Study of Heat-Hydraulic Efficiency of Asphalt-Resinous Paraffinic Oil Deposits in Field and Trunk Pipelines

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Abstract: The results of laboratory and numerical experimental studies of the thermal and hydraulic efficiency of a layer of wax deposits formed on the inner surface of the pipeline wall are presented. Measurements of the coefficient of thermal conductivity of wax samples of deposits taken from sections of existing main oil pipelines have been performed. To assess the effect of the sediment wax layer on the smoothness of the inner surface of the pipe wall, tests were carried out to determine the values of the roughness coefficient on samples of coils cut from sections of repaired main oil pipelines whose inner wall surface is covered with a layer of wax accumulated during their long operation and periodical pigging. The results of laboratory studies of the samples confirmed the relatively high thermal insulation properties and the smoothing capacity of the wax layer, and therefore, numerical experiments were also conducted to assess the effect of a formed wax layer on the heat and hydraulic regime mode of oil pipelines, including such parameters as the average kinematic viscosity of the flow, the final oil temperature, loss of pressure caused by the hydraulic resistance of the pipeline. Analysis of the results obtained in the course of mathematical modeling made it possible to evaluate the effective limits of the positive usage of a controlled oil wax layer as an internal thermal insulation coating for oil pipelines. Also, the paper discusses the effects of wax deposits on operational factors, such as the corrosion activity of the oil wax layer with respect to the inner surface of the pipeline wall metal.

1. Introduction
Asphalt-resinous paraffinic sediments of oil (wax) it is obvious result of heat-mass transfer processes occurring at the interface between the phases - the warm oil flow and the cold wall of the oil pipeline. Increasing amount of wax on the metal surface reduces the effective diameter of the oil pipeline, throughput capacity and leads to necessity of frequent periodic inline pigging.

The investigations of the pipeline paraffinization processes are many times discussed, both domestic and foreign scientists [1-30], the most significant of them are the works of Tronov, Mazepa, etc. [26-28, 16]. In this case, the most important is the temperature of mass crystallization of paraffins (WAT), while reaching which the volume wax structures influences on flow parameters - the static tension of the initial shear appears, leading to an increase in viscosity and a loss of fluidity of oil. Conditions in different types of pipeline systems also various - field networks, technological lines and
main trunk pipelines operate in absolutely different conditions, linked with both the composition of the oil, quality of treatment, and the thermal-hydraulic flow regime. So in the oil field nets with a high content of wax and high operating temperature - hot formation oil gets to the cooler surfaces of the equipment and wall of the collection pipeline networks, as a result - the intensity of wax deposition increases, while inside the oil flow - the sedimentation of wax practically does not occur because of hot average temperature of oil, higher than WAT point. The predominantly laminar regime of flow also does not contribute to mass-exchange processes between the hot center of flow and the cold internal wall surface. Exceptions are only gas condensate field with abnormally low reservoir temperatures. In oil trunk pipeline systems, as a rule, treated oil has low content of paraffins, while the pumping operating temperature is also not high, except cases of non-isothermal "hot" pipelines. Note, the flow regime for trunk pipelines is mainly turbulent. Thus, the main wax problem for trunk oil pipelines is inline inspection data lose by ultrasonic diagnostics, that requires high periodic pigging. Nevertheless, for both oilfield and main pipelines, the process of wax deposition is a rather serious problem, and many organizational and technical measures are directed at its solution, requiring considerable expenses, both temporary and material resources. The last one is not always justified, due to the fact that very often the adoption of certain measures is dictated by regulation documents on the basis of available experience and statistical data, due to the inability to really assess the actual state of the internal cavity and the amount of wax deposits inside the pipe.

In practice, an insignificant layer of deposits on the internal wall surface of the pipeline not only does not impair the hydraulic characteristics of the flow, but vice versa, as experience has shown in the launching of newly constructed sections, the hydraulic resistance can decrease due smoothing of the roughness of the non-ideal metallic internal surface of the pipe walls [1, 6, 7]. Recent papers [8, 23-25] also notes the possible thermal insulation properties of the artificial oil wax layer, the anticorrosion potential for use as a protective inner coating of oil pipelines. Consider these issues in details by analyzing experimental data of own laboratory and numerical studies.

2. Experimental determination of the thermal conductivity of wax
To determine the thermal conductivity coefficient of wax the «ITP-MG4» installation have been used. (Fig.1). The installation was supplemented with thin-walled hollow steel forms 13 and 27 mm thick for filling them with wax of different degree of compaction (Fig. 2).
For providing the homogenization of the wax samples before the testing the blender with frequency controlled electric drive have been used (Fig. 3). On the Fig. 4 shows the scheme of heat flow distribution in a flat multilayer wall formed by layer of wax and the metal surfaces of the molds used. Thus, the density of the heat flux through the multi-layered flat wall is equal to:

$$q = \frac{T_H - T_X}{\frac{\delta_1}{\lambda_1} + \frac{\delta_2}{\lambda_2} + \frac{\delta_3}{\lambda_3}}$$

where $\lambda_i$ – thermal conductivity of the i-th layer, W / m · K;
$\delta_i$ – thickness of the i-th layer of the sample, mm.

**Figure 3.** Filling forms by wax (preparation for testing).

**Figure 4.** Distribution of heat flux in a flat multilayer wall.

Calculation of the thermal conductivity coefficient of the wax sample $\lambda$ (so called effective thermal conductivity) and the calculated value of the thermal resistance $R_H$ (for a stationary thermal mode of measurement) is performed by the computing device of the device using the following formulas:

$$\dot{\lambda} = \frac{H \cdot q}{T_H - T_X},$$

$$R_H = \frac{T_H - T_C}{q} - 2 \cdot R_K,$$

where $\lambda$ – effective thermal conductivity, W / m · K;
$R_H$ – thermal resistance of the measured sample, m² · K / W;
$R_K$ – thermal resistance between the face of the sample and the working surface of the instrument plate, m² · K / W (taken into account in the calibration);
$H$ – thickness of the sample being measured, m;
$q$ – density of the stationary heat flux passing through the body of the sample being measured, W / m²;
$T_H$ – temperature of the hot face of the sample being measured, K;
$T_C$ – temperature of the cold face of the sample being measured, K.

Taking into account that the both walls of the mold are made of a steel sheet ($\lambda_1 = \lambda_3 = \lambda_{ST}$) of the same thickness ($\delta_1 = \delta_3 = \delta_{ST}$), using the measured values for the density of the stationary heat flux,
transforming equation (1) as follows, we obtain the thermal conductivity coefficient layer of wax $\lambda_{\text{wax}}$ ($\lambda_2$) with a layer thickness $\delta_{\text{wax}}$ ($\delta_2$):

$$\lambda_{\text{wax}} = \frac{\delta_{\text{wax}}}{\frac{T_H - T_C}{q} - \frac{2 \cdot \delta_{\text{ST}}}{\lambda_{\text{ST}}}}$$

(4)

The experimental data after statistical processing collected in Table 1. The calculated values of the coefficients of thermal conductivity also introduced there.

| №  | Wax sample     | Layer thickness, mm | Heat flow, W / m² | Thermal conductivity of wax layer, W / m · K |
|----|----------------|---------------------|-------------------|-------------------------------------------|
| 1  | 2              | 3                   | 4                 | 5                                         |
| 1  | Sample №1     | 13                  | 57,8              | 0,09                                      |
| 2  | Sample №2     | 13                  | 74,0              | 0,11                                      |
| 3  | Sample №3     | 13                  | 78,5              | 0,12                                      |
| 4  | Sample №4     | 13                  | 64,3              | 0,10                                      |
| 5  | Sample №5     | 13                  | 65,0              | 0,10                                      |
| 6  | Skilled test №1 (pressed) | 13 | 110,4          | 0,17                                      |
| 7  | Skilled test №2 (pressed) | 13 | 111,9          | 0,17                                      |
| 8  | Skilled test №3 (pressed) | 13 | 109,8          | 0,16                                      |
| 9  | Skilled test №4 (pressed) | 13 | 113,9          | 0,17                                      |
| 10 | Skilled test №5 (pressed) | 13 | 115,5          | 0,17                                      |
| 11 | Sample №1     | 27                  | 131,4             | 0,19                                      |
| 12 | Sample №2     | 27                  | 126,7             | 0,18                                      |
| 13 | Sample №3     | 27                  | 130,3             | 0,19                                      |
| 14 | Sample №4     | 27                  | 129,2             | 0,19                                      |
| 15 | Sample №5     | 27                  | 127,6             | 0,18                                      |
| 16 | Average value of the thermal conductivity coefficient of the oil wax | | | 0,15 |

The results of the experimental studies performed (Table 1) showed that the values of the wax thermal conductivity coefficients got on oil sediments of trunk pipelines have values close to the thermal conductivity of the oil itself (0,1-0,2 W / m·K), that proved about the relatively high thermal insulation properties of the oil wax layer and the possibility of its use as a thermal insulation. A positive effect can be achieved both by maintaining the high average temperature of the flow (by keeping low average viscosity of flow) along the length of pipeline, as well as reducing values of the temperature gradient at the wall surface and slowdown of heat-mass-exchange processes in cases of non-isothermal pumping.

3. Determination of corrosion activity and protective properties of the oil wax layer

Anticorrosive properties were determined by the gravimetric method in accordance with GOST 9.905-2007 using metal coupons made of cold rolled steel tape in accordance with GOST 503-81, which were kept in tap water and salted sea water. The measurements were made twice - before and after deposition of the AFS layer on the surface (Fig. 5-6).

Prepared control samples before testing were weighed on an electronic balance after drying and reaching a constant weight in the desiccator (Fig. 7).
Figure 5. Initial samples without wax layer.  

Figure 6. Samples covered by protective wax layer.

All the samples were re-maintained in desiccators before the control weighing until they reached a constant weight. After cleaning and drying, a visual inspection of the samples was performed (Fig. 8).

Figure 7. Drying samples (coupons) in a desiccator to a constant weight before and after testing.

Figure 8. Results of visual inspection (1,2 – coupons without protective layer, 3-8 – covered by protective wax layer).

The results of gravimetric control of samples, determination of the corrosion rate and evaluation of the protective anti-corrosion potential of wax layer are given in Tab. 2.

| №  | Type of wax sample | Test environment (water) | Change in the mass of the control sample, g | Corrosion rate, mm/year | Protective potential, % |
|----|--------------------|--------------------------|---------------------------------------------|-------------------------|-------------------------|
|    |                    |                          | m1 | m2 | Δm | 7 | 8 |
| 1  | no ASPO            | stale                    | 1,4539 | 1,4487 | 0,0052 | 0,0393 | - |
| 2  | no ASPO            | salty                    | 1,3770 | 1,3744 | 0,0026 | 0,0197 | - |
| 3  | ASPO 1             | stale                    | 1,4500 | 1,4495 | 0,0005 | 0,0038 | 90,4 |
| 4  | ASPO 2             | stale                    | 1,3994 | 1,3989 | 0,0005 | 0,0038 | 90,4 |
| 5  | ASPO 3             | stale                    | 1,4265 | 1,4258 | 0,0007 | 0,0053 | 86,5 |
| 6  | ASPO 1             | salty                    | 1,3765 | 1,3759 | 0,0006 | 0,0045 | 76,9 |
| 7  | ASPO 2             | salty                    | 1,4441 | 1,4430 | 0,0011 | 0,0083 | 57,7 |
| 8  | ASPO 3             | salty                    | 1,4056 | 1,4055 | 0,0001 | 0,0008 | 96,2 |
| 9  | Average protective potential (anti corrosive efficiency) | | | | | 83,0 |
4. Evaluation of roughness of the inner pipe wall surface of covered by oil wax layer

For the testing, segments of coils cut from long-running main oil pipelines have been used. (Fig. 9). For the experiment, segments of pipe coils cut from long-operated main oil pipelines have been used. The measurements were carried out using a portable automatic device «TR200» (Fig. 10). The results of the measurements are in Tab. 3.

![Figure 9. segments of coils cut from long-running main oil pipelines with oil wax layer.](image)

![Figure 10. Measurement of the roughness of the wax layer and initial wall by the «TR200» tool.](image)

| №  | Sample (coil pipe segment) | Average surface roughness, mkm | Effect of smoothing (hydraulic effect of oil wax layer), % |
|----|---------------------------|--------------------------------|--------------------------------------------------------|
| 1  | Sample № 1 (initial)      | 1,236                          | 57,2                                                   |
| 2  | Sample №1 (after mech. treatment) | 2,246                          | 22,3                                                   |
| 3  | Sample №1 (after chem. treatment) | 3,322                          | -15,0                                                  |
| 4  | Sample № 2 (initial)      | 1,903                          | 24,5                                                   |
| 5  | Sample №2 (after mech. treatment) | 1,978                          | 21,5                                                   |
| 6  | Sample №2 (after chem. treatment) | 1,919                          | 23,8                                                   |
| 7  | Average effect of smoothing (hydraulic effect of wax layer) |                                  | 40,9                                                   |

5. Conclusion

Analysis of the results of numerical simulation based on obtained experimental data and made thermal-hydraulic regime calculations of flow for non-isothermal oil pipelines presented that the greatest effect is observed in the laminar flow zone, where an increase in the final flow temperature leads to reduction of hydraulic friction losses by keeping low value of average oil viscosity. Also, a positive effect due to the smoothing of the inner surface covered by wax layer is observed on large diameter pipelines operating in developed turbulent flow regimes. An also important is the established protective anti corrosive effect of the oil wax layer. The influence of the heat-insulating wax layer on the variation in the intensity of the paraffinization of the pipeline was not considered in this paper, but is of great interest for subsequent investigations.
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