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GRAPH-ANALYTICAL METHOD FOR DETERMINATION OF CAVITATION AREAS IN OIL PIPELINES IN STEADY REGIME

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A B S T R A C T

The article provides an overview of free-flow fields and lists the conditions and consequences of their formation, currently known as a hydraulic phenomenon. It is noted that the study and determination of free flow areas is of particular importance for the safe and efficient operation of the oil pipeline system. Although the consumption of oil in the free-flow areas of the pipeline is the same in the steady-state operation, the flow rates are different. Because the velocity in the pressure zone is lower than the velocity in the free flow zone, according to the law of continuity, the movement of the liquid in the latter zones does not occur along the entire cross-section of the pipe. For this, the authors have developed a grapho-analytical method for determining free flow areas in oil pipelines in a fixed mode. The possibility of determining the location and volume of free flow zones in oil pipelines in the determined movement modes by the proposed grapho-analytical method was shown, and the results of the test of the method in a real oil pipeline were satisfactory.

1. INTRODUCTION

The creation of voids (free flow areas) in oil and oil product pipelines is often observed even in the fixed operating modes of the pipeline. The study and determination of free flow areas is of particular importance for the safe and efficient operation of the oil pipeline system. Since these depressurized zones are mainly associated with the transition point (or points), their presence is not necessarily the case depending on the mode of operation of the belt. Because, when the hydraulic slope line does not cut the profile of the belt, since there is no crossing point, those zones are not created. In other words, the formation of free flow areas is not excluded, since the fixed operating mode of the pipeline can be at different pressures. The emergence of an extreme point or free flow zones is possible during a change in the operating mode of the pipeline, stopping the work of any pumping station, and changing the rheological and physico-chemical properties of the transported oil. In order to determine the presence of a tipping point, as already mentioned, the hydraulic gradient should be calculated and plotted (Figure 1). From the end point of the belt (K) until it intersects the profile, the line of hydraulic slope (i) is drawn. The point of contact (D) with the profile of the line (3) which is parallel to that line and does not intersect the profile anywhere will be the crossing point.

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If there is an additional pressure (Ps) at the end of the belt, then the hydraulic slope line $H_s = Z_s + \frac{P_s}{\rho g}$ at the end is drawn from the point K′ corresponding to the pressure height until it crosses the profile of the belt (2). In this case, the line that does not cross the profile (3) will determine that point D is the transition point. In order not to have an extreme point (no free-flow areas), the hydraulic slope line should not cut or touch the profile at any point (4 dashed lines). In all cases where a tipping point exists, areas of free (unstressed) flow will develop after that point (or points). The beginning of the free flow areas will be the corresponding crossing points, and the end will be the corresponding intersection point of the hydraulic slope line drawn from the end of the belt with the profile. For example, in figure 1, the hydraulic slope lines 1 and 2 will be indicated by points a and b, respectively, the endpoints of the resulting free flow fields (Goroshko 2003).

2. LITERARATURE REVIEW

In order not to create voids, the piezometric pressure (height – H) at any point of the oil pipeline should not be less than the geodetic height (Z) taking into account the vacuumometric height (hv):

$$H \succ Z + h_v \,, h_v = \frac{P_{b.e}}{\rho g} \quad (1)$$

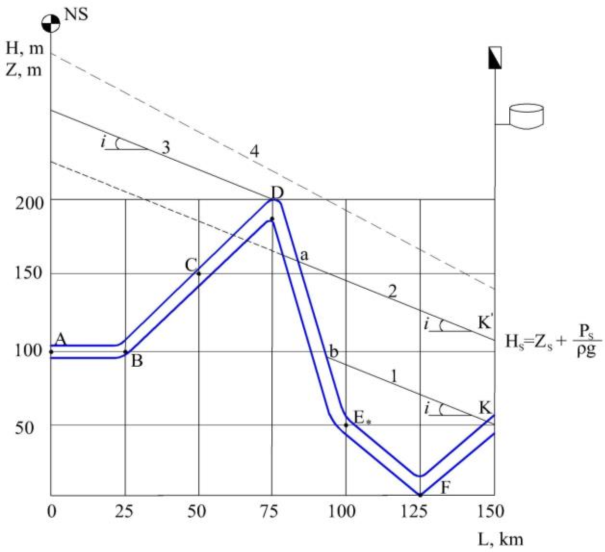

Figure 1. Free flow zone in the condensed profile of the conditional pipeline determination

Here, Pb.e. is the oil vapor elasticity pressure, Pa.

Note that at this time the velocity pressure is not taken into account because it is very small $\left(\frac{v^2}{2g} = 0\right)$. To determine the coordinate of the free flow area, a perpendicular straight line is drawn from the point of intersection of the profile with the hydraulic slope line to the abscissa (L) axis. At this time, the point x obtained from the intersection (Figure 2.) will determine the coordinate of the end point of the free flow field.

To determine the length of the free flow zone, the following transport parameters are first set:

Flow rate:

$$v = \frac{4Q}{\pi d^2} \quad (2)$$

Reynolds number

$$Re = \frac{vd}{\nu} \quad (3)$$

Coefficient of hydraulic resistance

$\lambda = \frac{64}{Re}$ – for laminar mode (Re<2300)

$\lambda = \frac{0{,}3164}{\sqrt[4]{Re}}$ – for smooth bumpy zone (Re>2300)

$\lambda = 0{,}11\left(\frac{k}{d} + \frac{68}{Re}\right)^{0{,}25}$ – for the mixed friction (4)

zone (10′ $Re \cdot \frac{k}{d}$ <500)

$\lambda = 0{,}11\left(\frac{k}{d}\right)^{0{,}25}$ - for quadratic motion mode

zone ($Re \cdot \frac{k}{d}$ >500)

Here, k is called the equivalent roughness for the tube. For large-diameter pipelines, k=0.1 mm can be accepted.

Hydraulic slope

$$i = \lambda \frac{v^2}{2gd} \quad (5)$$

According to Figure 2 (in part DE), since the angle α is known, the hydraulic slope in the free flow area will be as follows (the line of hydraulic slope is parallel to the profile in that area and passes at a distance hv from it):

$$i^* = tg\alpha = \frac{Z_{fl} - Z_{E_*}}{L_{E_*} - L_{fl}} \quad (6)$$

Here, Z_{fl}, L_{fl} and L_{E_*} - respectively, the transition point and the free flow area are the geodetic height, taking into account the vacuum height for the end of the existing pipeline section (segment), and the distances from the beginning of the pipeline, m.

Then, according to figure 2, the following equation can be written:

$$Z_{E_*} + i^* \cdot \left(L_{E_*} - x\right) = H_{E_*} + i\left(L_{E_*} - x\right) \quad (7)$$

From expression (7), we get the following expressions for determining the coordinate (x) and length (ls.a.) of the end point of the free flow zone:

$$\begin{cases} x = L_{E_*} - \frac{H_{E_*} - Z_{E_*}}{i^* - i} \\ l_{s.a} = x - L_{fl} \end{cases} \quad (8)$$

Here, i* and i – hydraulic slope in the free-flow and full-flow parts of the pipeline, respectively; $H_{(E*)}$ - is the pressure at the end of the pipeline section (segment) with free flow area and is calculated as follows:

$$H_{E_*} = H_s - i \cdot (L_{b.k} - L_{E_*}) \quad (9)$$

Here, Hs represents the pressure at the end of the pipeline. This pressure is usually known.

If the initial compression or pressure is not given, then it can be calculated. For this, the pressure at the beginning is determined as follows, using the hydraulic gradient of the pressurized zone and the data of the transition point, i.e. Z_{fl}, Lash, as well as vacuumometric height (h_v):

$$H_b = Z_{aş} + h_v + i \cdot L_{aş} \quad (10)$$

Here $i \cdot L_{fl}$–is the pressure loss in the pipeline up to the extreme point, m. Then the pressure P_b corresponding to the initial pressure will be:

$$P_b = \rho \cdot g \cdot H_b, \text{ Pa} \quad (11)$$

Here, ρ is the density of transported oil, kg/m^3; g=9.81 m/s^2.

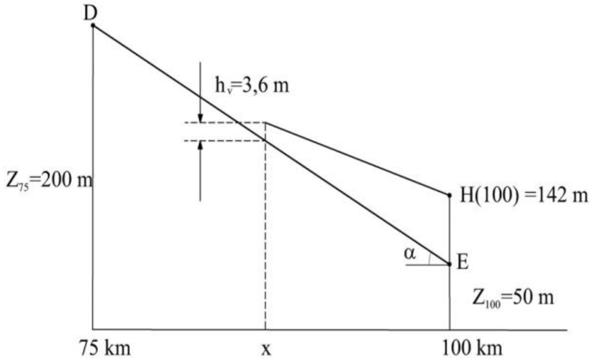

Figure 2. Finding the free flow zone

Although the consumption of oil in the free-flow areas of the pipeline is the same in the steady-state operation, the flow rates are different. Since the velocity in the pressure zone is less than the velocity in the free flow zone, according to the law of discontinuity (constancy of flow), the fluid movement in the latter zones will not occur along the entire cross-section of the pipe. In this case, the cross-sectional area of the pipe filled with liquid in each free-flow area will be less than the full cross-section of the pipe (Sorokin et al. 2007). The filling factor (K_f) of the free flow areas is determined based on the consumption module corresponding to the diameter of the pipeline (Mineev et al. 2004). Table 1 shows the change of consumption modulus for a given diameter according to different filling ratios. Based on the calculated values of the hydraulic slope for the known and free flow area of the flow, the flow modulus (M) is determined as follows:

$$M = Q/\sqrt{i^*}, \text{ m}^3/\text{s} \quad (12)$$

Here, Q – consumption of oil, m^3/s; i* is the hydraulic slope in the free flow field, m/m.

Based on Table 1, the value of the filling factor (K_f) is determined according to the value of the consumption module determined by the formula (12) (Persiyantsev 2000). If the obtained value of M does not coincide with the values in the table, the fill factor is found by interpolation as follows:

$$K_d(M) = K_d(M_1) \cdot \frac{(M_1 - M)}{(M_1 - M_0)} + K_d(M_0) \cdot \frac{(M - M_0)}{(M_1 - M_0)} \quad (13)$$

Here, M_0, M_1 – table values close to the lower and upper M obtained in the given diameter; $K_f(M_0)$, $K_f(M_1)$ are the values of fill factors corresponding to M0 and M_1, respectively (Tronov 1970; Kayumov et al. 2006).
Thus, the volume of voids in the free flow field can be determined as follows:

$$V_{emp} = (1 - K_d)\frac{\pi d^2}{4} \cdot l_{s.a} \quad (14)$$

This volume is subtracted from the geometric volume of the pipeline during the inventory operation (Sorokin et al. 2009).

Table 1. Variation of fill factor and flow modulus values for free flow areas as a function of pipeline diameter

Fill factor, K_f	The diameter of the pipeline d,mm				
	200	600	800	1000	1200
0,05	0,018	0,344	0,7417	1,3449	2,1869
0,10	0,036	0,688	1,4835	2,6897	4,3738
0,15	0,055	1,033	2,2252	4,0346	6,5607
0,20	0,073	1,377	2,9669	5,3794	8,7476
0,25	0,092	1,722	3,7087	6,7243	10,934
0,30	0,110	2,066	4,4504	8,0692	13,121
0,35	0,128	2,410	5,1922	9,4140	15,308
0,40	0,147	2,755	5,9339	10,758	17,495
0,45	0,165	3,099	6,6756	12,103	19,682
0,50	0,184	3,444	7,4174	13,448	21,868
0,55	0,202	3,788	8,1591	14,793	24,055
0,60	0,220	4,133	8,9008	16,138	26,242
0,65	0,239	4,477	9,6425	17,483	28,429
0,70	0,257	4,821	10,384	18,828	30,616
0,75	0,276	5,166	11,126	20,172	32,803
0,80	0,294	5,510	12,609	21,517	34,990
0,85	0,312	5,855	13,351	22,868	37,177
0,90	0,331	6,199	14,093	24,207	39,364
0,95	0,349	6,543	14,835	25,553	41,550
1,00	0,350	6,888	15,576	26,897	43,738

Now let's look at the issue of determining the free flow area in the conventional pipeline profile (Figure 1) (Nebogina et al. 2008). Let's assume that oil with a density of ρ=850 kg/m^3 and a kinematic viscosity of ν=15 sSt is transported through an oil pipeline with a length of L=150 km and a diameter of D=530×7 mm. If the pressure at the end of the belt is Ps=0.3 MPa, what must be the pressure at the beginning in MPa so that the oil consumption is Q=500 m^3/h. In the calculations, the pressure of oil vapor elasticity (Goroshko, 2003) can be assumed to be $P_{b.e}$=0.03 MPa, k=0.1 mm.

3. RESEARCH METHODOLOGY

As can be seen from the profile, point D is the crossing point of the belt, and from this point on, a free flow zone will exist. Based on formulas (2 and 3), let's first find the transport parameters:

$$v = \frac{4Q}{\pi d^2} = \frac{4 \cdot 500}{3{,}14 \cdot (0{,}516)^2 \cdot 3600} = 0{,}67\ m/s$$

$$Re = \frac{vd}{\nu} = \frac{0{,}67 \cdot 0{,}516}{15 \cdot 10^{-6}} = 23048$$

$$\lambda = \frac{0{,}3164}{\sqrt[4]{23048}} = 0{,}0257$$

$$i = \lambda \frac{1}{d}\frac{v^2}{2g} = 0{,}0257 \cdot \frac{1}{0{,}516} \cdot \frac{(0{,}67)^2}{2 \cdot 9{,}81} = 0{,}001139 \frac{m}{m} = 1{,}139\ m/km$$

For the considered case, the vacuometric height will be as follows:

$$h_v = \frac{P_{b.e}}{\rho g} = \frac{0{,}03 \cdot 10^6}{850 \cdot 9{,}81} = 3{,}6\ m$$

Let's set the pressure at the end of the pipeline (at point K) H(150):

$$H_K(150) = Z_{150} + \frac{P_s}{\rho g} = 50 + \frac{0{,}3 \cdot 10^6}{850 \cdot 9{,}81} \approx 86\ m$$

Then the pressure values for other points of the pipeline (F, E, D) will be as follows:

$$H_F(125) = H_K(150) + i \cdot 25 = 86 + 1{,}139 \cdot 25 = 114{,}0\ m > 0 + 3{,}6 = 3{,}6\ m$$

$$H_E(100) = H_F(125) + i \cdot 25 = 114 + 1{,}139 \cdot 25 = 142\ m > 50 + 3{,}6 = 53{,}6\ m$$

$$H_D(75) = H_E(100) + i \cdot 25 = 142 + 1{,}139 \cdot 25 = 170\ m < 200 + 3{,}6 = 203{,}6\ m$$

As can be seen from the expression of the last raid, HD(75)<203.6 m. It is known that the pressure cannot be less than the geodetic height. Therefore, between the 75th and 100th km (between points D and E) there will be a free flow zone. At this time, x=75th km will be the beginning of the free flow zone (Figure 2).

The hydraulic gradient in the free flow field will be:

$$i^* = tg\alpha = \frac{Z_0 - Z_E}{(100-75) \cdot 10^3} = \frac{200 - 50}{25000} = 6 \cdot 10^{-3}$$

(8) let's determine the coordinate of the end point of the free flow field based on the expression (Sharifullin 2006).

$$x = L_E - \frac{H_E - Z_E}{i^* - i} = 10^5 - \frac{142 - 50}{(6 - 1{,}139) \cdot 10^{-3}} = 81074\ m = 81{,}074\ km$$

Then the length of the free flow field will be:

$$l_{s.a} = x - L_{aş} = 81{,}074 - 75{,}0 = 6{,}074\ km = 6074\ m$$

Then let's check the full pressures for the remaining cuts (points C, B, A).

$$H_C(50) = H_D(75) + i \cdot 25 = 203{,}6 + 1{,}139 \cdot 25 = 232{,}1\ m > 150 + 3.6 = 153{,}6\ m$$

$$H_B(25) = H_C(50) + i \cdot 25 = 232{,}1 + 1{,}139 \cdot 25 = 260{,}6\ m > 100 + 3{,}6 = 103{,}6\ m$$

$$H_A(0) = H_B(25) + i \cdot 25 = 260{,}6 + 1{,}139 \cdot 25 = 289{,}1\ m > 100 + 3{,}6 = 103{,}6\ m$$

Thus, as can be seen from the calculations, there are no other free flow zones. Then the pressure at the beginning of the pipeline will be as follows (Baimukhametov 2005).

$$P_b = \rho \cdot g[H(0) - Z_0] = 850 \cdot 9{,}81[289{,}1 - 100] = 1{,}58 \cdot 10^6 Pa = 1{,}58\ MPa$$

Now let's determine what part of the cross-section of the pipeline is filled in the free flow zone (Goroshko 2003). First, let's calculate the consumption module according to the formula (12):

$$M = \frac{Q}{\sqrt{i^*}} = \frac{500}{\sqrt{6 \cdot 10^{-3}} \cdot 3600} = 1{,}793\ \frac{m^3}{s}$$

Determining that M_0=1.6944, M_1=1.9062, $K_f(M_1)$=0.45 and $K_f(M_0)$=0.40 according to the value of M and diameter (D=500 mm) from Table 1 (13) we determine the fill factor based on the expression (Zevakin et al. 2008).

$$K_d(M) = 0{,}45 \cdot \frac{(1{,}9062 - 1{,}793)}{(1{,}9062 - 1{,}6944)} + 0{,}40 \cdot \frac{(1{,}793 - 1{,}6944)}{(1{,}9062 - 1{,}6944)} = 0{,}43\ (43\%)$$

Since the degree of filling of the cross-sectional area with liquid in the free flow zone is 43%, the volume of the resulting cavity will be as follows according to expression (14):

$$V_{boş} = (1 - 0{,}43)\frac{3{,}14 \cdot 0{,}516^2}{4} \cdot 6074 = 723{,}6\ m^3$$

The issue of determining free flow zones was also considered in the example of a real oil pipeline. For this purpose, the compressed profile of the oil pipeline and transport indicators were used. Determination of the existence, coordinates and volume of free flow zones was carried out in two variants - for the minimum and maximum values of transport parameters (Sharifullin et al. 2006).

Option-1 (minimum values of transport parameters) Initial data:

- -Pressure at the beginning of the belt Pb=6 kgs/cm^2;
- -Pressure at the end of the belt Ps=0.6 kgs/cm^2;
- -Oil consumption Q=300 m^3/hour=0.0833 m^3/s;
- -Inner diameter of belt d_{in}=0.704 m;
- -Belt length $L_{b.k.}$=35984 m;
- -Oil density ρ_o=855.0 kg/m^3;
- -Vapor elasticity of oil $P_{v.e.=}$23996 Pa;
- -Effective roughness coefficient k=0.1 mm;
- -Kinematic viscosity of oil ν=11.8·10-6 m^2/s;
- -Condensed profile of the belt (figire 3);
- -Z_b=12.8 m; Z_s=12.7 m

Calculated transport parameters: x

v =0.214 m/s; Re=12171; λ=0.0299; i=0.0001 m/m=0.1 m/km; hυ=2.86 m

Based on the known pressures, let's calculate the pressures at the end and beginning of the belt:

$$H_s = Z_s + \frac{P_s}{\rho g} = 12{,}7 + \frac{60000}{855{,}0 \cdot 9{,}81} = 19{,}85\ m$$
$$H_b = Z_b + \frac{P_b}{\rho g} = 12{,}8 + \frac{600000}{855{,}0 \cdot 9{,}81} = 84{,}33\ m$$

If there were no free flow zones, then the hydraulic gradient would be:

$$i = \frac{H_b - H_s}{L_{b.k}} = \frac{84{,}33 - 19{,}85}{35984} = 1{,}792\ \frac{m}{km}$$

However, in this case, there is a transition point (point E) in the belt, and the pressure at that point is $H_E = Z_E + h_v = 84{,}6 + 2{,}86 = 87{,}46\ m$ according to the formula (1), so the pressure at the beginning of the belt is H_b'H_E. This means that the pressure in the closure is not enough for the pipeline to work (Sergienko 1959).
Based on the data, the pressure or pressure required at the start should be as follows:

$$H_B = H_E + i \cdot L_E = 87{,}46 + 0{,}1 \cdot 22{,}53 = 89{,}72\ m$$
$$P_b = \rho g[H_b - Z_b] = 855 \cdot 9{,}81[89{,}72 - 12{,}8] \approx 6{,}4\ \frac{kqs}{sm^2}$$

Then the hydraulic slope should be as follows:

$$i = \frac{H_b - H_E}{L_E} = \frac{89{,}72 - 87{,}46}{22{,}53} = 0{,}1\ \frac{m}{km}$$

For this case, let's check the presence of free flow zones in the pipeline (Ibragimov et al. 1986).
As can be seen from the profile of the belt, free flow areas may exist in the following segments: [E; E_1]; [D; D_1]; [C; C_1]; [B; B_1] and [A; A_1] (figure 3).

The geodetic heights and distances from the origin for the points indicated on the profile will be as follows (m, km):

Z_E=84,6	Z_D=66,0	Z_C=58,1	Z_B=53,9
L_E=22,53	L_D=24,4	L_C=25,2	L_B=27,4
Z_{E_1}=43,7	Z_{D_1}=55,5	Z_{C_1}=52,3	Z_{B_1}=46,5
L_{E_1}=23,6	L_{D_1}=24,7	L_{C_1}=25,7	L_{B_1}=27,8

Based on the pressure at the end of the belt, let's calculate the pressures for characteristic points (sections) A, B, C, D and E and reconcile them with geodetic heights:

$$H_A = H_S + (L_{b.k} - L_A) \cdot i = 19{,}85 + (35{,}984 - 28{,}5) \cdot 0{,}1 = 20{,}6\ m < Z_A + h_v = 50{,}4 + 2{,}86 = 53{,}26\ m$$
$$H_B = H_A + (L_A - L_B) \cdot i = 20{,}6 + (28{,}5 - 27{,}4) \cdot 0{,}1 = 20{,}71\ m < Z_B + h_v = 53{,}9 + 2{,}86 = 56{,}76\ m$$

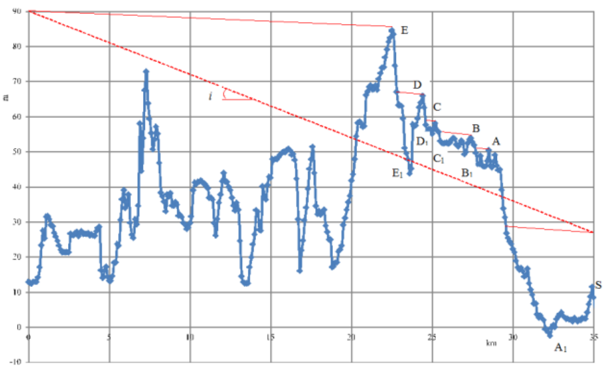

Figure 3. Condensed profile of an oil pipeline (cavitation areas)

$$H_C = H_B + (L_B - L_C) \cdot i = 20{,}71 + (27{,}4 - 25{,}2) \cdot 0{,}1 = 20{,}93\ m < Z_C + h_v = 58{,}1 + 2{,}86 = 60{,}96\ m$$
$$H_D = H_C + (L_C - L_D) \cdot i = 20{,}93 + (25{,}2 - 24{,}4) \cdot 0{,}1 = 21{,}01\ m < Z_D + h_v = 66 + 2{,}86 = 68{,}86\ m$$
$$H_E = H_D + (L_D - L_E) \cdot i = 21{,}01 + (24{,}4 - 22{,}53) \cdot 0{,}1 = 21{,}19\ m < Z_E + h_v = 84{,}6 + 2{,}86 = 87{,}46\ m$$

4. RESEARCH RESULTS AND DISCUSSION

As can be seen from the calculations, since the pressure is less than the geodetic height at all the considered points (sections), free flow zones will exist (Petrova et al. 2005). The free flow area starting from the point (cross-section) E [A; A1] will also continue in the segment. Now let's define the end of the free flow area (Ibragimov 2003; Kusi-Sarpong et al. 2018). As can be seen from the profile, the free flow zone begins at point E and ends at [A; A1] will be available in the segment. According to expression (6), the hydraulic slope in the free flow field will be as follows:

$$i^* = \frac{Z_{aş} - Z_{E_*}}{L_{E_*} - L_{aş}} = \frac{Z_E - Z_{A_1}}{L_{A_1} - L_E} = \frac{84,6 + 2,5}{32,3 - 22,53} = 8,915\ \frac{m}{km}$$

Given the pressure vacuometric height at point A1

$$H_{A_1} = h_v + H_S + \left(L_{b.k} - L_{A_1}\right) \cdot i = 2,86 + 19,85 + (35,984 - 32,3) \cdot 0,1 = 23,08\ m$$

Then, according to expression (8), the coordinate and length of the free flow zone will be as follows:

$$x = L_{E_*} - \frac{H_{E_*} - Z_{E_*}}{i^* - i} = L_{A_1} - \frac{H_{A_1} - Z_{A_1}}{i^* - i} = 32,3 - \frac{23,08 + 2,5}{8,979 - 0,1} = 29,398\ km$$

$$l_{s.a} = x - l_{aş} = x - L_E = 29,398 - 22,53 = 6,868\ km = 6868\ m$$

Let's calculate the consumption module according to the expression (12) based on the known (Sharifullin 2006) values of the consumption, the calculated values of the hydraulic inclination (i*):

$$M = \frac{Q}{\sqrt{i^*}} = \frac{0,0833}{\sqrt{8,915 \cdot 10^{-3}}} = 0,8824\ \frac{m^3}{s}$$

From Table 1, we find the following according to the diameter d=700 mm and the value M=0.8824: M_0=0.5195; M_1=1.0390; $K_f(M_0)$=0.05; $K_f(M_1)$=0.1.
Then, according to expression (13), the consumption coefficient will be as follows:

$$K_f(M) = 0,1 \cdot \frac{1,0390 - 0,8824}{1,0390 - 0,5195} + 0,05 \cdot \frac{0,8824 - 0,5195}{1,0390 - 0,5195} = 0,065 = 6,5\ \%$$

As can be seen, the degree of liquid filling of the pipe in the free flow area is very low, 6.5% (Sharifullin et al. 2006). Then, the volume of the created space will be as follows according to expression (14):

$$V_{emp} = (1 - 0,065) \cdot \frac{3,14 \cdot (0,704)^2}{4} \cdot 6868 = 2498\ m^3$$

Option-2 (maximum values of transport parameters) Initial data:

- The pressure at the beginning of the belt is P_b=6.5 kgs/cm^2;
- Pressure at the end of the belt P_s=1.2 kgs/cm^2;
- Oil consumption Q=630 m^3/hour=0.175 m^3/s;
- Inner diameter of belt d_{in}=0.704 m;
- Belt length $L_{b.k.}$=35,984 km;
- Oil density ρ_o=855.0 kg/m^3;
- Vapor elasticity of oil $P_{v.e.}$=23996 Pa;
- Effective roughness coefficient k=0.1 mm;
- Kinematic viscosity of oil $\nu=11.8\cdot10^{-6}$ m^2/s;
- Condensed profile of the belt (figure 3);
- Z_b=12.8 m; Z_s=12.7 m

Calculated transport parameters:

v =0.45 m/s; Re=26847; λ=0.0247; i=0.00036 m/m=0.36 m/km; hυ=2.86 m

Based on the known pressures, let's calculate (Ismayilov et al. 2015) the pressures at the end and beginning of the belt:

$$H_s = Z_s + \frac{P_s}{\rho g} = 12,7 + \frac{120000}{855,0 \cdot 9,81} = 27,0\ m$$
$$H_b = Z_b + \frac{P_b}{\rho g} = 12,8 + \frac{650000}{855,0 \cdot 9,81} = 90,19\ m$$

If there were no free flow zones, then the hydraulic gradient would be:

$$i = \frac{H_b - H_s}{L_{b.k}} = \frac{90,19 - 27,0}{35,984} = 1,756\ \frac{m}{km}$$

However, since the line of hydraulic slope intersects the profile in this case, there is a transition point (point E) in the belt, and the pressure at that point is $H_E = Z_E + h_v = 84,6 + 2,86 = 87,46\ m$ according to the formula (1), so the hydraulic slope is as follows will be like:

$$i = \frac{H_b - H_E}{L_E} = \frac{90,19 - 87,46}{22,53} = 0,12\ \frac{m}{km}$$

Based on the pressure at the end of the belt, let's calculate the pressures for characteristic points (sections) A, B, C, D and E and compare them with geodetic heights:

$$H_A = H_S + (L_{b.k} - L_A) \cdot i = 27,0 + (35,984 - 28,5) \cdot 0,12 = 27,9\ m < Z_A + h_v = 50,4 + 2,86 = 53,26\ m$$
$$H_B = H_A + (L_A - L_B) \cdot i = 27,9 + (28,5 - 27,4) \cdot 0,12 = 28,0\ m < Z_B + h_v =$$

$$= 53{,}9 + 2{,}86 = 56{,}76\ m$$

$$H_C = H_B + (L_B - L_C) \cdot i = 28{,}0 + (27{,}4 - 25{,}2) \cdot 0{,}12 = 28{,}3\ m < Z_C + h_v = 58{,}1 + 2{,}86 = 60{,}96\ m$$

$$H_D = H_C + (L_C - L_D) \cdot i = 28{,}3 + (25{,}2 - 24{,}4) \cdot 0{,}12 = 28{,}4\ m < Z_D + h_v = 66 + 2{,}86 = 68{,}86\ m$$

$$H_E = H_D + (L_D - L_E) \cdot i = 28{,}4 + (24{,}4 - 22{,}53) \cdot 0{,}12 = 28{,}6\ m < Z_E + h_v = 84{,}6 + 2{,}86 = 87{,}46\ m$$

As can be seen from the calculations, since the pressure is less than the geodetic height at all the considered points (sections), free flow zones will exist (Usubaliev et al. 2015; Zevakin et al. 2008). Free flow zone starting at point E (cross-section) [A; A1] will also continue in the segment (Figure 3). According to expression (6), the hydraulic slope in the free flow field will be as follows:

$$i^* = \frac{Z_{aş} - Z_{E_*}}{L_{E_*} - L_{aş}} = \frac{Z_E - Z_{A_1}}{L_{A_1} - L_E} = \frac{84{,}6 + 2{,}5}{32{,}3 - 22{,}53} = 8{,}915\ \frac{m}{km}$$

Given the pressure vacuometric height at point A1

$$H_{A_1} = h_v + H_S + \left(L_{b.k} - L_{A_1}\right) \cdot i = 2{,}86 + 27{,}01 + (35{,}984 - 32{,}3) \cdot 0{,}12 = 30{,}3\ m$$

Then, according to expression (8), the coordinate and length of the free flow zone will be as follows:

$$x = L_{E_*} - \frac{H_{E_*} - Z_{E_*}}{i^* - i} = L_{A_1} - \frac{H_{A_1} - Z_{A_1}}{i^* - i} = 32{,}3 - \frac{30{,}3 + 2{,}5}{8{,}915 - 0{,}12} = 28{,}571\ km$$

$$l_{s.a} = x - l_{aş} = x - L_E = 28{,}571 - 22{,}53 = 6{,}041\ km = 6041\ m$$

Let's calculate the consumption module based on the expression (12) based on the known values (Nurullayev et al. 2021) of the consumption and the calculated values of the hydraulic gradient:

$$M = \frac{Q}{\sqrt{i^*}} = \frac{0{,}175}{\sqrt{8{,}915 \cdot 10^{-3}}} = 1{,}853\ \frac{m^3}{s}$$

From Table 1, we find the following according to the diameter d=700 mm and M=1.853: M0=1.5586; M_1=2.0781; $K_f(M_0)$=0.15; $K_f(M_1)$=0.2.

Then, according to expression (13), the consumption coefficient will be as follows:

$$K_f(M) = 0{,}2 \cdot \frac{2{,}0781 - 1{,}853}{2{,}0781 - 1{,}5586} + 0{,}05 \cdot \frac{1{,}853 - 1{,}5586}{2{,}0781 - 1{,}5586} = 0{,}1150 = 11{,}5\ \%$$

Then, the volume of the created (Usubaliev et al. 2015; Nurullayev 2014) space will be as follows according to expression (14):

$$V_{emp} = (1 - 0{,}115) \cdot \frac{3{,}14 \cdot (0{,}704)^2}{4} \cdot 6041 = 2080\ m^3$$

Analysis of the physical and chemical properties of low-paraffin Azerbaijani oils (mixture of May 28 and Oilstones) at the transition boundaries of cavitation was carried out in laboratory conditions, the results of which are given in table 2.

Table 2. Analysis of physical and chemical properties of low-paraffin Azerbaijani oils at the transition boundaries of cavitation

Taken for oil names of analyses.	Results prior to cavitation probable zone	Results prior to cavitation probable zone	Test conducted methods
Density at 20°C, kg/m3.	863.4	862.2	GOST 3900
Saturated vapor pressure, kPa.	31.6	34.7	GOST 1756
Pour point °C.	-24	-27	GOST20287
Paraffins in % mass.	4.21	3.53	GOST11851
Kinemat. viscosity at 20 °C, mm^2/sec.	15.8	13.6	GOST 33
Fraction comp: B.P. °C. Volume in % at 350°C.	68 59.5	59 63.0	GOST 2177
Iod num.	0.9	1.7	GOST 2070

As can be seen from table 2, some parameters of the oil passed through the cavitation zone have changed compared to the initial oil parameters as follows: paraffin hydrocarbons-0.68%, freezing temperature–3 ^{0}C, kinematic viscosity-2.2 mm^2/sec, density - 1.2 kg/m^3 decreased, saturated vapor pressure - 3.1 kPa, volume of fractions expelled in atmospheric conditions - 3.5%, iodine number-0.8 grams increased. Apparently, some rheological properties of oil improve after passing through the cavitation zone. The increase in the amount of light hydrocarbons (fractions up to 180 ^{0}C -gasoline fraction) once again suggests that a phase change occurs in the oil. The reason for the change of phases is the formation of cavitation zones during oil transportation. After this process, fractional analysis of oil in the temperature range of 59-350 ^{0}C showed that the total amount of light, gasoline and diesel fractions of oil increased by 3.5% due to phase transitions.

4. CONCLUSION

As can be seen from the calculations, the volume of the voids created at the maximum values of the transport parameters will be 2498-2080-418m3 less. This shows that by adjusting the transport parameters, it is possible to reduce the volume of gaps, or even bring them to a minimum.

Thus, the possibility of determining the location and volume of free flow zones in oil pipelines in the determined motion modes using the proposed grapho-analytical method was shown, and the results of the test of the method in a real oil pipeline were satisfactory.

Thus, during the transportation of oil, the formation of zones called out-of-state cavitation zones in some areas of the pipelines leads to positive changes in the rheological properties of oil. The creation of such zones has both positive and negative aspects. Although the formation of such zones is under technical control, it is impossible to regulate it, the consequences caused by it are very severe and their elimination is very expensive. The losses caused by it are measured in millions and result in unfortunate events.

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References:

Baimukhametov, M. K. (2005). *Improved technologies to combat the asphalt, resin, and paraffin deposits in oilfield systems in the fields of Bashkortostan* (Ph.D. thesis). Ufa, Russia.

Goroshko, S. A. (2003). *Effect of inhibitors of wax on the efficiency of gas transport at "Pribrezhnoe" field* (Ph.D. thesis). Krasnodar, Russia.

Ibragimov, G. Z., Sorokin, V. A., & Khisamutdinov, N. I. (1986). *Chemical reagents in petroleum production: Handbook.* Moscow: Nedra.

Ibragimov, N. G. (2003). *Petroleum production problems.* Ufa, Russia.

Ismayilov, G. G., Nurullayev, V. H., & Zeynalov, E. A. (2015). Graph-analytic method for determining the free flow areas of oil pipeline at an established regime. *Herald of the Azerbaijan Engineering Academy, 7*, 91–104.

Kayumov, M. Sh., Tronov, V. P., Gus'kov, I. A., & Lipaev, A. A. (2006). Account of the features of formation asphaltene deposits in the late stage of development of oil fields. *Neftyanoe khozyaistvo, 3*, 48–49.

Kusi-Sarpong, S., Varela, M. L., Putnik, G., Avila, P., & Agyemang, J. (2018). Supplier evaluation and selection: A fuzzy novel multi-criteria group decision-making approach. *International Journal for Quality Research, 12*(2), 459–486. https://doi.org/10.18421/IJQR12.02-10

Mineev, B. P., & Boligatova, O. V. (2004). Two types of paraffin dropping on the downhole equipment in oil production. *Neftepromyslovoe delo, 12*, 41–43.

Nebogina, N. A., Prozorova, I. V., & Yudina, N. V. (2008). Features of the formation and precipitation of water-oil emulsions. *Neftepererabotka i neftekhimiya, 1*, 21–23.

Nurullayev, V. H. (2014). Theoretical analysis of crude oil vapor pressure and cavitational technologies studying of physical and chemical properties of transported oil in the course of cavitation. *Science and Applied Engineering Quarterly, 5*, 23–29.

Nurullayev, V. H., & Usubaliyev, B. T. (2021). New methods of struggle with asphalt-resin-paraffin deposits in processes of oil transportation. *Proceedings on Engineering, 1*, 193–200.

Nurullayev, V. H., Gahramanov, F. S., & Usubaliyev, B. T. (2016). Education mechanisms cavitational zones by means of asphalten-pitch-wax deposits on the surface of pipelines. *International Journal of Engineering Sciences and Research Technology, 1*, 441–447.

Persiyantsev, M. N. (2000). *Oil production under complicated conditions.* Moscow: Nedra-Biznestsentr.

Petrova, L. M., Fors, T. R., Yusupova, T. N., Mukhametshin, R. Z., & Romanov, G. V. (2005). Effect of deposition of solid paraffins in a reservoir on the phase state of crude oils in the development of oil fields. *Petroleum Chemistry, 3*, 189–195.

Sergienko, S. R., Taimova, B. A., & Tatalaev, E. I. (1959). *High-molecular non-hydrocarbon compounds of oil.* Moscow: Nauka.

Sharifullin, A. V., Baibekova, L. R., & Suleimanov, A. T. (2006). Features of the structure and composition of oil deposits. *Tekhnologii nefti i gaza, 6*, 19–24.

Sharifullin, A. V., Baibekova, L. R., Khamidullin, R. F., & Sharifullin, V. N. (2006). Composition and structure of asphalt-resin-paraffin deposits of Tatarstan. *Tekhnologii nefti i gaza, 4*, 34–41.

Sorokin, A. V., & Tabakaeva, A. V. (2009). Influence of the gas content in petroleum on ARDO formation in the well lift. *Burenie i neft', 2*, 25–26.

Sorokin, S. A., & Khavkin, S. A. (2007). Features of the physical and chemical mechanism of production of asphalt-resinous-paraffin formations in wells. *Burenie i neft', 10*, 30–31.

Tronov, V. P. (1970). *Mechanism of formation of resin-wax deposits and their prevention.* Moscow: Nedra.

Usubaliev, B. T., Ramazanova, E. E., & Nurullayev, V. H. (2015). The use of nanostructured coordination compounds to reduce viscosities of heavy commercial oils during transportation. *Scientific and Technical Journal: Problems of Collecting, Preparing and Transporting Oil and Oil Products, 3*, 117–126.

Zevakin, N. I., & Mukhametshin, R. Z. (2008). Paraffin deposits in formation conditions of horizon D1 Romashkinskoye field. *Proceedings of TatNIiPINeft, VNIIOEG, 176*, 134–145.

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