Features of heavy oil spraying with single evaporation

S Petrov\textsuperscript{1,2}, A Nosova\textsuperscript{1}, N Bashkirtseva\textsuperscript{1}, R Fakhrutdinov\textsuperscript{1}

\textsuperscript{1}Kazan National Research Technological University, 68 Karl Marx St., Kazan, Russia
\textsuperscript{2}Kazan Federal University, 18 Kremlevskaya Str., Kazan, Russia

E-mail: nostya_98@mail.ru

Abstract. Development of resources of heavy hydrocarbons is possible due to the evolution of technologies of their processing, including through the intensification of technological methods implemented in the field of their production at oil treatment plants. The research is devoted to the creation of a method of refining heavy hydrocarbon raw materials based on multiple increases in the working surface of the liquid phase during its intensive evaporation. The intensification of the single evaporation process is based on the fact that the heated raw material is sprayed in a hollow apparatus with the division of the final product into a distillate and a bottomless residue. Due to the spraying of raw materials, the interface of the phases is greatly increased, the supramolecular convective mass transfer becomes so large that it is comparable to the diffusional transfer. The aim of the study is to obtain the data necessary to create energy-saving technologies for the separation of heavy hydrocarbon resources. The paper discusses the possibility of improving the process of single evaporation of heavy oil due to the development of the working surface of the liquid phase, which is realized by spraying the latter. The process of crushing oil into droplets is considered in unity and interrelation with all phenomena occurring in the apparatus. The phase boundary increases several times, which makes supramolecular convective mass transfer comparable to diffusional transfer, which allowed for the separation of heavy oil to increase the distillate selection more than 3 times, with the weighting of the residual product.

1. Introduction

Oil-producing companies are increasingly paying attention to the development of heavy oil and natural bitumen deposits. Consideration of super-viscous oil as a source of hydrocarbon feedstock is associated with large volumes, on the one hand, and with a significant depletion of reserves of oils traditionally used for these purposes, on the other. Their reserves are among the main alternative sources of energy raw materials of the future [1, 2]. However, their processing with the help of known technologies is very difficult, energy-consuming and
sometimes unprofitable, because by their physicochemical properties, heavy oils differ significantly from standard oil in low content of fuel fractions, high content of sulfur compounds, resins, asphaltenes, which leads to their anomalously high density, viscosity and lower thermal stability [2, 3, 4]. To ensure an acceptable refining depth for such oil, significant investments are required, as well as high percentage rates of operating costs and working capital. In some cases, the use of features of the flow of gas-liquid media from the nozzles allows to intensify hydrodynamic and heat exchange processes in chemical technology and to reconstruct existing installations for the preparation and processing of oil without attracting large investments. According to most specialists of oil producing companies, the development of heavy oil can become cost-effective due to the evolution of technologies of primary oil refining that can be realized at the production sites at crude oil treatment plants [3, 4, 5].

The work is devoted to the study of the intensification of the process of single evaporation of heavy oil through a multiple increase in the working surface of the liquid phase, due to its dispersion.

2. Experimental section

One of the promising fields of super-viscous oil in the territory of Tatarstan is Ashalchinskoye, which is currently in pilot development. The highly viscous oil of the Ashalchinskoye field is characterized by high viscosity 10000 mPa·s, density 0.9715 g/cm³, content of a significant amount of resins 25-28 wt %, asphaltenes 4.8-5.5 wt %, sulfur 4.0-4.56 wt % and a low concentration of paraffins 0.9-1.6 wt %. The initial thermodynamic parameters of the single evaporation process were: volume flow 1.0 m³/h, temperature 300 °C, nozzle pressure 1.0 MPa. To determine the specific surface area, it is necessary to make a sequential calculation, including. Calculate the median droplet diameter: 

\[ d_m = \delta_c \times 15 \times \left( \frac{\delta_c \times W_c}{v} \times 10^{-3} \right)^{-0.4}, \delta_c - \text{film thickness of the fluid in the outlet section of the nozzle}, \delta_c \times W_c = Re - \text{Reynolds number.} \]

Calculation of surface linear diameter: 

\[ d_o = \sqrt{\frac{6 \times m}{\pi \times p}}, m - \text{distribution coefficient of droplets by fractions; } \rho - \text{the density of heavy oil at } t = 300 \, ^\circ \text{C.} \]

The calculation of the increase in surface: 

\[ \frac{n \times \pi \times d_m}{d_o} = \frac{d_o}{d_m}, \text{The diameter of the nozzle of the nozzle is calculated by the following formula: } d_c = \sqrt{\frac{4 \times m}{\pi \times m^{1.36}}} \times \frac{1}{\sqrt{1.36 \times d_o}}, m - \text{mass flow through the nozzle } \frac{kg}{s}, \rho = \rho_{20} - \beta \times (t - 20) - \text{the density of heavy oil at } t = 20 \, ^\circ \text{C}, \rho_{300} = \rho_{300} - \beta \times (t - 20) - \text{the density of heavy oil at } t = 300 \, ^\circ \text{C, } \beta - \text{expansion coefficient, } V_{20} = \frac{m}{\rho_{20}} - \text{volumetric flow rate through the nozzle at } t = 20 \, ^\circ \text{C, } V_{300} = \frac{m}{\rho_{300}} - \text{volumetric flow rate through the nozzle at } t = 300 \, ^\circ \text{C, m³/h, } \mu - \text{consumption coefficient.} \]

Film thickness in nozzle exit section: 

\[ \delta = 0.5 \times d_c \times (1 - \sqrt{1 - \phi}), \bar{\delta} = \delta \times d_c = 0.5 \times (1 - \sqrt{1 - \phi}), \phi - \text{live stream coefficient.} \]

The formula for calculating the warm-up time: 

\[ \tau_\theta = \left( \frac{\delta}{2} \right)^2 \times 365 \times 3600 \times \ln \frac{\theta_{30}}{\theta}, \theta - \text{film thickness; } Bi - \text{criterion } "Bio"; \alpha_\theta - \text{thermal diffusivity.} \]

The experimental part of the work was carried out in a laboratory unit operating at atmospheric pressure, equipped with lines for feeding raw materials, distilling the distillate vapor-liquid mixture, and discharging residual fractions (Figure 1). The installation includes a heated R-102 single-evaporation reactor with a volume of 1 l. Raw material enters R-102,
sprayed through a nozzle located at the bottom of the reactor. The evaporated part of the raw material is discharged through the top of the vessel, enters the heat exchanger-condenser C-101, then through the back pressure regulator BPR-101 enters the separator S-101. From the separator S-101 gaseous reaction products are removed through the upper part, liquid - the drain valve at the bottom of the vessel. VAT residue is pre-cooled in a heat exchanger-condenser C-102, then pumped R-103 in the heated tank T-102. Installation is intended for work in the flowing mode.

3. Results and discussion
In the first approximation, the process was regulated by the aero-thermodynamic parameters in the reactor, depending on the dispersion of the ensemble of drops of their speed, spray angle, contact time of the vapor and liquid phases. With a decrease in the diameter of the centrifugal nozzle and an increase in pressure, the average droplet size decreases (Figure 2), the specific surface area is predicted to be 100 m\(^2\)/kg. The result obtained is quite consistent with the information on the increase in the surface when 1 l is disintegrated into droplets with a diameter of 100 nm: ≈ 1200 times and 1240 times. However, bearing in mind the presence of droplets of both large and smaller median diameters, the increase in the surface will be ≈6400 times, since the initial sphere of 0.052 m\(^2\) turns into a collection of drops with a total surface of 330 m\(^2\).

![Figure 1. Schematic diagram of the installation.](image-url)
On the contrary, an increase in the nozzle diameter leads to an increase in the thickness of the liquid film and, accordingly, to an increase in the median droplet diameter and a decrease in the total surface of the droplets (Figure 3). The pressure in front of the nozzles of about 5 MPa prevents heavy oil feedstock from boiling in the pipeline and delays the process of vaporization inside the screwing chamber of the nozzle, while the dispersion of the torch improves, the total surface of the droplets increases.

The residence time of the liquid phase in the atomized state after exiting the nozzle provides evaporation of the droplets, for large droplets the evaporation process is delayed due to poor heating. With an increase in the size of the droplets, the heating time also increases, the evaporation process of the droplets deteriorates, and the range and diameter of the torch increase. Preference should be given to torches with a moderate root-spray pattern. Opened to a large angle, the torch increases the diameter of the apparatus, on the contrary “narrow” torches are better assembled, but the height of the apparatus increases markedly.

The warm-up times increase very rapidly with increasing size of the droplets. For heating large drops, $\theta \approx 1$ s are needed. However, it is difficult to implement such regimes. Therefore, warming up the small drops in a dispersed state, when they form an aggregate torch, you need to take care of the heating of large drops. Since the process of heating large droplets is delayed in time, it is necessary to organize the flow of the liquid film vertically downwards, and the thickness of the film should be minimal and comparable, for example, with a median diameter. The residence time of the liquid in this state should be an order of magnitude longer than the warm-up time for large droplets. Small film thickness will not prevent steam bubbles from escaping.

**Figure 2.** A plot of the nozzle diameter of the centrifugal nozzle, the pressure and the average size of the droplets.
Figure 3. A plot of the nozzle diameter of the centrifugal nozzle, the thickness of the liquid film and the median size of the droplets.

The necessary pressure for the high-quality spraying of heavy oil heated to a temperature of 200-350 °C is 3-5 MPa. To increase the dispersion, it is possible to use acute water vapor or nozzles with rotating elements, thus it is possible to achieve a polydisperse plume of sprayed oil with an average size of droplets from 30 μm to 40 μm. Also, the supply of raw materials in the form of a water-oil emulsion with a water content of up to 10 wt % leads to an improvement in the dispersion of the spray of crude oil due to the additional crushing of droplets due to the instantaneous evaporation of moisture and rupture of the droplets (microexplosions) the diameter of the droplets of liquid fuel sharply decreases to 2 microns.

Under established thermophysical conditions, the heavy oil even before the nozzle will be in a superheated or at least metastable state when it enters the laboratory unit, where the pressure is an order of magnitude lower and the temperature is higher than in the history of the stream, the sprayed oil boils condenses in the refrigerator and is discharged as a distillate. The liquid phase, which is the remainder of the process of single evaporation, is also cooled and collected in a collection. Spraying the raw material in the bottom-up direction allows the light-boiling components enclosed in the drops to diffuse to its surface and evaporate. The evaporation from the surface of the droplet also contributes to their blowing in of the lighter fraction rising from the bottom upwards, while drip entrainment of more high-boiling components occurs, which remain in the residue during classical evaporation (Figure 4). Along with molecular diffusion, convective mass transfer across the interface is initiated.
Figure 4. Graph of droplet diameter versus speed and ablation distance.

A significant effect is achieved with increasing process temperature. Comparison of the results of single evaporation of heavy oil without spraying and with spraying through nozzles shows an increase in the distillate yield with raising the process temperature from 15 to 44 wt %.

The spraying of a heavy hydrocarbon feedstock, which is a highly viscous multicomponent liquid, was achieved through the use of a hydraulic centrifugal nozzle. A compact region of suspended droplets of boiling liquid was obtained using a tangential feed of raw materials to the nozzle. Structurally, the nozzle consists of two main parts: a twist chamber and a nozzle (Figure 5, 6).

Figure 5. Sketch nozzle.

Figure 6. 3D nozzle model.

In the swirling chamber, the oil makes a complex rotational-translational motion and is pressed by the centrifugal force to the walls of the chamber and the nozzle, a space not occupied by oil is formed around the axis of the nozzle - a gas vortex cord that expands when moving towards the nozzle.

Thus, the outflow of oil from the nozzle occurs through the annular section of the nozzle, minus the radius of the gas vortex. The pressure in the cavity of the vortex cord is atmospheric and equal to the pressure in the apparatus, in which the separation of heavy oil.
An increase in temperature leads to a significant ablation of high-boiling compounds. From this point of view, the small residence time of the droplets in the column and their large sizes should be avoided, which results in an incomplete selection of the distillate part from the potential content in the feedstock. So, for example, the yield of the light part when separated in the apparatus of intensive evaporation at 300 °С was 43 wt %, with the potential content of light fraction boiling up to 300 °С in oil 29 wt %, in turn the yield of the heavy part was 57 wt % (Table 1).

| Table 1. Fractional composition. | Single Evaporation | Process temperature | Yield, wt % |
|---------------------------------|--------------------|---------------------|-------------|
| Classic                         | 200                | 12                  | 88          |
| Spray                           | 200                | 22                  | 78          |
| Classic                         | 250                | 19                  | 81          |
| Spray                           | 250                | 33                  | 67          |
| Classic                         | 300                | 25                  | 75          |
| Spray                           | 300                | 43                  | 57          |

At the same time, the content of the gasoline fraction boiling up to 200 °C in the light part decreased 1.5 times to 32% compared with the classical version of the process. From the data obtained it follows that with an increase in the distillate yield at process temperatures of 250 °C and 300 °C to 35 and 43 wt %, respectively, their viscosity at 20 °C does not exceed 20 mm² / s, that is, is similar to traditional light oils (Table 2). As a result of intensive single evaporation, sulfur compounds are concentrated in the residual part (Table 3). The sulfur content in the distillate decreases by 2 times, and increases with increasing process temperature.

| Table 2. Distillate output. |
|----------------------------|
| Fractional composition, i.b.p.-e.b.p., °C | Classical 200 °C | Spray 200 °C | Classical 250 °C | Spray 250 °C | Classical 300 °C | Spray, 300 °C |
|---------------------------------|-----------------|--------------|-----------------|--------------|-----------------|---------------|
| i.b.p.-200                      | 91              | 63           | 72              | 49           | 57              | 37            |
| 200-250                         | 8               | 15           | 16              | 11           | 14              | 11            |
| 250-300                         | 1               | 16           | 9               | 21           | 17              | 17            |
| 300-350                         | -               | 6            | 3               | 19           | 12              | 35            |

| Table 3. Residue. |
|------------------|
| Indicators        | Heavy oil 200°C | 250°C | 300°C | Distillate | Brent | WTI |
|--------------------|----------------|-------|-------|------------|-------|-----|
| Density at 20 °C, g/cm³ | 925.1          | 765.9 | 791.5 | 819.9      | 0.825-0.828 | 0.817-0.822 |
| Output fractions up to 350 °C, wt % | 32            | 100   | 100   | 76         | >62   | >72 |
| Sulfur content, wt %       | 3.47          | 0.95  | 1.44  | 1.9        | 0.37  | 0.24 |
The heavy residue resulting from the process includes significant amounts of asphalt-resinous substances with an asphaltene content of up to 15 wt %, and boiling fractions in the temperature range 350-500 °C, ~ 30 wt %.

The separation efficiency, at a constant temperature and pressure gradient, is determined by the equilibrium state between the liquid and vapor phases, which depends on the residence time of oil in the apparatus and the specific evaporation surface area that the raw material will have when sprayed through the nozzle. The optimum is the state of hydrodynamic equilibrium, at which at each moment in time the number of molecules moving from the liquid phase to the vapor phase and back increases. The composition of the distillate can be set over a wide range by adjusting the droplet entrainment of the higher-boiling oil components with a vapor phase, by changing the aero-thermodynamic conditions, the design of the nozzle and its location in the apparatus. Thus, it is possible to ensure the maximum possible yield of distillate with given characteristics.

The proposed process flow diagram for the installation of this process is shown in Figure 7, where heavy oil, pump $H$, is taken from the heated tank $E$-1 to the furnace $P$, where it is heated to the required temperature, then enters the EV evaporator, the vapor phase is then condensed in a heat exchanger $T$-1 and discharged in the form of distillate. The liquid phase, which is the remainder of the process of single evaporation, is also cooled by the heat exchanger $T$-2 and is collected in tank $E$-3.

**Figure 7.** 3D model of technological installation.

4. Conclusions

As a result of the research, the following conclusion can be made: due to spraying of raw materials, the interface of the phases increased significantly, supramolecular convective mass transfer became significant and comparable to diffusion transfer, the shift from phase equilibrium occurs towards increasing the yield of distillate, enriching it with heavy components.

The process of intensive single evaporation can be successfully applied to refining heavy oil. As a result of the process, oil is divided into two components: the distillate is a high-quality light oil enriched in fuel fractions, and the remainder may be suitable for the production of residual bitumens.
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References
[1] Petrov S M et al 2015 Chem. Technol. Fuels Oils 1 80
[2] Kayukova G P, Mikhailova A M, Feoktistov D A et al 2017 Energy Fuels 31 7789
[3] Kayukova G P, Mikhailova A N, Kosachev I P et al 2018 Energy Fuels 32 6488
[4] Pat. 2013120452 (RF)
[5] Pat. 2566775 (RF)