Development of technologies for the pour point depressant treatment of an annular near-wall layer of oil pumped through a main pipeline

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Abstract. The technology of depressant utilization, which essentially depends on the method of its addition to oil, has a substantial impact on the efficiency of the main pipeline. Direct injection of a pour point depressant into the reservoir enables to maintain optimal conditions for oil processing, namely, to cool the oil at an optimal rate and, which is especially important, in static conditions. But in this case, significant capital investments will be required for mixing devices, devices for cooling oil, for the construction of additional tanks, etc. The addition of pour point directly into the pipeline (before or after the head pumping and heating stations) cannot provide optimal cooling conditions. This process does not significantly improve the rheological properties of oil as compared to the introduction of a depressant directly into the reservoir. The introduction of a pour point depressant directly into the pipeline will significantly reduce capital costs for processing highly paraffinic oil and the advantages of this method are obvious. The proposed method of depressant utilization will reduce their consumption, and energy consumption for heating oil. This goal is achieved by the fact that the pour point depressant is not added to the entire volume of highly paraffinic oil pumped through the pipeline, but only to the annular near-wall layer of oil in the pipe, thus creating a low-viscosity near-wall layer of the pumped highly paraffinic oil. This paper presents a scheme for the implementation of the proposed method and formulas for thermal calculations of the pipeline sections considering depressant addition to oil.

1 Introduction and literature review

The technology of depressant utilization, which essentially depends on the method of its addition to oil, has a substantial impact on the efficiency of the main pipeline [1-6]. It is known that the rheological parameters of highly paraffinic oil are significantly influenced by:

- Oil heating temperature when adding a depressant;
- Concentration of the depressant in oil;
- Oil cooling conditions, etc.

There are two ways to add a pour point depressant to oil:

1. Into the tanks at the head pumping station;
2. Into the pipeline before or after the main pumping and heating station.

The first method of depressant addition to oil enables to maintain the optimal conditions of oil treatment with a depressant, i.e. to cool oil at an optimal cooling rate and under static conditions. However, in this case, significant investments will be required for mixing devices, oil cooling devices, for the construction of additional tanks, etc. When a pour point is added directly into the pipeline before or after the head pumping and heating stations, it is not possible to provide optimal cooling conditions, which will somewhat worsen the oil rheological properties. In this case, capital costs will be many times higher than in the first method. The operating costs of oil treatment with a depressant will also significantly reduce. Since the advantages of the second method are obvious, only the second method will be considered in this paper.

A method of adding a pour point depressant to an oil stream also will have a significant impact on the economic performance of the pipeline. Consider two options for adding a depressant into an oil stream:

- Introduction of a depressant to the entire volume of pumped oil;
- Introduction of a depressant into the annular near-wall layer of the oil pumped through the pipeline.

Other pumping options also exist, for example, the so-called "capsule" pumping [7-10], when capsules of solidified oil without additives are introduced into the oil flow with the addition of a depressant. Definitely, the oil temperature with the addition of a depressant must be lower than the pour point of pure oil. "Capsules" of solidified oil are cylinders with a diameter slightly smaller than the pipeline diameter and a length equal to 2-3 pipe diameters. The flow structure created in

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principle slightly differs from the flow structure with continuous introduction of the additive into the annular wall layer of the oil pumped through the pipeline.

2 Materials and methods

The Mangyshlak oil, the original oil and oil with addition of ECA 4242 depressant were studied. The rheological parameters were determined at temperatures of 10, 15, 20, 25, 30, 35, 40, 50, 60, 70, 80 °C and for the concentration of the additive in oil of 0.05; 0.10; 0.15; 0.20; 0.30; 0.50%. Oil treatment with a depressant was carried out taking into account the optimal conditions for its introduction and oil cooling, as well as taking into account the real conditions of the main pipeline.

The performed rheological studies made it possible to determine the parameters providing the greatest depressant effect:

- Oil temperature upon the depressant introduction is about 60-70 ° C. Another way is to introduce the depressant at a temperature of 40-50 °C and further to heat oil to 60 -70 °C;
- Concentration of the depressant in oil is approximately 0.20% by weight of oil;
- Cooling rate of oil with a depressant is 10-20 °C/hour;
- The cooling conditions are static.

The following technology for introducing a depressant into oil has been developed based on the performed studies:

1. Introduction of a pour point depressant in a given amount into a turbulent flow of oil heated to 60-70 °C. The place of the additive introduction is the head pumping station, the pipeline after the heating devices;
2. Introduction of a pour point depressant in the form of a "concentrate" into an oil stream having a temperature of 40-50 °C. The place of introduction of the additive is the head pumping station, the pipeline before the booster pumps.

The passage of oil through the booster and main pumps ensures a uniform distribution of the depressant throughout the entire oil volume. The subsequent heating of oil with the depressant in heating devices to 60-70 °C provides an improved depressant effect of the additive.

"Concentrate" is a solution of the depressant in the pumped oil in a ratio of 1:1 or 1:2. The use of a “concentrate” promotes a more uniform distribution of the additive throughout the entire volume of pumped oil. It is recommended to introduce the "concentrate" of the pour point depressant according to the technological scheme shown in Figure 1.

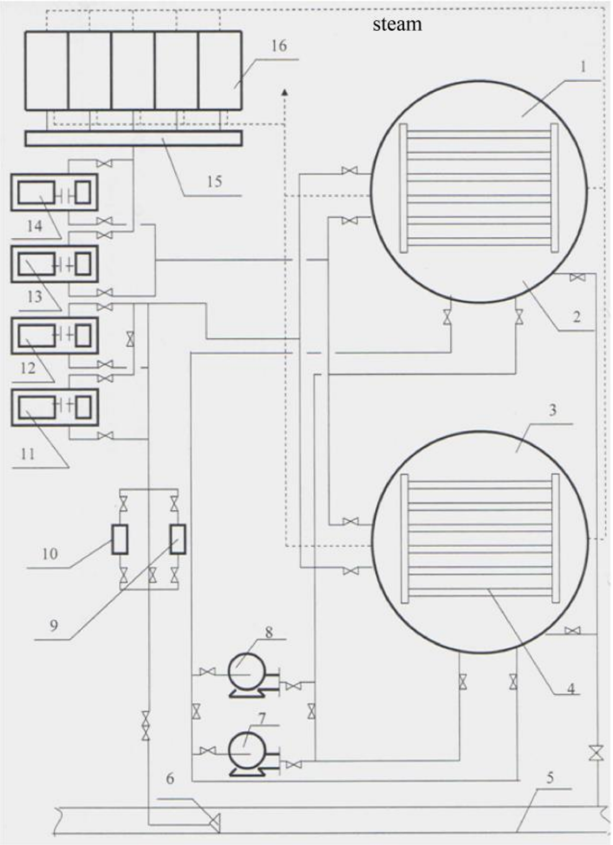

Fig. 1. Schematic diagram of a dosage unit for depressant addition:1, 3 – tanks; 2, 4 - heat exchangers; 5 – pipeline; 6 - spraying device; 7, 8 - centrifugal pumps; 9, 10 – filters; 11-14 - metering plunger pumps; 15- collecting manifold, 16 - thermal chamber.

Highly paraffinic oil is poured into one of the reservoirs 1 or 3 in an amount corresponding to a given additive-oil ratio. It is desirable to take oil from pipeline 5 after the installation site of the spray device 6. The depressant is heated in a special thermal chamber 16 to a temperature of 60-65 °C, at which the additive turns into a liquid state, and it is discharged into the collecting manifold 15. From the collecting manifold, the additive is pumped into the oil reservoir by pump 13(14). This sequence promotes better mixing of the components. After draining the additive, the mixture is thoroughly mixed by centrifugal pumps 7, 8. To maintain the "concentrate" temperature within 60-65 °C, tanks 1, 3 are equipped with heat exchangers 2 and 4.

The "concentrate" is fed into the pipeline by the dozing plunger pump 11 (12). The capacity of the metering pump is set depending on the specified percentage of the additive in the oil, the weight ratio of the components in the "concentrate", and the pipeline capacity.

The tanks are put into operation one after another. For example, when the "concentrate" is supplied from one tank to the pipeline, the other one at this time is used to prepare the "concentrate". When the tank is emptied, the system switches to another tank with the newly prepared "concentrate". In order to thoroughly mix the components, circulating centrifugal pumps must work constantly, both during the preparation of the "concentrate" and during its injection into the pipeline. The uniform distribution of the "concentrate" over the entire volume of the pumped oil is performed by the spraying device 6, which is installed at the axis of pipeline 5.

Filters 9, 10 are installed since the "concentrate" can contain mechanical impurities and this can cause clogging of the spray device. If, for some reason, the installation of the spraying device is difficult, then the "concentrate" can be fed into the pipeline through an ordinary choke. The practice shows that the passage of oil with an additive through booster and main pumps ensures its fairly good distribution over the entire volume of oil. To exclude the solidification of the additive or "concentrate", as well as paraffinic oil in the pipes of the metering unit, it is necessary to equip the pipelines with steam traces and cover them with thermal insulation. If the additive is introduced into the pipeline in its pure form, the technological scheme of the metering unit is somewhat simplified. The lines for the supply of highly paraffinic oil to the tanks become unnecessary, but the rest of the unit technological scheme remains unchanged.

This technology was successfully applied at the Uzen-Atyrau-Samara pipeline when the ECA 4242 depressant was introduced into the highly paraffinic Mangyshlak oil.

As was mentioned above, not all of the listed optimal parameters can be maintained within this technology. In particular, the rate of oil cooling in the pipeline is much lower than the optimal one and the oil is cooled in dynamics. Since the influence of these parameters on the rheological characteristics of oil is not so significant, their implementation is impractical because of high material costs.

A significant disadvantage of the method of pipeline transportation of highly paraffinic oils using depressants with their addition to the entire volume of pumped oil is a relatively high consumption of depressants, as well as significant energy consumption for heating oil when adding them.

3 Results

The used depressants are mainly polymeric substances, the cost of which is quite high. So, the use of depressants in pipeline transport of highly paraffinic oils is in most cases less economically profitable compared to other methods [11], for example, with oil preheating before pumping, oil thermal treatment, etc.

The advantages of this method include a significant decrease in the oil rheological parameters, the stability of the additive influence on oil, the ease of implementation of the method, low capital investments during its implementation. So, the task is to preserve these advantages together with significant reduction of the operating costs, the main part of which is the cost of a depressant and, to a lesser extent, the cost of heating oil when adding them.

Since the currently available depressants are synthesized based on expensive chemical reagents (higher alcohols, carboxylic acids, etc.), and the creation of additives based on cheaper raw materials is not expected in the near future, one cannot expect a significant reduction in the cost of additives. Consequently, one should seek the reserves for reducing operating costs in improving the technology of using depressants. The proposed method of depressant utilization will reduce their consumption, and energy consumption for heating oil. This goal is achieved by the fact that the pour point depressant is not added to the entire volume of highly paraffinic oil pumped through the pipeline, but only to the annular near-wall layer of oil in the pipe, thus creating a low-viscosity near-wall layer of the pumped highly paraffinic oil.

Accordingly, when a depressant is added to a highly paraffinic oil, not the entire volume of oil is heated, but only the wall oil layer in the pipe.

The prototype of the proposed method can be the already known method of pipeline transportation of highly paraffinic oils. In order to reduce the hydraulic resistance of the pipeline when pumping highly paraffinic oils near the pipeline wall, an annular wall layer is created from a low-viscosity liquid - water, aqueous solutions of polymers, low-viscosity oils or petroleum products with or without polymer additives [10]. This method, despite the obvious advantages, has a number of significant disadvantages, such as: a decrease in the pipeline utilization rate, increased corrosion of the pipeline wall in case of utilizing water or aqueous polymer solutions, low stability of a low-viscosity near-wall liquid layer, separation of water and oil at the end point of the pipeline, the need for a significant amount of water or low-viscosity oil (petroleum products), polymers.

The proposed method does not have these disadvantages. The pipeline is used only for pumping highly paraffinic oil. The formed system - liquid oil of the annular near-wall layer and solidified oil of the central part of the pipeline has high stability, since highly paraffinic oil with and without a depressant has the same density, and the same concentration of paraffin both in the liquid annular near-wall oil layer and in oil without additive prevents the dissolution of frozen oil in the central part of the pipeline in liquid oil of the annular wall layer.

In order to exclude the mixing of oil from the annular near-wall layer with the rest of the oil mass, local heating of the annular near-wall layer of oil in the pipe and the addition of a depressant to it is carried out at some distance from the pumping station so that oil can cool during pumping to a temperature close to the pour point at which a structural regime of oil flow is established in the pipeline.

In order to facilitate the dosage of the depressant and improve its mixing with the heated oil of the annular wall layer, not a pure depressant is added to the oil, but its solution with highly paraffinic oil in a 1:1 ratio.

For the normal formation of a liquid annular near-wall oil layer along the entire length of the pipeline, highly paraffinic oil plugs with the addition of a depressant throughout its volume are first pumped into the pipeline.

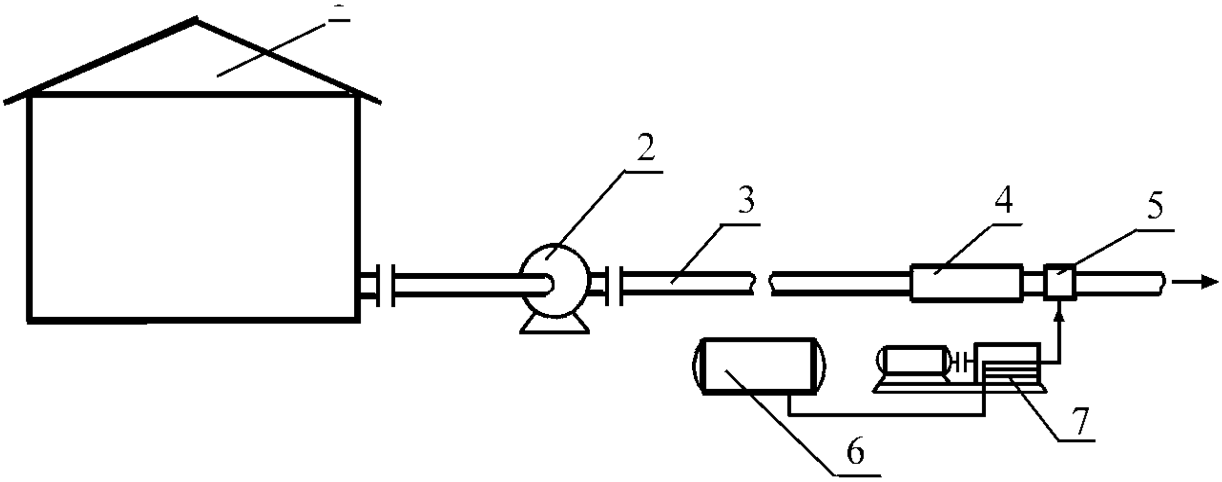

Fig. 2. Schematic diagram of the implementation of the method of pipeline transport of highly paraffinic oils with the introduction of a depressant into the annular near-wall layer of oil: 1 - reservoir; 2 - centrifugal pump; 3 - pipeline; 4 - heater; 5 - device for solution addition; 6 - container, 7 - metering pump.

Figure 2 shows a schematic diagram of the implementation of the proposed method at the head pumping station of the oil pipeline.

Highly paraffinic oil in reservoir 1 heated higher than pour point by several degrees, is pumped by pump 2 into pipeline 3. Here the oil temperature, as it moves through the pipeline, decreases due to natural cooling. At the point of pipeline 3, where the summer oil temperature is expected to be close to the pour point, an annular heater 4 is installed. It is used to heat the annular near-wall layer of oil to the melting point of the bulk of the paraffins contained in oil. Also a device 5 is installed for addition a depressant solution into the heated oil of the annular near-wall layer. A solution of a depressant with highly paraffinic oil is prepared in tank 6 and fed to device 5 by a metering pump 7. In winter, the temperature of oil when pumping it into pipeline 3 is somewhat increased so that oil flows to the point of heating the near-wall oil layer and adding the depressant at the same temperature as in summer.

Thermal and hydraulic calculations of the pipeline were carried out for the addition of a depressant to the entire volume of pumped oil. Since the depressant must be added to oil heated to 60-70 °C, the oil flow regime in the initial section of the pipeline will be non-isothermal. Considering this flow mode conditionally stationary [12-14], thermal and hydraulic calculations of the pipeline are made according to the formulas of the stationary regime. The law of the change in oil temperature along the length of the pipeline is taken according to the formula of V.G. Shukhov:

$$t = t_0 + (t_{ini} + t_0)e^{SH} \qquad (1)$$

where t_0 is the soil temperature in an undisturbed thermal state; t_{ini} is the initial soil temperature,

$$SH = \frac{K\pi DL}{QC_p\gamma}$$

K is the total heat transfer coefficient;

D is the pipeline diameter;

L is the pipeline length;

Q is the volumetric productivity of the pipeline;

Cp is the weight heat capacity of oil;

γ is the specific oil weight.

Since, in general case, there can be two flow regimes at the pipeline - turbulent and laminar, and taking into account the change in the coefficients u, a_1, b, η_o and the appearance of viscoplastic properties in oil, the head losses are calculated for individual sections of the pipeline.

The critical temperature t_{cr}, corresponding to the transition of the turbulent flow regime to the laminar one, is determined by the formula

$$t_{cr} = t_o + \frac{1}{u}\ln\frac{\eta_o\pi D \quad \mathrm{Re}_{cr}}{4Q(1+100C)\,[a_1+b(t \quad t_o)]} \qquad (2)$$

Approximate calculations showed that at C≠0 t_{ini} differs insignificantly from the values obtained by formula (8), i.e. regardless of the amount of additive in oil, τ_0 appears at approximately the same temperature.

In general, the pipeline can have three temperature regimes for the flow of a two-component system:

- The temperature of oil with an additive differs from the heating temperature of oil when the additive is introduced (1st section of the pipeline);
- The temperature of all oil changes from the final temperature of the 1st section of the pipeline to the soil temperature (2nd section of the pipeline);
- Oil takes the soil temperature of the ground - isothermal flow regime (3rd section of the pipeline).

In a particular case, when the pipeline has a small length, the isothermal flow regime may not occur.

The simplest case (isothermal flow of a two-component system) is considered.

The problem is solved based on the following assumptions:

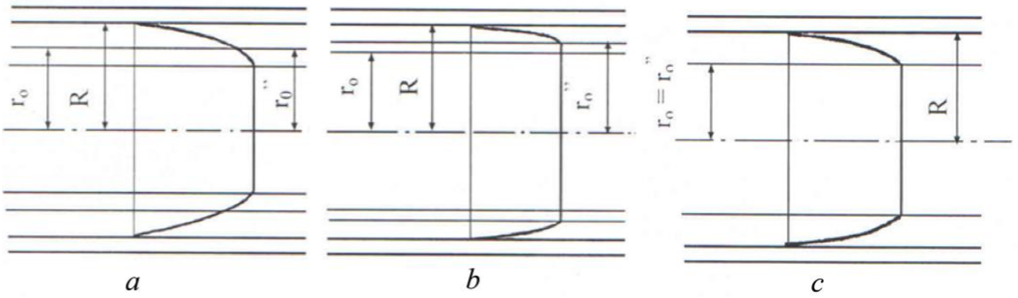

Fig. 3. Velocity profiles during the flow of a two-component system oil with an additive - oil without an additive.

- Oils with or without an additive move coaxially;
- Oils with or without an additive move in a laminar flow regime;
- Oils with or without an additive it in the considered temperature range (soil temperature) have viscoplastic properties.

All the above assumptions are feasible, since oils with or without an additive at the same temperature are of equal densities. Moreover, the considered highly paraffinic oils with or without an additive at the indicated temperatures have viscoplastic properties, and due to the rather high viscosity, the flow regime of such oils through pipelines is mainly laminar.

Various types of oil flow can occur depending on the rheological parameters of oil with or without additives, and on the flow rate of oil through the pipeline, Figure 3.

4 Discussion

Analysis of the obtained results shows that the rheological parameters of oil without additives do not affect the head loss.

The pumping method with the depressant introduction to the entire volume of pumped oil was compared with the pumping method with the depressant introduction only into the annular near-wall layer. It can be concluded that in the laminar flow regime and for $r_0 > r_{01}$, the 1st method provides a higher pipeline productivity than the 2nd, and for $r_0 < r_{01}$ the pipeline productivity is the same. To determine the optimal value of r_0, it is necessary to proceed from the minimum costs for the dispersed additive and for the pumping energy.

The turbulent flow regime for oil pumped by the 1st method begins much earlier than for oil pumped by the 2nd method, since $D > D - d_0$.

The throughput capacity of the pipeline when pumping oil according to the 1st method will be slightly less than when pumping oil according to the 2nd method. The productivity of the pipeline according to the 2nd pumping method is approximately 1.2 times higher than that using the 1st pumping method, and the additive consumption for the same concentration in oil is almost 10 times less.

A more complex problem is to calculate the initial section of the pipeline, where the temperature of oil with a depressant changes from the temperature of oil during the depressant addition to the temperature of the rest of oil mass.

For simplicity of solution, the hydraulic calculation of the initial section of the pipeline is carried out according to the formulas derived for the isothermal flow regime, considering the physical parameters of oil at the annular near-wall layer at an average temperature

$$t_{\text{av}} = \frac{1}{3} t_{\text{ini}} + \frac{2}{3} t_k \tag{3}$$

This assumption can be considered legitimate, since in this temperature range, the change in viscosity with the depressant and the pressure loss relative to the total losses are insignificant.

Thermal calculation of the initial section of the pipeline is made based on the following assumptions: the temperature of the oil without additives is constant; the oil flow regime of the annular near-wall layer is laminar; the heat transfer coefficients at this section are constant.

These assumptions are fair enough, since the flow rate of heated oil in the annular near-wall layer will be many times less than the flow rate of the rest of the oil mass, and the thickness of the annular near-wall layer of heated oil is small enough to form a turbulent flow regime. After the oil with the depressant is cooled to the temperature of pure oil, the thermal calculation of the next section of the pipeline can be carried out according to the formula of V.G. Shukhov.

$$t = t_o + (t_1 - t_o) e^{\frac{K_1 \pi D}{Q \gamma_{\text{av}}} x} \tag{4}$$

where Q is the total oil consumption.

The hydraulic calculation in this section of the pipeline is carried out according to the formulas usual for the flow of viscoplastic fluids.

5 Conclusion

ECA depressants can significantly reduce the rheological parameters of highly paraffinic oils. The ECA 4242 depressant recommended for Mangyshlak oils, at 20 °C and at a concentration of 0.2% wt. reduces the plastic viscosity by more than 2 times. The limiting dynamic shear stress is reduced by 3.5 times, the limiting static stress for oil with an additive is absent, and for the initial one τ_{st}=209 N/m^2. Based on the experimental data, empirical relationships between the oil rheological parameters and the temperature of the ECA 4242 depressant concentration were obtained. In order to save depressant and reduce energy consumption for heating oil, it is proposed to add a depressant not to the entire volume of oil pumped through the pipeline, but only to the annular near-wall layer of oil in the pipe.

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