0.00
N-C_4H_{10}	886.98	0.64	885.67	0.86	8.16	0.00
Iso-C_5H_{12}	124.34	0.09	124.07	0.12	1.37	0.00
N-C_5H_{12}	31.78	0.02	31.71	0.03	0.35	0.00
75–105	4863.19	3.52	4827.44	4.68	135.74	0.00
105–125	3550.68	2.57	3517.01	3.41	112.85	0.00
125–145	4738.85	3.43	4683.13	4.54	169.45	0.00
145–165	9035.59	6.54	8902.49	8.63	368.15	0.01
165–185	2528.31	1.83	2481.17	2.41	118.91	0.00
185–205	5526.36	4.00	5394.59	5.23	303.92	0.01
205–225	5567.80	4.03	5396.30	5.23	362.68	0.01
225–245	7046.10	5.10	6762.91	6.56	550.50	0.02
245–265	4324.37	3.13	4095.48	3.97	410.07	0.01
265–285	6769.79	4.90	6293.92	6.10	787.63	0.02
285–305	7046.10	5.10	6384.01	6.19	1014.91	0.03
305–325	8469.14	6.13	7401.03	7.18	1519.84	0.04
325–345	15017.87	10.87	12475.46	12.10	3365.64	0.10
345–375	21456.08	15.53	16251.21	15.76	6314.27	0.18
>375	30132.46	21.81	6154.41	5.97	19501.56	0.56
H_2O	69.08	0.05	68.95	0.07	2.51	0.00
Total	138158.9	100	103,104	100	35054.88	100

Table 5.
The material balance of tube furnace.

Feedstocks	ton/year	% mass	Products	ton/year	% mass
1. Oil emulsion	1,159,200	99.56	1. Gases (LPG)	4938.72	0.42
2. Chemical agent (demulsifiers)	3.48	0.00	2. Fractions 35–145	69109.88	5.93
			3. Fractions 145–230	125052.05	10.74
			4. Fractions 230–320	201243.36	17.28
3. Water processing (freshwater)	115.92	0.01	5. Fractions 320–350	231212.84	19.86
			The target products. (sum. fractions)	631556.87	54.25
			6. Associated product (Atmospheric residues)	413475.76	35.51
4. Water vapor	4968	0.43			
			7. Drainage water	119254.770	10.24
Total	1164287.39	100	Total	1164287.39	100

Table 6.
The material balance of atmospheric distillation unit with operating time 340 days by year (365 days −20 days) • 24 h = 8280 h.

2.6 Crude distillation unit (CDU) used in Russia compared to the typical model

Based on the evaluation of the concept of the technological scheme for the construction of a technological scheme of crude distillation unit at refineries in Russia. The topping column K-1 in most cases is a simple design as shown in **Figure 13** [28], although it fractionates the crude oil into the many components like ethane, light gasoline, etc.. There are schemes in which light gasoline is displayed under the distillate in the top of the column, and heavy gasoline on the side flanks of the column. The topping column K-1 collects 50–60% of the potential of light gasoline. The residues of column K-1 are therefore the raw material of the main atmospheric column. The composition of this raw material is weighted in such a way that an excessively high feed temperature is required, permissible temperature (380°C). The singularities of the topping column K-1 operation are as follows [1, 28]:

- The low yield of rectified gasoline (5–15% of the mass of the column load) makes it difficult to collect the gasoline fraction from the oil;

- Extremely high liquid loading in the heating zone of the pre-evaporation column due to the low steam load worsens the conditions for steaming light fractions from the residue under the action of hot jet reflux;
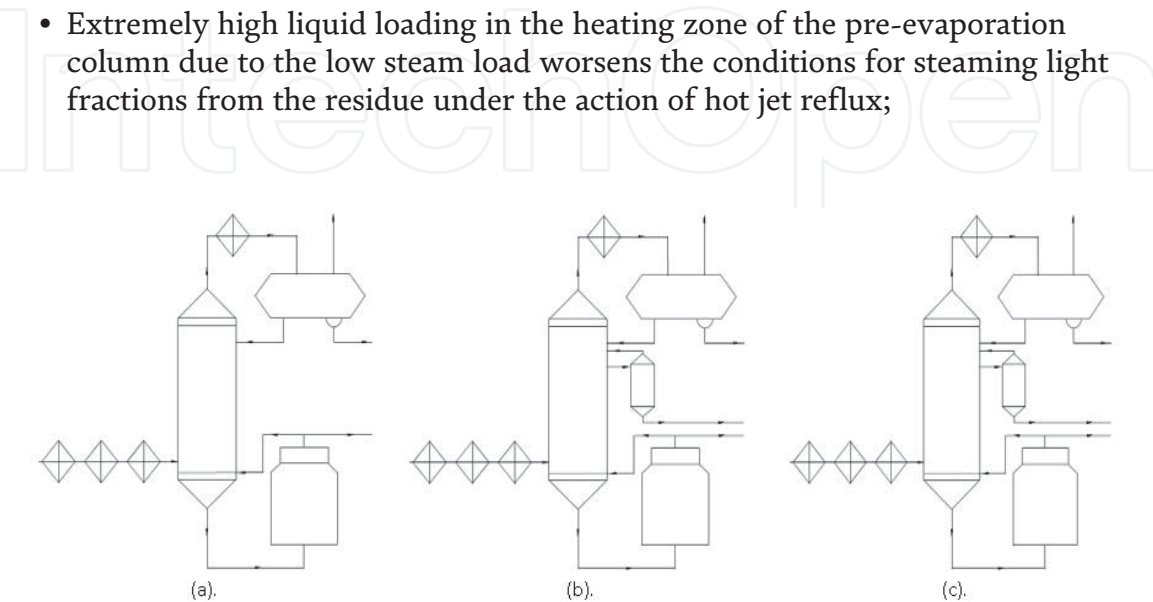

(a).   (b).   (c).

Figure 13.
Possible schemes of operation with oil topping column K-1. (a) Column K-1 with back topped crude. (b) Column K-1 with heavy gasoline and back topped crude. (c) Column K-1 without back topped crude.

- The relatively small enthalpy of crude oil (220°C) introduced into the column does not create sufficient heat flow for distillation, therefore, it is necessary to introduce additional heat in the form of hot jet reflux;

- Maintaining high pressure in the column to ensure air and water condensation of light gasoline fractions in condensers-refrigerators (separators).

The purpose of this column is to extract from the oil the remains of dissolved gas (if the oil has not been stabilized) and a light gasoline fraction with a boiling point of 85°C. After atmospheric residue of K-2 shipped to the vacuum column K-5 for to obtain vacuum distillates (heavy gasoil) and tar. In order to illustrate our argument, a typical P&ID flow diagram process of the atmospheric distillation unit in Russian refineries is presented in **Figure 14**.

2.7 Summary

A general technological approach to the atmospheric distillation unit (ADU) can be described as below [28].
The oil topping column K-1:

- Top temperature, °C – no higher than 245;

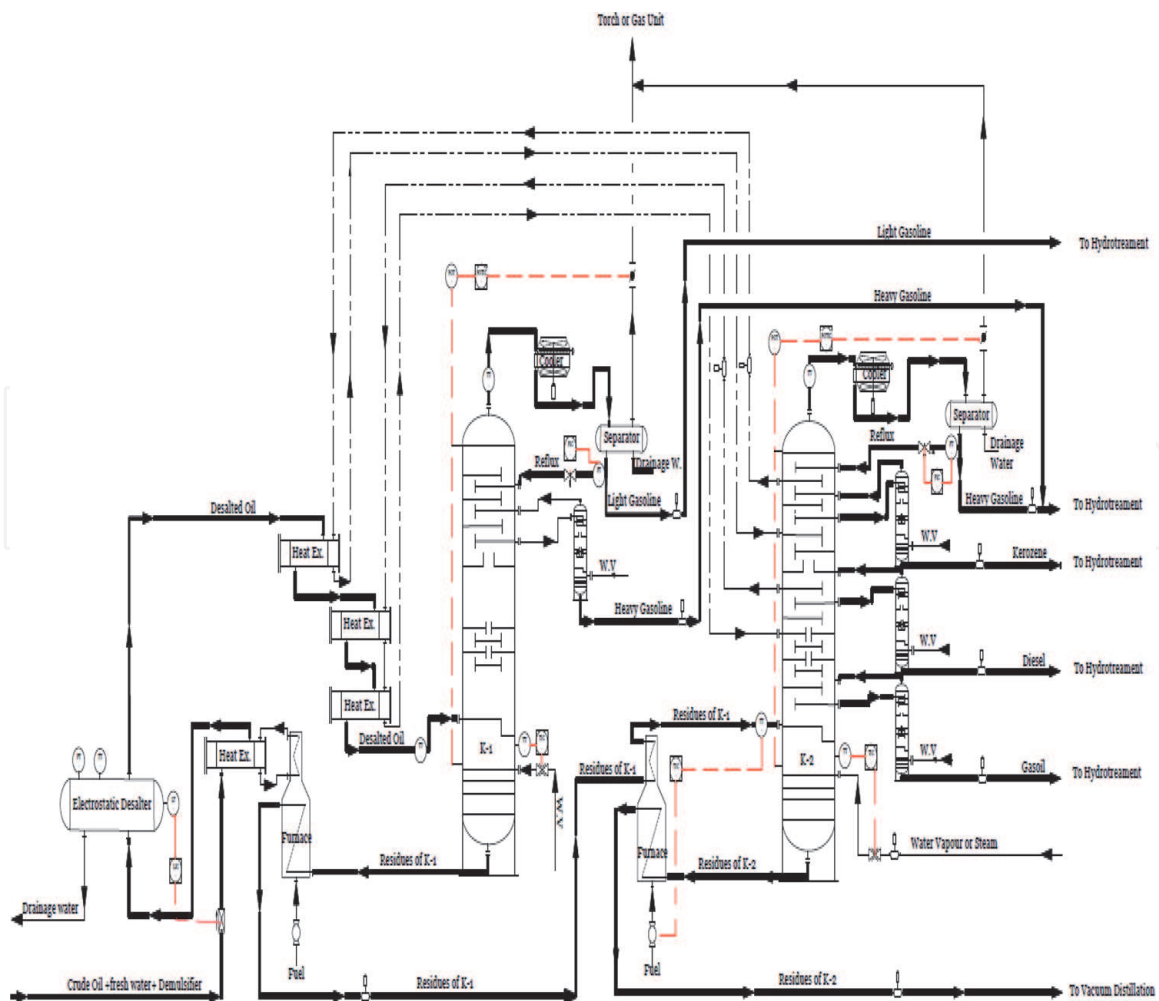- Low temperature, °C – no higher than 150;

Figure 14.
The typical P&ID flow diagram process of atmospheric distillation unit at refineries in Russian Federation.

- Pressure, bar – no more than 3.0.

The typical products of K-1 are;

- Gases

- Light straight run naphtha (light gasoline or light naphtha)

- Heavy gasoline (or military jet fuel)

- Topped crude

The main atmospheric column K-2:

- Top temperature, °C – no higher than 350;

- Low temperature, °C – no higher than 150;

- Pressure, bar – no more than 1.4.

The typical products of K-2 are:

- Heavy gasoline (or military jet fuel)

- Kerosene (light distillate or jet fuel)

- Middle distillates or light gas oil (LGO) – Diesel

- Heavy distillates – atmospheric gas oil (AGO) or heavy gas oil (HGO)

- Crude column bottoms -atmospheric residue or topped crude

The distillation processes are the processes of oil separation into more or less homogeneous fractions without chemical conversion of its constituent substances. The process of separation of liquid substances by their boiling temperatures is atmospheric and vacuum. The atmospheric distillation can be carried out in the following ways:

- With a single separation – furnaces and separation of distillate in one (main) distillation column k-2;

- Double separation in two distillation columns- in the pre-evaporation column k-1 with separation of light gasoline fractions and the main column-2;

- Gradual separation.

The oil topping column K-1, in atmospheric distillation, collects 50–60% of the potential of light gasoline from oil [28]. Otherwise, the composition of oil for the atmospheric column K2 is so weighted that an excessively high supply temperature is required, permissible temperature (380°C). The oil topping column K-1 is especially important in the general crude distillation unit technology in Russia. We know that the choice of flow process technology is dictated by the physicochemical properties of the oils and their compounds. Indeed, the choice of structure of

Types of CDU	Crude distillation unit with K-1	Crude distillation unit without K-1
Advantages	• Flexibility of technology for adaptation on any crude oil • Increased reliability with more products (range of products more) • Stabilization of oil for K-2 (main column) • Increased durability and viability of the equipment by avoiding the overload of k-2 (main column)	• Simplicity of construction compares to those with k-1 • Known technology is widely used • Reasonable project cost • Less scrap metal
Disadvantages	• The increase in the complexity of the design • The increase in the cost of the project • More scrap metal	• Modeling more stringent for to determine oil • No flexibility of technology for adaptation on any crude oil • Not enough products

Table 7.
Summary of advantages and disadvantages of different types of technology.

atmospheric vacuum distillation units or atmospheric distillation units is determined by the characteristics of crude oil. Finally, according to our studies, the distillation unit with the oil topping column K-1, is more flexible and versatile, which on the whole allows processing any feedstock. **Table 7** shows the conclusions on the different types of atmospheric distillation [28].

3. Conclusion

The crude oil is a complex mixture of paraffin, naphthenic, aromatic, and other hydrocarbons with different molecular masses and boiling temperatures. Also, the oil contains sulfur, oxygen, and nitrogen-containing organic compounds. Therefore, to obtain from oil commodity products for various purposes, apply methods of separation of oil into fractions or groups of hydrocarbons. The modern dewatering-desalting processes are designed with electrostatic desalter only by horizontal geometry design: Atmospheric and atmospheric-vacuum. The horizontal design of electrostatic desalter has a lot of advantages, such as a large area of electrodes and, accordingly, a larger amount of oil per unit section of the device, a lower vertical speed of the moving oil flow, which provides favorable conditions for water sedimentation, as well as implementing processes with higher pressure and temperature. The electrostatics desalters are characterized by:

- More favorable conditions for the deposition of water drops;

- Specific performance, 3 times higher than vertical and ball structures in the presence of low specific gravity and lower cost of the device;

- Simplicity of design, a small amount of electrical equipment, ease of installation, availability of maintenance and maintainability;

- Ability to work with high pressure and temperature parameters.

However, the pretreatment of crude oil is not only concerned with its desalting and dewatering, but also with its degasification and packaging into a semi-product under the standard like ASTM D 1250-97, API Petroleum Measurement and GOST R 51858.

The distillation processes are the processes of oil separation into more or less homogeneous fractions (cups) without chemical conversion of its constituent substances. The process of separation of liquid substances by their boiling temperatures is atmospheric and vacuum. The oil distillation via single and multiple evaporations. In industrial conditions, the processes are carried out on the equipment of continuous action. During the single-evaporation distillation, the oil is heated to a certain temperature and all fractions that have passed into the vapor phase are collected. The distillation of the oil by multiple evaporations consists in that the oil is first heated to a temperature allowing to separate the light gasoline fraction. Then the crude without the fraction of light gasoline is heated to a higher temperature, and fractions that boil at about 375°C (that is, fractions of heavy gasoline, jet fuel, and diesel fuel) are also collected. In the residue from distillation, atmospheric residues are obtained. The atmospheric residues are distilled under vacuum, from which the lubricating oil fractions are obtained. Finally, the tar is obtained as residues from vacuum distillation. In other words, oil is consistently heated three times, each time separating the vapor phase from the liquids. The resulting steam and liquid phases are subjected to rectification in columns. Thus, industrial processes of oil distillation are based on a combination of distillation with single and multiple evaporations and subsequent rectification of the steam and liquid phases. We want to emphasize that this is the case, we use the K-1 oil topping column. However, if the process is executed without column k1, the same process is shorter and with the results already mentioned above. In the distillation column, there are distillation plates on which the vapors rising along the column are in contact with the flowing liquid (reflux). Reflux is created due to the fact that part of the upper product returns to the liquid state to the upper plate and flows down, enriching the rising vapors with low-boiling components. One of the ways to increase the concentration of high-boiling components in the residue from oil distillation is to introduce an evaporator into the lower part of the distillation column. As such, you can use water vapor, inert gas (nitrogen, carbon dioxide, petroleum gas), gasoline vapor or kerosene. The water vapor is most widely used as an evaporator for oil refining. Its presence in the distillation column reduces the partial pressure of hydrocarbons, and therefore their boiling point. As a result, the lowest-boiling hydrocarbons in the liquid phase, after single evaporation, pass into a vaporous state and, together with water vapor, rise up the column. In many literatures, it is recommended to use super-heated water vapor and enter it into the column with a temperature equal to the temperature of the feedstock or slightly higher. Usually, the water vapor used after steam pumps and turbines at a pressure of 2–3 bar is superheated in a tube furnace and introduced into a column with a temperature of 350–450°C. The use of wet vapor steam is not practiced, since its temperature and pressure are interrelated, for example, when introducing a column of 350°C, its pressure is equal to 170 bar. Besides, with increasing pressure, the cost of saturated water vapor increases sharply, so it is not economical to use it. If the wet vapor steam enters a column of low-pressure saturated water vapor, for example, 10 bar and, accordingly, with a temperature of 180°C, then part of the heat will go to heat it.

Abbreviation

GOST	Russian Interstate-standard
ASTM	American Society for Testing and Materials
NF EN ISO	French Norms European Norms International Organization for Standardization
ρ^{90}	density at $90^{\circ}C$

$\mu_{oil\ crude}$	kinematic viscosity of crude oil
AVDU	atmospheric-vacuum distillation unit
ADU	atmospheric distillations unit
CDU	crude distillation unit
Refinery	petroleum refinery plant
VDU	vacuum distillation unit
K1	oil topping atmospheric column
K2	main atmospheric column
TBP	true boiling point
t/h	ton/hour
kg/h	kilogram/hour
WV	water Vapor
P&ID	piping and instrumentation diagram

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