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THE EFFICIENCY ASSESSMENT OF THE "COLD FLOW" METHOD AGAINST THE DEPOSITION OF ASPHALTENES, RESINS AND PARAFFINS

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ОЦЕНКА ЭФФЕКТИВНОСТИ МЕТОДА «ХОЛОДНЫЙ ПОТОК» В БОРЬБЕ С АСФАЛЬТЕНОСМОЛОПАРАФИНОВЫМИ ОТЛОЖЕНИЯМИ

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Key words:
mechanisms of formation of deposition of asphaltenes, resins and paraffins, DARP, molecular diffusion, temperature gradient, hydraulic calculation, cold flow, equation of fluid state, rheological curve, component composition, viscosity, flow temperature.

Mechanisms of formation of deposition of asphaltenes, resins and paraffins (DARP) are considered. Molecular diffusion based on the influence of the temperature gradient is the main mechanism for DARP formation. The analysis of existing methods against DARP is given. Modern methods of DARP prevention that affect the temperature gradient are aimed at maintaining the oil temperature above the crystallization temperature of paraffin. The cold flow method is an alternative control method which involves cooling the oil to a surrounding temperature. The purpose of the work is to assess the effectiveness of the cold flow method against DARP; its advantages and disadvantages are revealed. In order to assess the effectiveness of the proposed method. The sample of oil and produced water was taken at the pumping station. Using gas chromatography, the fractional composition of an oil sample was determined using the SimDis method. Using a calibration table, a component composition of oil up to C_{52} was calculated using values of boiling point and equations of fluid state were formed in PVTsim software. Rheological studies of the transported oil are carried out. Based on results of laboratory studies in OLGA software package, a hydraulic calculation of the pipeline was performed for various values of the flow temperature using the "Wax deposition" paraffin deposition module on the Matzain model. Thus, having the flow with temperature equal to the ambient temperature, in 10 days 5.6 kg of paraffin is formed on pipeline walls, whereas in the current conditions it is 100 kg.

As a result, it is established that the effectiveness of the application of the cold flow method against DARP is 94 %. Proposed method can significantly reduce production costs associated with paraffin oil transportation.

Ключевые слова:
механизм образования асфальтеносмолопарафиновых отложений, АСПО, молекулярная диффузия, градиент температуры, гидравлический расчет, «холодный поток», уравнение состояния флюида, реологическая кривая, компонентный состав, вязкость, температура потока.

Рассмотрены механизмы образования асфальтеносмолопарафиновых отложений (АСПО). Основным механизмом формирования АСПО является молекулярная диффузия, основанная на влиянии температурного градиента. Проведен анализ существующих методов борьбы с АСПО. Современные методы предупреждения АСПО, воздействующие на температурный градиент, направлены на поддержание температуры нефти выше температуры кристаллизации парафина. Альтернативным способом борьбы является метод «холодный поток», предполагающий охлаждение нефти до температуры окружающей среды. Целью работы является оценка эффективности применения метода «холодный поток» в борьбе с АСПО, выявлены его преимущества и недостатки. Для оценки эффективности предлагаемого метода построена модель существующего трубопровода от дожимной насосной станции до установки предварительного сброса воды. На дожимной насосной станции отобран образец нефти и пластовой воды. С помощью газовой хроматографии методом SimDis определен фракционный состав образца нефти. По значениям температуры кипения с помощью калибровочной таблицы рассчитан компонентный состав нефти до С52 и сформированы уравнения состояния флюидов в программном продукте PVTsim. Проведены реологические исследования транспортируемой нефти. На основе результатов лабораторных исследований в программном комплексе OLGA выполнен гидравлический расчет трубопровода при различных значениях температуры потока с использованием модуля осаждения парафина Wax deposition на модели Matzain. Таким образом, при температуре потока, равной температуре окружающей среды, за 10 дней на стенках трубопровода формируется 5,6 кг парафина, тогда как в текущих условиях – 100 кг.

В результате работы установлено, что эффективность применения метода «холодный поток» в борьбе с АСПО составляет 94 %. Его использование может значительно уменьшить издержки производства, связанные с транспортировкой парафинистой нефти.

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Introduction

Pipeline transportation is the integral part of the fuel and energy complex of Russia. Nowdays, more than 95 % of oil is transported via pipelines. However, this method of transportation has a number of disadvantages such as deposition of asphaltenes, resins and paraffins (DARP) during the transportation of crude oil. Nearly every fifth accident is caused by precipitation of DARP [1]. A decrease in pressure and temperature as well as oil degassing create conditions required for precipitation of DARP. If the temperature of oil is higher than the crystallization temperature of paraffin, then paraffin components are in the dissolved as a liquid phase of the oil system. A decrease in temperature forces the components to crystallize out of the oil and form spatial structures [2-6].

DARP decrease the capacity and can totally plug and break the pipeline, which leads to disastrous environmental consequences. Besides, there is a decrease in effectivness of systems, efficiency of operation of pumping facilities and time between overhauls. All these consequences entail significant economic costs to restore the ecology and the performance of the oil gathering system [7-8].

All the factors mentioned above make it clear that environmental safety, smooth-running, durability and economical operation of pipelines directly depend on timely prevention of DARP precipitation. Today, the greatest attention is paid to the prevention and control of sediments. The issue of reducing and eliminating paraffin deposits remains unresolved [9].

In order to select the most effective method to fight with DARP it is necessary to have an idea about the mechanisms its formation. That will allow to carry out the selection of the most effective method of reducing the amount of paraffin deposits.

Mechanisms of DARP development

The mechanism of development of paraffin deposits consists in the release and growth of paraffin crystals on the surface in contact with oil and then on the resulting DARP layer. There are various mechanisms for the precipitation of paraffin hydrocarbons, including molecular diffusion, shear dispersion, Brownian diffusion, and gravitational sedimentation [10].

The mechanism of molecular diffusion is based on the transfer of dissolved paraffin components from the volume of oil to the wall of the pipeline. The remaining mechanisms consider the movement of suspended paraffin particles released in the volume of oil as a result of lowering the oil temperature below the crystallization temperature of paraffin [11]. However, paraffin crystals developed in the volume of oil practically do not participate in the process of DARP formation, but are transferred in the oil flow in a suspended state. Many results in the dynamics of dissolved particles indicate that particles located in a viscous layer near a wall are usually re-captured into a volume flow under the action of a lifting force created by a turbulent flow known as "Saffman lifting force" [12, 13].

Based on extensive experimental observations of the deposition of paraffin over the past few decades, we note that molecular diffusion is the main mechanism of DARP development [14-16]. The diffusion mechanism for DARP development is considered next (Fig. 1). Oil, in contact with the cooled wall of the pipeline, begins to cool. A radial temperature gradient arises between the inner wall of the pipeline and the boundary layer of the flow (see Fig. 1*a*). When the temperature drops below the saturation temperature of the oil with paraffin, the process of crystallization of paraffinic components (PC), which are in a dissolved state, begins and the precipitation of paraffin crystalson the internal surface of the pipeline. As a result, the concentration of dissolved PC at the pipe wall is reduced compared with the concentration in the volume of oil − a gradient of concentration of dissolved paraffin appears. Under the action of the diffusion process, the dissolved PCs move from a region with a high concentration to a region with a low concentration, i.e. from the volume of oil to the wall, where the crystallization process continues (see Fig. 1*b*). The diffusion coefficient of PC in oil usually ranges from 10^{-10} to 10^{-9} m^2/s [17].

When the first layer of paraffin deposits on the wall is finished, the process of deposition of paraffin crystals continues, but now on the

boundary surface of the oil region (see Fig. 1c). Not all the PCs crystallize when they reach the pipeline wall. Some of them continue to diffuse in the layer of paraffin deposits. This phenomenon is known as "sediment aging". Internal diffusion of dissolved PCs leads to an increase in the paraffin fractioning the sediment layer (see Fig. 1d). Consequently, a large part of PCs in the layer of paraffin deposits with an increased solubility limit may further crystallize, leading to an increase in the hardness of the DARP layer.
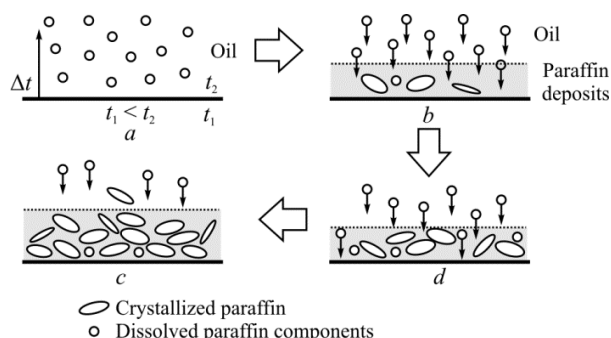

Fig. 1. Schematic representation of the diffusion mechanism of DARP development

Thus, the main driving force during the DARP development is the temperature gradient.

By affecting it, it is possible to change change the amount of paraffin deposits that form on the inner surface of the pipeline.

Cold flow

There are two directions where fight against DARP is occur such as the prevention of the formation of deposits and the removal of the formed deposits. The most rational use of methods for preventing the formation of DARP, as this eliminates pipeline downtime and, as a consequence, significant economic losses to restore the efficiency of the system for collecting and transporting oil. Measures to prevent the formation of paraffin deposits involve the use of chemical and physical methods, as well as the use of protective coatings [18]. A protective coating is expensive, and the application process is time consuming. Chemical methods are based on the addition of chemical reagents to the pumped product that prevent DARP development [19]. The main disadvantages of chemical methods are the high cost and difficulty of selecting an effective reagent. Physical methods are based on the effects of

mechanical and ultrasonic vibrations on the products being transported, as well as the effects of electric, magnetic and electromagnetic fields. The disadvantages of physical methods include their high cost and complexity in technical performance [20-24].

The cold flow method is an alternative to modern measures to prevent the formation of DARP, which involves the transportation of oil cooled to ambient temperature. This method is more effective than other methods of preventing DARP development, as it affects the cause of the formation of paraffin deposits – temperature gradient [25]. The cold flow method can find its application in pipelines, where the use of mechanical cleaning devices is not possible. These include variable-diameter pipelines, as well as pipelines with constrictions, sharp turns and other local resistances.

The use of this method in underwater pipelines and in permafrost areas should also be considered. Underwater pipelines cleaning is a difficult operation from a technical and organizational point of view. In the event of an unplanned stop of the in-line cleaning device, the fluid is cooled and crosslinked gels are formed [26]. To restart the pipeline, great pressure will be required to destroy the formed gels. If the pressure required to restart the pipeline exceeds the allowable one, then the line must be left or completely replaced, which entails significant economic losses. During the operation of pipelines in permafrost zones, dynamic equilibrium disturbances occur, accompanied by heaving and subsidence of freezing, thawing soils. Intensive processes of watering and bogging occur, which leads to the destruction of the embankment and the emersion of the pipeline [27-34].

All the cases given above can use the cold flow method, which will reduce the risk of accidents and prevent significant economic losses. However, when considering this method, it is necessary to consider the viscosity of the oil, which increases when the flow is cooled and leads to an increase in the pressure required to transport the fluid.

Modeling paraffin precipitation in cold flow conditions

In order to evaluate the effectivenes of the cold flow method for preventing the formation of paraffin

oil hydraulic calculation conducted in the simulator OLGA multiphase flow using paraffin deposition module Wax Deposition in MATZAIN model.

The Wax Deposition module allows you to simulate the process of separating paraffin from oil and deposition on the inner surface of the pipeline wall. The crystallization and melting of paraffinic hydrocarbons are calculated depending on pressure and temperature. The theory of molecular diffusion of dissolved paraffin due to heat transfer between the fluid and the wall, as well as the transfer of precipitated paraffin as a result of shear dispersion, is the basis of the mechanism of paraffin hydrocarbon deposition in the MATZAIN model [35].

The system of oil transportation from a pumping station to a water separation unit was selected as an object to study. The pipeline considered is characterized by intense precipitation of paraffin. Separated oil with a water content of 15 % is transported through a steel pipeline with a diameter of 219 mm to a distance of 5,282 m with a flow rate of 7,175 m^3/day. The pressure at the inlet of the PWH is 0.1 MPa.

A sample of oil and produced water was taken at the pumping station to determine the parameters required as input data when calculating in OLGA. Using gas chromatography, the fractional composition of an oil sample was determined using the SimDis method. Then the component composition of oil was calculated up to C52 (see Table) using the calibration table.

Using the PVTsimfluid software phase diagram was built (Fig. 2).

Transported water-oil emulsion was studied in order to determine rheological parameters using balance mixtures of oil and water at the temperature of 5 ℃. Density of oil is 835 kg/m^3, density of water is 1,087 kg/m^3. As a result of research, a rheological curve is obtained, shown in Fig. 3.

Hydraulic design was carried out for 10 days at various values of the flow temperature. According to the current state, the oil flow at the outlet from the pumping station has a temperature of 14.44 ℃. The pipeline is laid underground. The ambient temperature is 2.1 ℃.

As a result of the design, graphs of the distribution of the layer of paraffin deposits along the pipeline, are presented in Fig. 4

T a b l e

Oil composition

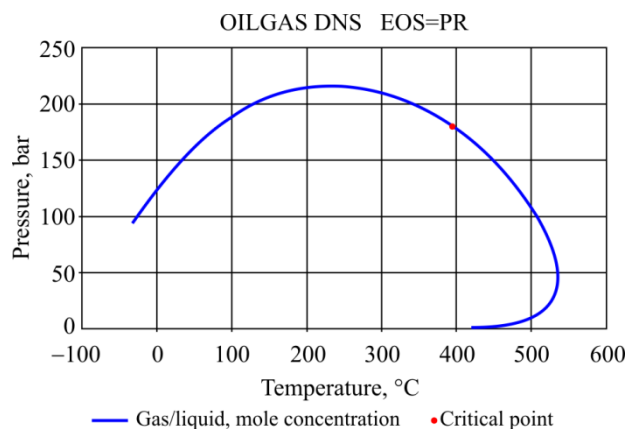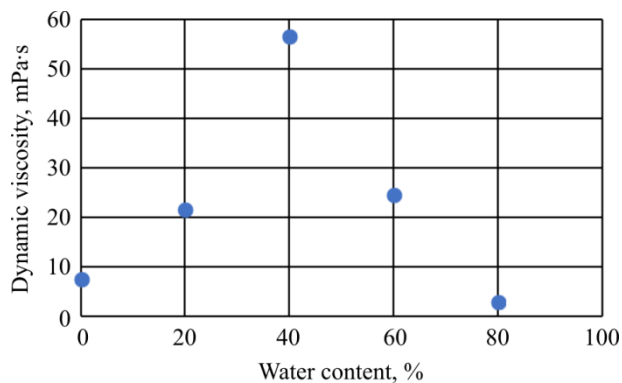| Component	Component mass, g	Content, mas. %
C5	2.533	2.58
C6	2.788	2.84
C7	4.001	4.08
C8	4.846	4.95
C9	4.849	4.95
C10	4.654	4.75
C11	4.411	4.50
C12	3.805	3.88
C13	4.279	4.37
C14	4.136	4.22
C15	3.902	3.98
C16	3.716	3.79
C17	3.440	3.51
C18	3.132	3.20
C20	6.023	6.15
C24	10.180	10.39
C28	7.859	8.02
C32	6.207	6.33
C36	4.610	4.70
C40	3.367	3.44
C50	4.758	4.85
C52	0.504	0.51
Total	98	100

Fig. 2. Phase Fluid Diagram

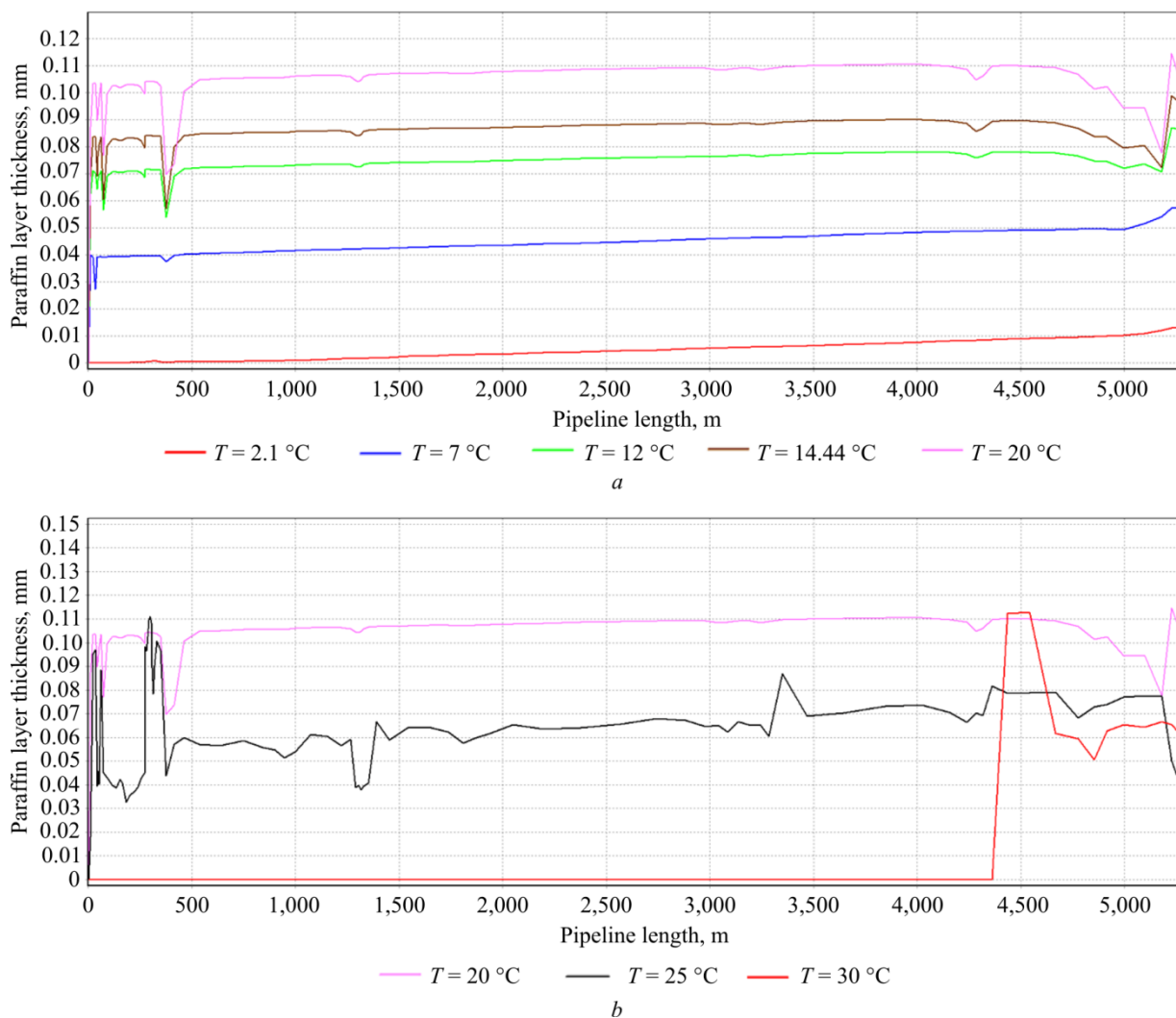Fig. 3. Dependence of the emulsion dynamic viscosity on water content

Fig. 4. Graph of the DARP layer thickness distribution along the pipeline at the temperature of pumped liquid:
a – up to 20 ºC; *b* – from 20 ºC

At the flow temperature of 14.44 ºC, a paraffin layer 0.02 mm thick is deposited on the inner surface of the pipe along the entire length (Fig. 4*a*). The lower the temperature of the oil the lower the thickness of the DARP layer. At a temperature of 2.1 ºC maximum thickness of DARP layer is 7 times less than at temperature of 14.44 ºC.

As the temperature increases from 20 ºC, the geometry of the paraffin distribution layer varies (see. Fig. 4*b*). At 30 ºC the minimum amount of paraffin is deposited along the entire length of the pipeline, the main part falls at the end. This is caused by the fact that paraffin approaches the melting point of 31 ºC. Fig. 5 shows a plot of precipitated paraffin mass and pumping pressure versus flow temperature.
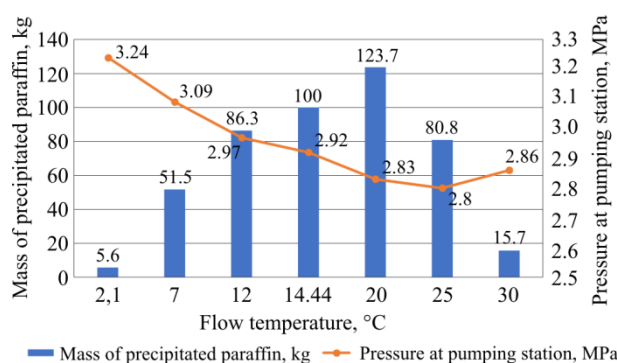

Fig. 5. Dependance of deposited mass of paraffin and pumping pressure from the flow temperature

The graph (Fig. 5) shows a tendency to decrease the mass of precipitated paraffin with decreasing flow temperature. At the flow temperature of 2.1 ºC, 5.6 kg of paraffin is precipitated on the pipeline wall in 10 days, while

under current conditions (14.44 ºC) the mass of paraffin deposited is 100 kg.

Thus, in order to reduce the amount of DARP, it is necessary to cool the oil to the temperature of the pipeline wall, thereby eliminating the effect of the temperature gradient. However, the lower the oil temperature the higher its viscosity and as a result, the higher the required pressure for transporting the liquid to the water separation unit [36]. Pumping station pressure reaches the highest value (3.24 MPa) at a temperature of 2.1 ºC, which exceeds the current pressure by 0.32 MPa (see Fig. 5). Such a slight change in pressure will not affect the characteristics of the pump. The research results show that the use of the cold flow method will reduce the amount of DARP by 94 % and increase the time between overhauls in 8 times.

Oil cooling equipment

Heat exchangers and refrigerators are traditional equipment for oil cooling. However, in case of cooling the oil to low temperatures and paraffin precipitates intensively on the equipment and can cause its subsequent failure [37]. At the moment, the main challange with the use of the cold flow method is the lack of suitable equipment used in practice. Some inventions for cooling the oil flow are considered next.

Kellogg, Brown and Root (Halliburton) proposed apparatus "Paraffin absorber" for use in underwater systems. The flow is cooled as follows: the oil is passed through a loop-shaped tube, in which the external temperature of the wall is below the saturation temperature of the oil with paraffin, as a result of which the flow is cooled and the paraffin drops out. Developed DARP are removed by periodic cleaning of the pipe with scrapers and further transportation together with the stream in the form of a suspension that is resistant to sedimentation. The risk of gradual pipeline plugging and blockage of the scraper is the main disadvantage. In addition, the surface of the pipeline wall is covered with scars under the influence of a scraper, the number of places for paraffin adhesion increases (Fig. 6) [38].

There is a method of Instantaneous cooling proposed by Shell Western E&P Inc. (Houston, Texas, USA) (Fig. 7). Oil mixes with gas and is passed through a choke coil, which leads to a sudden decrease in pressure and paraffin in the stream. The idea of this work is to use the Joule-Thomson effect to cool the flow [39].
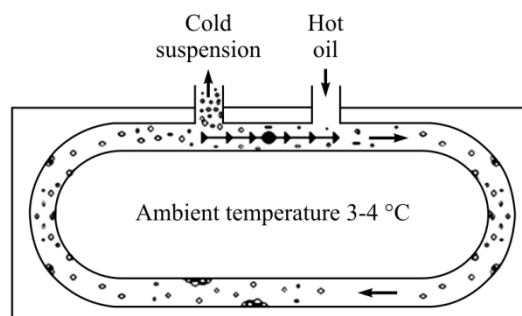

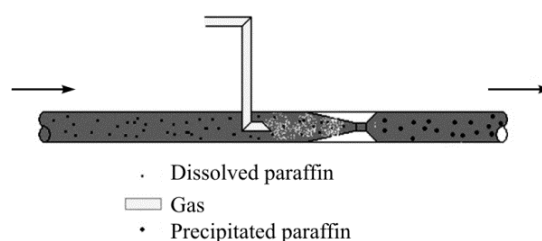Fig. 6. Schematic view of the Paraffin Absorber apparatus

Fig. 7. Instantaneous Cooling Method scheme

According to the Injection of oil or solution method (C-FER Technologies, Edmonton, Canada) cooling is achieved by adding a cold oil or solvent recycle stream. It is also proposed to introduce an overcooled gas. To supercool the gas introduced into the oil flow, the Joule-Thomson expansion is used, which leads to the formation of a suspension [40]. All of these apparatus for cooling oil are patented, but not tested in real conditions.

Conclusion

The paper discusses the mechanisms of DARP development. Molecular diffusion is the main mechanism in the formation of paraffin deposits on the inner surface of the pipeline. Molecular diffusion is based on the transfer of dissolved paraffin components from the volume of oil to the wall of the pipeline. Paraffin precipitation is the result of a temperature gradient. Thus, an amount of DARP depends on the value of the temperature gradient. Methods based on the reduction of the temperature gradient effect are the most effective. These methods include cold flow.

The method involves transportation of oil cooled to ambient temperature; can find its

application in pipelines, where the use of mechanical cleaning devices is not possible. These include variable-diameter pipelines, as well as pipelines that have constrictions, sharp turns, and other local resistances.

The hydraulic disign of the pipeline was carried out in the OLGA multiphase flow simulator in order to assess the effectiveness of the use of the cold flow method to prevent DARP precipitation. Calculation results show that the use of the cold flow method will reduce the DARP amount by 94% and increase the time between overhauls in 8 times.

Thus, cold flow method can significantly reduce production costs associated with the transportation of paraffin oil. However, there are no examples of its application in practice. At the moment, technological limitations associated with cooling process are the main disadvantage of the method proposed.

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