Methods for improving the energy efficiency of the installation with a discrete secondary part

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Abstract. Hydrodynamic cavitation, created by the intensive movement of the secondary discrete part in an electromechanical device, is the most important energy effect in the processing of petroleum products. The presented work contains and summarizes the results of the study of the main parameters of cavitation processing, including the geometric parameters of the elements of the secondary discrete part, the speed and trajectory of the secondary discrete part, as well as the parameters of the processed raw materials. It is established that to achieve an intense cavitation field, it is necessary, depending on the parameters of the processed raw material (its rheological properties), to maintain the optimal temperature and ensure the speed of movement of the elements of the secondary discrete part.

1 Introduction

The modern oil refining industry faces a number of challenges. In the conditions of strict requirements for the quality of petroleum products and depletion of reserves of "light" grades of liquid hydrocarbons, new promising and energy-efficient systems for primary processing of crude oil are in demand. These systems should provide processing of the material without the use of expensive catalysts, increasing the depth of processing of liquid petroleum products, reducing the content of harmful impurities, improving the quality of the output product.

The presented device is one of the representatives of devices with a discrete secondary part, which treat various types of liquid substances with intensive movement of a large set of ferromagnetic elements moving under the influence of an external electromagnetic field. The vast majority of similar devices are processed using vortex layer activation, in which the secondary discrete part in the working chamber moves randomly. The processing is carried out due to the effects of the elements hitting each other or the elements hitting the walls of the working chamber.

In the work [1], the author conducted studies that disclose the efficiency of using the energy of vapours in the treatment of crude oil, where the technology using a vortex layer activator is positioned as pre-cracking oil treatment. As a result of the conducted experimental studies, the author found that the treatment of oil in the vortex layer activator allowed to increase the yield of light fractions to 12%, in comparison with the source oil.

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The principle of influence on treated oil presented in [1] is similar to the principle of mechanical activation used in ball and colloid mills. The efficiency of the plant in oil treatment is explained by the high specific power supplied to the unit of volume of the processed product. According to the data [2-5], the specific power of the supplied energy in the dynamic discrete ferromagnetic medium reaches a value of the order of 10^3 kV/m^3, which is several orders of magnitude higher than in colloidal mills. In addition, energy is localized in separate zones, for example, in places of impact, where the specific power reaches extremely high values. In the impact zone, conditions are created for such physical and chemical processes, which are normally difficult or impossible.

In vortex layer activators, the configuration of the discrete secondary part is not so important, including shape and size, since the main effect is achieved only by collisions. Electromechanical converter with discrete secondary part is a continuation of developments related to the development of vortex layer activators. However, unlike vortex layer activators, hydrodynamic cavitation is the main energy effect used in the treatment. The use of hydrodynamic cavitation poses many additional requirements for the configuration of the secondary discrete part, including its shape and size, speed and path of movement, as well as the physical parameters of the processed raw material itself.

When selecting the optimal parameters of the plant for a particular type of oil, cavitation treatment in the device can provide the oil industry with an energy-efficient and relatively selective technology for deepening the processing and purification of crude oil from impurities. This technology is able to have a number of positive effects in comparison with traditional methods due to:

- complete absence or significant reduction in the number of catalysts used;
- reducing the negative impact on the environment;
- significant reduction in the cleaning process time (controlled by the number of installations).

At the same time, an electromechanical converter with a discrete part has a significant requirement for optimal parameter setting for energy-efficient processing of petroleum products. In this paper, the necessary studies are carried out to confirm the effectiveness of changing the parameters of the raw material and the configuration of the secondary discrete part on the effectiveness of creating a cavitation effect.

2 Materials and methods

In this paper, the authors propose studies to confirm the effectiveness of changing the parameters of the processed raw materials and changing the configuration of the elements to the intensity of the created cavitation. According to the laws of cavitation, the creation and stability of cavitation in liquid raw materials can be influenced by both the parameters of the oil, including the viscosity and, accordingly, the temperature, as well as the speed of movement of the elements relative to the processed raw materials.

In early studies, it was found that mechanical activation of oil without the use of cavitation can reduce the sulfur content in the processed product. It was found that the main energy impact was the energy of collision of the elements of the discrete secondary part with each other or with the walls of the working chamber. The use of hydrodynamic cavitation can significantly enhance the effect of oil desulfurization. For these reasons, in the study, the degree of oil desulfurization was chosen as the criterion for the intensity of cavitation. In a number of experiments conducted on an existing sample of a hydrodynamic cavitation generator, the influence of the temperature of the raw material and the configuration of the elements on the degree of desulfurization was studied. In all experiments, the same grade of raw materials was studied, only the parameters under study changed, including the temperature of the raw materials changed in the range from 50 to

80 °C in increments of 10°C. The speed of movement of the elements varied from 2 to 5 m / s in increments of 1 m/s.

3 Results of the study

Cavitation is the process of the occurrence in the liquid flow of cavities (bubbles, cavities) filled with gas, as a result of local pressure reduction, and subsequent collapse, accompanied by local increases in temperature and pressure, microbreaks and acoustic waves of the ultrasonic range. Since an electromechanical converter with a secondary discrete part is supposed to treat oil and oil residues, that is, a liquid viscous medium, during micro-explosions of cavitation bubbles that initiate the occurrence of an impact spherical wave, the nuclei (cavities, bubbles) present in such media begin to grow. These properties of the liquid lead to the emergence and development of the process of impact-cavitation action.

The intense movement of ferromagnetic elements under the influence of a rotating magnetic field is accompanied by a constant change of directions. Between the liquid flows moving along the ferromagnetic elements in opposite directions, zones of reduced pressure appear, cavities (cavitation bubbles) are formed, filled with steam of the treated raw material.

Due to the local pressure increase during the flow of the intensively moving working ferromagnetic elements with the processed raw material, cavitation bubbles are formed, which collapse when they enter the high pressure zone.

It has been found that the obtained energy at collapse of cavitation bubbles is sufficient for destruction of molecular compounds in the region of weakest carbon-sulfur C-S bonds [6]. The process of splitting organic sulfur compounds is similar to a similar cracking process, the difference is the short-term effect of high temperatures on the raw materials, equal to the collapse time of each single cavitation bubble.

In the process of implementing cavitation processes, caverns, "embryos" are sequentially formed in the raw material, followed by their growth and inevitable collapse, with the concomitant release of high energies. Growth of cavitation bubble occurs due to increase of internal pressure of vapors, under influence of processes of evaporation of treated liquid raw material into internal area of cavitation bubble. Further collapse of the bubble, which has reached the maximum possible radius, when it enters the zone with higher pressure, is accompanied by the release of accumulated kinetic energy.

However, a significant impact-cavitation effect will be available only with a corresponding complex effect of a plurality of forming, growing and collapsing cavitation bubbles. In many ways, the ability of the processed raw materials to be treated with cavitation impact is determined by several important parameters:

- temperature;
- gas inclusion in the form of cavities, "embryos";
- insoluble impurities.

In our case, the use of crude oil, as well as oil residues as the main processed raw material, allows to fulfill all these conditions, which allows, according to scientific studies given in works [7], to obtain a concentration of cavitation bubbles in the range from 10^{11} to 10^{12} m^{-3}.

A significant effect of cavitation processes is associated with a high concentration of energy released during the collapse process in the treated medium. This phenomenon is explained by the small volume of the substance when the bubble reaches its minimum radius preceding the collapse. According to scientific studies of various authors, the radius of the cavitation bubble at the time of collapse can reach, as a rule, 10^{-7}-10^{-8} m, against the radius in an equilibrium state of $10 \cdot 10^{-6}$ m. Changing the volume of the cavitation bubble, reaching 1000 values, leads to high values of stored energy.

Thus, the most important physicochemical manifestation of the cavitation process is the amount of pressure achieved on the surface of the bubbles when they are compressed to a minimum radius size with respect to the rest state.

Cavitation in the liquid flow is observed only when there is a rapid change in the flow rate, which in turn, according to the laws of hydrodynamics, entails a change in the pressure of the liquid, leading to the subsequent growth and collapse of cavitation bubbles. The most important difference between hydrodynamic cavitation and acoustic cavitation is the impossibility of storing energy with a gas bubble, that is, in this case, the possibility of a one-time energy effect on the cavitation "embryo" is observed. Another important difference is the absence of the so-called cavitation cloud in the processed raw materials, which in turn indicates the impossibility of developing a further cavitation process.

Based on a theoretical study of scientific literature and materials on the cavitation effect and treatment of liquid hydrocarbons in the impact-cavitation field, significant factors affecting the efficiency of treatment of liquid raw materials, including petroleum products, in an electromechanical converter with a discrete secondary part are:

- intensive movement of ferromagnetic elements, including speed and trajectory;
- uniform distribution of ferromagnetic elements over the entire volume of processed raw materials, or ensuring the elements pass through the central area of the working chamber;
- the shape of a separate ferromagnetic element with a supercavitating profile;
- properties of processed raw materials.

3.1 Environment Properties

Cavitation bubbles are formed where the liquid pressure is below a certain critical value (saturated vapor pressure). At the shape of the flowing cavitating element, cavitation will occur at a certain value of the dimensionless parameter:

$$X = 2\frac{p - p_{ss}}{\rho \upsilon^2}, \quad (1)$$

where p is the hydrostatic pressure of the incoming flow, p_{ss}- the pressure of saturated steam, υ - the density of the treated liquid medium, - the velocity of the element relative to the treated liquid medium.

$$\lg(P) = 2.68(1 - \frac{f(T)}{f(T_0)}, \quad (2)$$

$$f(T) = \frac{1250}{\sqrt{T^2 + 108000} - 307.6} - 1, \quad (3)$$

$$f(T_0) = \frac{1250}{\sqrt{T_0^2 + 108000} - 307.6} - 1, \quad (4)$$

where P - pressure of saturated vapors, MPa, T - boiling point at pressure P, K, T_0 - boiling point at pressure of 105 kPa (for oil fraction - average boiling point), K.

The oil density versus temperature is defined by the following expression [8,9]:

$$\rho = \rho_{20}[1 + \varepsilon(20 - T)], \quad (5)$$

where ρ_{20} - density of oil at 20°C; ε - coefficient of volumetric temperature expansion (0.000937 deg^{-1} - for light grades of oil, 0.000490 deg^{-1} - for heavy grades of oil).

Depending on the size of the dimensionless cavitation criterion, 4 types of flow [10] can be distinguished:

- X>1 - no cavitation;
- X≈1 - cavitation;
- X<1 - developed cavitation;
- X<<1 – super cavitational.

The intensity of hydrodynamic cavitation is significantly influenced by the properties of the medium being treated, including the viscosity, the pressure of saturated steam dissolved in the liquid medium gas. High viscosity contributes to the negative pressure in the expansion phase, thereby raising the cavitation threshold. The increase in the pressure of the saturated steam contributes to the increase in the energy released when the cavitation bubble collapses, as the amount of steam inside the bubble increases. In turn, the gas dissolved in the treated medium helps to reduce the cavitation threshold.

At the same time, it is worth noting that the properties of the processed raw materials and the critical speed of movement of ferromagnetic elements are necessary at which hydrodynamic cavitation is created. In this regard, experimental studies were carried out to assess the effect of the temperature of the raw materials on the intensity of cavitation, and the effect of the speed of movement of elements on the intensity of cavitation.

The efficiency of cavitation was assessed by estimating the degree of oil desulfurization. The process of oil desulfurization in this case is one of the popular methods of primary oil treatment. According to the studies given in, the energy released during cavitation is sufficient to overcome the C-S bond energy, since the C-S bond energy is 230-280 kJ/mol.

As part of this work, the temperature of the treated raw materials and its effect on the intensity of hydrodynamic cavitation created in the treated crude oil were studied. Experimental studies were conducted for temperatures of 50 °C, 60 °C, 70 °C, 80 °C. The treatment time for each test temperature was 25 seconds.

Table 1. Effect of temperature on desulfurization

Temperature of the processed raw materials, °C	Weight fraction of sulphur in treated feedstock,%
50	2,8
60	2,6
70	1,68
80	1,64

Table 2. Effect of the rate on the desulfurization process

Speed of movement of elements, m/s	Weight fraction of sulphur in treated feedstock,%
2	2,8
3	2,4
4	1,9
5	1,75

Thus, the optimum temperature for the crude oil desulfurization process was about 70 °C. At the same time cavitation occurs when the elements move at a speed of at least 4 m/s.

3.2 Discrete Secondary Part Parameters

In this work, the search for the optimal geometric shape of the elements of the secondary discrete part and the path of their movement was carried out both on the analysis of scientific and technical literature and experimental studies on the model of an electromechanical device with a discrete secondary part.

As previously described, unlike vortex layer activators, where cavitation existed as a secondary energy effect, in an electromechanical converter with a discrete secondary part, hydrodynamic cavitation is purposefully created by cavitation elements with a super cavitating profile. In addition to the principle of influence, in this case it is worth noting that unlike the activators of the vortex layer, in this case it does not apply a rotating magnetic field, but a discrete electromagnetic field, the direction of which is controlled by special algorithms for switching winding coils.

The configuration of the secondary discrete part elements for an electromechanical device with a discrete secondary part should be determined not only based on the efficiency of creating hydrodynamic cavitation, but also in accordance with the features of the device itself. Electromechanical device with discrete secondary part consists of four main elements [11,12]:

1. Inductor with 10 rectangular teeth;
2. Concentrated winding embedded in inductor slots;
3. Working chamber made of non-magnetic material;
4. Set of ferromagnetic elements.

The most optimal are two paths of movement of elements of the discrete secondary part [13] along the volume of the working chamber, which includes movement of elements along the circumference along the working chamber and movement through the center of the working chamber, to mix the processed raw materials. In this trajectory, the most popular will be the movement along the circle, since in this case the elements are able to gain a critical speed at which hydrodynamic cavitation is created. During operation, under action of external discrete electromagnetic field, ferromagnetic elements move from one active tooth of inductor to another.

It is worth noting that the proposed configuration, like other devices with a discrete part, has corresponding problems, consisting in the absence of a monolithic inner core. In this case, in the working chamber of the device there are areas that are referred to in most scientific publications as "dead" zones, that is, zones in which there is practically no intensive movement of ferromagnetic elements. There are two such zones in existing devices with a discrete secondary part. The "dead" zone of the 1st order in the region of the angles of the inductor teeth is due to the sticking of ferromagnetic elements due to large values of magnetic induction. The "dead" zone of the 2nd order appears mainly due to the inhomogeneity of the electromagnetic field distribution, when the value of magnetic induction in the center of the inductor is so small that it does not significantly affect the working elements, significantly inferior to other external influences, including hydrodynamic forces from the liquid material and centrifugal forces. As a result, these conditions impose additional difficulties in selecting the configuration of the ferromagnetic element and their concentration during the operation of the device.

Analysis of possible configurations of the elements of the secondary discrete part made it possible to conclude that the most optimal geometric parameters of the elements of the secondary discrete part to create cavitation in the liquid are a double-edged rod with a supercavitating profile, which is a wedge-shaped body, while the ratio of length to diameter is 6 to 1. Ferromagnetic element consists of two parts of supercavitating profile. Outside the medial section, the second half of the profile is a mirror image of the first half of the profile.

At the same time, in accordance with the conditions for the presence of "dead" zones, it is impractical to increase the dimensions of ferromagnetic elements, since at large sizes such elements will not be able to perform relative smooth movement around the circle, but will become stuck in the region of the inductor teeth. It is worth noting that the most optimal is to use ferromagnetic elements with a density in the working chamber of not more than 0.2 kg/m3 during operation. A further increase in the number of elements will lead to a situation where, with a large concentration of ferromagnetic elements, the free run length of each single element will be significantly reduced, thereby reducing the effect of hydrodynamic cavitation. Increasing the concentration of ferromagnetic elements that have a significant effect on the nature of the electromagnetic field in the inductor at a certain critical value can lead to a significant decrease in the efficiency of cavitation processes.

References

This paper presents a study of the influence of various parameters on the intensity of cavitation processes on the example of oil desulfurization. The cavitation intensity is affected by a large number of different parameters that must be taken into account when designing the plant for each type of refined petroleum product. A comprehensive accounting of the parameters of the oil refining process can ensure the creation of a stable cavitation cloud in the processed product.

The cavitation effect in this device is created by the intense movement of the elements of the secondary discrete part under the influence of an external electromagnetic field. In this regard, the main energy costs for the occurrence and maintenance of stable hydrodynamic cavitation fall on the creation of an electromagnetic field in the working chamber. Optimal selection of process parameters that take into account the rheological properties of the processed oil and the parameters of the plant operation, including the trajectory and configuration of the elements of the secondary discrete part, can achieve the most energy-efficient technological process, reducing energy costs. At the same time, for the selected and studied oil product, the most optimal parameters were the product temperature of at least 70 °C and the speed of movement of the elements of at least 4 m/s.

In the future, this technology can significantly increase the energy efficiency of the entire oil industry, reducing the cost of expensive traditional methods of primary processing of crude oil. However, this requires further research. In particular, the requirements for the selectivity of the processing of petroleum products will require researchers to study the degree of the effect of cavitation on individual molecules and compounds of oil.

Here are some examples:

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