10 APRIL 1979 (FOUO 8/79) 1 OF 2

FOR OFFICIAL USE ONLY

JPRS L/8391

10 April 1979

USSR

TRANSLATIONS ON USSR RESOURCES
(FOUO 8/79)
PIPELINE TRANSPORT OF PETROLEUM

U. S. JOINT PUBLICATIONS RESEARCH SERVICE

FOR OFFICIAL USE ONLY

NOTE

JPRS publications contain information primarily from foreign newspapers, periodicals and books, but also from news agency transmissions and broadcasts. Materials from foreign-language sources are translated; those from English-language sources are transcribed or reprinted, with the original phrasing and other characteristics retained.

Headlines, editorial reports, and material enclosed in brackets [] are supplied by JPRS. Processing indicators such as [Text] or [Excerpt] in the first line of each item, or following the last line of a brief, indicate how the original information was processed. Where no processing indicator is given, the information was summarized or extracted.

Unfamiliar names rendered phonetically or transliterated are enclosed in parentheses. Words or names preceded by a question mark and enclosed in parentheses were not clear in the original but have been supplied as appropriate in context. Other unattributed parenthetical notes within the body of an item originate with the source. Times within items are as given by source.

The contents of this publication in no way represent the policies, views or attitudes of the U.S. Government.

COPYRIGHT LAWS AND REGULATIONS GOVERNING OWNERSHIP OF MATERIALS REPRODUCED HEREIN REQUIRE THAT DISSEMINATION OF THIS PUBLICATION BE RESTRICTED FOR OFFICIAL USE ONLY.

JPRS L/8391

10 April 1979

TRANSLATIONS ON USSR RESOURCES

(FOUO 8/79)

PIPELINE TRANSPORT OF PETROLEUM

Moscow TRUBO-PROVODNYY TRANSPORT NEFTI I GAZA ("Pipeline Transport of Petroleum and Gas") in Russian 1978 signed to press 19 May 78 pp 146-192, 322-374

[Chapters 5 and 8 of book edited by V.A. Yufin, Izdatel'stvo "Nedra," 7,700 copies, 408 pages]

CONTENTS PAGE

TECHNICAL DESIGN OF MAIN PETROLEUM PIPELINES

Moscow TRUBO-PROVODNYY TRANSPORT NEFTI I GAZA in Russian 1978 pp 146-192

[Chapter 5 by V. D. Belousov, E. M. Bleykher, A. G. Nemudrov, V. A. Yufin and Ye. I. Yakovlev from the book TRUBO-PROVODNYY TRANSPORT NEFTI I GAZA edited by V. A. Yufin, Izdatel'stvo "Nedra," 7,700 copies, 408 pages]

[Text] The technological designing of a petroleum pipeline involves solution of the following fundamental problems:
determination of the economically most advantageous parameters (pipeline diameter, pressure at the petroleum pumping stations, pipeline wall thickness and the number of petroleum pumping stations);
determination of the positioning of stations along the pipeline route;
computation of the pipeline operating regimes.

Using several diameter values it is possible to carry out hydraulic and mechanical computations determining (for each variant) the number of petroleum pumping stations and the pipeline wall thickness. The best variant is found from the reduced expenditures, that is, economic computations.

The positioning of the petroleum pumping stations is determined graphically on a compressed profile of the route.

The computation of the operating regimes involves a determination of the pressures at the stations, the backups before them and the throughput capacity of the pipelines under pumping conditions differing from the computed conditions. In addition, the problem of regulating pipeline operation is solved.

#5.1. Initial Data for Technological Design of Pipeline

The following data are necessary when designing a pipeline: throughput capacity; dependence of petroleum viscosity and density on temperature; ground temperature at the depth at which the pipeline is laid; mechanical properties of pipe material; technical-economic indices and a sketch of the compressed route profile.

The throughput capacity of a pipeline is given in millions of tons per year in the design specifications; for computations it is converted into m^3/hour and m^3/sec (in the computed density values). It is assumed that a pipeline operates 350 days (or 8,400 hours) annually.

Throughput capacity is the principal factor determining the pipeline diameter and the pressure at stations.

The technological design norms give the pipeline diameter values and pressures at petroleum pumping stations as a function of throughput capacity (Table 5.1).

Table 5.1

Pipeline Diameters and Output Pressures at Stations as a Function of the Throughput Capacity

Нефтепродуктопроводы 1			Нефтепроводы 2		
Диаметр, мм 3	Давление, кгс/см^2 4	Пропускная способность, млн. т/год 5	Диаметр, мм 3	Давление, кгс/см^2 4	Пропускная способность, млн. т/год 5
219	90—100	0,7—0,9	529	54—65	6—8
273	75—85	1,3—1,6	630	52—62	10—12
325	67—75	1,8—2,3	720	50—60	14—18
377	55—65	2,5—3,2	820	48—58	22—26
426	55—65	3,5—4,8	920	46—56	32—36
529	55—65	6,5—8,5	1020	46—56	42—50
			1220	44—54	70—78

KEY:

1. Petroleum product pipelines
2. Petroleum pipelines
3. Diameter, mm
4. Pressure, kg/cm^2
5. Throughput capacity, millions of tons annually

Table 5.2

Capital Expenditures on Linear Part of Main Pipelines

Диаметр трубопровода, мм 1	Капитальные затраты, тыс. руб/км 2		Диаметр трубопровода, мм 1	Капитальные затраты, тыс. руб/км 2	
	на основную магистраль 3	на параллельную магистраль 4		на основную магистраль 3	на параллельную магистраль 4
219	22,8	18,0	630	71,0	56,0
273	24,9	20,1	720	77,5	62,1
325	28,8	22,8	820	91,1	74,9
377	33,6	27,5	1020	136,1	119,6
426	37,6	31,5	1220	180,8	165,6
530	56,6	45,1			

KEY:

1. Pipeline diameter, mm
2. Capital expenditures, thousands of rubles/km
3. on main pipeline
4. on parallel pipeline

Table 5.3

Capital Expenditures on One Pumping Station (in Thousands of Rubles)

Пропускная способность, млн. т/год 1	Новая площадка 2		Совмещенная площадка 3	
	головная 4	промежуточная 5	головная 4	промежуточная 5
6 Нефтепродуктопроводы				
0,7—0,9	1 339	830	985	500
1,3—1,6	1 504	854	1 060	515
1,8—2,3	1 643	920	1 160	555
2,5—3,2	1 837	1127	1 320	680
3,5—4,8	2 556	1274	1 800	765
6,5—8,5	3 890	1669	2 720	1005
7 Нефтепроводы				
6—3	5 418	1926	3 820	1160
10—12	6 730	2012	4 700	1210
14—18	8 077	2170	5 605	1315
22—26	9 202	2554	6 355	1535
42—50	15 896	3023	10 925	1815
70—78	16 193	3550	11 845	2135

KEY:

1. Throughput capacity, millions of tons annually
2. New site
3. Matched site
4. Main (head)
5. Intermediate
6. Petroleum product pipelines
7. Petroleum pipelines

Table 5.4

Costs of Pumping Under Technological Design Norms

Диаметр трубопровода, мм 1	Себестоимость перекачки, коп/(т·км) 2	Диаметр трубопровода, мм 1	Себестоимость перекачки, коп/(т·км) 2
219	0,3	630	0,094
273	0,24	720	0,082
325	0,21	820	0,069
377	0,17	1020	0,065
426	0,15	1220	0,062
530	0,13		

KEY:

1. Pipeline diameter, mm
2. Cost of pumping, kopecks/(ton·km)

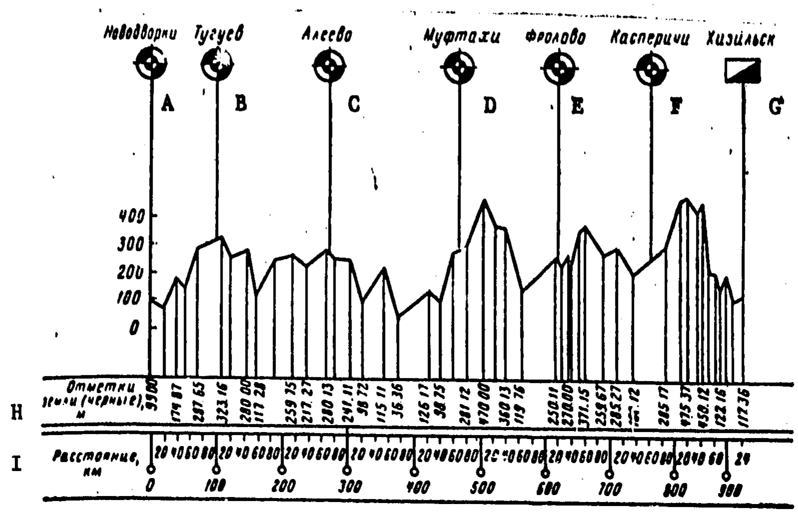


Fig. 5.1. Route profile. Note: The names of the stations are given arbitrarily.

KEY:

- A. Novodvorki
- B. Tuguyev
- C. Aleyevo
- D. Muftakhi
- E. Frolovo
- F. Kasperichi
- G. Khizil'sk
- H. Ground elevations (black), m
- I. Distance, km

The petroleum density and viscosity are determined by laboratory analyses.

The density ρ is usually determined at 20°C. At other temperatures

$$\rho_t = \rho_{20} - \xi (t - 20),$$

where ρ_t and ρ_{20} are densities at the temperatures t and 20°C, kg/m^3; ξ is the temperature correction, kg/(m3·°C),

$$\xi = 1,825 - 0,001315\rho_{20}.$$

The results of laboratory viscosity determinations are given in the form of a viscosity-temperature curve.

In the absence of this curve the kinematic viscosity ν at the necessary temperature can be found using the empirical formula (in centistoke)

$$\lg\lg(\nu+0.8)=a-b\lg T,$$

where a and b are constants which can be determined using this same formula if one knows the viscosity values for two different temperatures; T is the absolute temparature, °K.

The ground temperature at the depth at which the pipeline is laid is determined using field data. It must be known for determining the computed values of density and viscosity of the pumped petroleum.

The mechanical properties of the pipe material are given in the corresponding handbooks. Depending on the grade of steel, the tensile strength and yield stress fall in the range from 50 and 35 kg/mm^2 (for 14KhGS) to 60 and 40 kg/mm^2 (for 16G2SAF).

The technical-economic indices are necessary for determining the reduced expenditures.

The capital expenditures can be computed by using consolidated indices taken from the technological design norms (Tables 5.2 and 5.3).

The capital expenditures on the linear part consist both of the cost of the pipes and of the cost of all the work on pipeline construction (welding, insulation, digging of trenches, etc.). The capital expenditures at the station include the cost of the equipment, pipeline communication system, buildings, and for the head stations, also the cost of the tank farm. About 80% of the total capital expenditures are spent on the linear part. Approximately 45-50% of the capital expenditures on the linear part constitute the cost of the pipes.

The operating expenditures consist of the following principal items:

deductions for amortization (8.5% of the capital expenditures on the station and 3.5% of the capital expenditures on the linear part) and on current repair (1.3 and 0.3% respectively);

expenditures on electric power -- 0.7-1.5 kopeck/(KWH);

expenditures on lubrication, water, heating, electric power and "housekeeping" needs;

wages;

maintenence, preservation, control;

other expenditures.

The first three items in the expenditures are fundamental. Thirty-forty percent of all the expenditures are for amortization and current repair. The expenditures on electric power constitute 40-60%.

The total operating expenditures, determining the cost of pumping operations, is the most important index which characterizes the economy of pipeline operation.

In finding the economically most advantageous variant the operating expenditures Op can be determined using the formula

$$Op = SGL,$$

where S is the cost of pumping, rubles/(ton·km) -- see Table 5.4; G is the throughput capacity of the pipeline, tons/year; L is the extent of the pipeline, km.

The route profile (Fig. 5.1) is used for determining the computed values of the length of the pipeline and the difference in geodetic elevations and also for finding the places for siting pumping stations.

The profile is a diagram on which the characteristic points on the route are plotted and connected with one another. The distances from the initial point and the geodetic elevations of these points are their coordinates. The distance between any two points thus is determined not by the length of the line connecting them but by its projection onto the x-axis. In other words, the distances on the profile are plotted along the horizontal. This is very important to bear in mind.

The route profile is plotted in compressed form: the scale along the vertical is greater than along the horizontal. Therefore, all the rises and depressions along the route stand out sharply and the diagram is graphic.

***

§5.2. Principal Formulas for Hydraulic Computations of Pipeline

Steady motion of a liquid in a pipeline is described by the equation

$$\frac{dp}{\rho}+\lambda\frac{dx}{D}\frac{w^2}{2}+d\frac{w^2}{2}+g\,dz=0, \tag{5.1}$$

where p is pressure; ρ is liquid density; λ is the hydraulic resistance coefficient; x is length; D is pipeline diameter; w is the mean velocity of motion of the liquid; g is the acceleration of gravity; z is the leveling elevation.

The dp/ρ value represents the work of movement of the liquid in the segment dx, related to a unit mass [the measurement unit (H/m^2)(m^3/kg) = Hm/kg].

This work is expended on the overcoming of frictional forces [$\lambda(dx/D)(w^2/2)$], on a change in the kinetic energy of the liquid [$d(w^2/2)$] and on raising the liquid to the height dz.

Taking into account that ρ = const (droplet liquid) and that in this case with a constant diameter of the pipeline $d(w^2/2) = 0$, after integration we obtain:

$$\frac{p_1-p_2}{\rho}=\lambda\frac{L}{D}\cdot\frac{w^2}{2}+g\,\Delta z, \tag{5.2}$$

where L is the distance between points 1 and 2, that is, the length of the pipeline; $\Delta z = z_2 - z_1$ is the difference in the geodetic elevations of the end and beginning of the pipeline.

We divide expression (5.2) by g:

$$\frac{p_1-p_2}{\rho g}=\lambda\frac{L}{D}\cdot\frac{w^2}{2g}+\Delta z. \tag{5.3}$$

In equation (5.3) each term represents the work, no longer related to a unit mass, but to a unit weight of the liquid, that is, height. The $p_1/\rho g$ value (or for brevity p_1/γ, where $\gamma = \rho g$ is the specific gravity of the liquid) is the height H_1 to which the liquid rises in the piezometer under the influence of the excess pressure p_1 at the initial point in the pipeline. The value $p_2/\rho g$ is the height H_2 to which the liquid rises in the piezometer under the influence of the excess pressure p_2 at the final point. The value $p/\rho g$ (or p/γ) is called the head, or, to be more precise, the piezometric head. Its dimensionality is (H/m^2)(m^3/H) = m.

Equation (5.3) can be written differently:

$$H=h_{\tau}+\Delta z, \tag{5.4}$$

where $H = H_1 - H_2$ is the difference in heads at the initial and final points on the pipeline;

$$h_\tau = \lambda \frac{L}{D} \frac{w^2}{g} \qquad (5.5)$$

The H value is also called the general or total head loss. In a general case it also includes the head losses on local resistances and in velocity change.

Coefficient of Hydraulic Resistance

Formula (5.5) is called the Darcy-Weisbach formula. The hydraulic resistance coefficient entering into it is a function of the Reynolds number Re and the relative roughness ε :

$$\mathrm{Re} = \frac{wD}{\nu} = \frac{4Q}{\pi D \nu}; \qquad \varepsilon = \frac{2e}{D},$$

where ν is the kinematic viscosity of the pumped petroleum; Q is the volume flow; e is the absolute equivalent roughness of the pipeline walls.

In the case of laminar flow, and also in the case of turbulent flow in a zone of relatively small Re there is a smooth flow of liquid around the roughness projections; roughness exerts no influence on the head loss and the hydraulic resistance coefficient is dependent only on Re. With an increase in Re the coefficient λ decreases.

The region of turbulent flow, in which $\lambda = \lambda(\mathrm{Re})$, is called the smooth friction region.

As a result of an increase in Re eddies begin to be detached from the roughness projections. Eddy formation occurs the sooner the greater the roughness. Now the resistance to liquid flow is dependent not only on Re, but also on roughness.

The region in which $\lambda = \lambda(\mathrm{Re}, \varepsilon)$ is called the mixed friction region.

Here with an increase in Re its influence on λ is gradually decreased and the influence of ε increases (there is an increase in the intensity of eddy formation on roughness projections).

In the case of large Re the λ coefficient ceases to be dependent on it.

The region in which $\lambda = \lambda(\varepsilon)$ is called the region of completely rough friction or the region of a quadratic friction law, since here λ is a constant value and the head loss is directly proportional to the square of velocity.

In the case of laminar flow ($\mathrm{Re} < 2000$) the hydraulic resistance coefficient is found using the Stokes formula:

$$\lambda = \frac{64}{\mathrm{Re}}$$

The laminar regime occurs during the pumping of very viscous petroleums. For computing λ in a turbulent regime ($\mathrm{Re} > 3000$) in the smooth friction region we use the empirical Blasius formula

$$\lambda = \frac{0,3164}{\sqrt[4]{\mathrm{Re}}}.$$

Usually this formula is used in designing pipelines for petroleums of medium viscosity.

For the quadratic region the hydraulic resistance coefficient is determined using the Nikuradze formula

$$\frac{1}{\sqrt{\lambda}} = 2\lg\frac{1}{\varepsilon} + 1,74.$$

A. D. Al'tshul' recommends use of the Shifrinson formula

$$\lambda = 0,11\left(\frac{k}{D}\right)^{0,25},$$

where k is the equivalent roughness, characterizing the total influence of the state of the internal surface of the pipeline wall on hydraulic resistance.

In the Nikuradze formula and in all the formulas cited below the ε value also must be determined using the equivalent roughness $\varepsilon = 2k/D$. Sometimes it is only assumed approximately that in the case of a quadratic friction law light petroleum products can be pumped. The quadratic friction law can be used in computations for main gas lines.

Universal formulas are used for determining the hydraulic resistance coefficient in the mixed friction zone. Their structure is such that in the case of small Re they are transformed into the formulas $\lambda = \lambda(\mathrm{Re})$, and in the case of large Re are transformed into the formulas $\lambda = \lambda(\varepsilon)$. For the first time a formula of such a type was proposed by Colebrook and White:

$$\frac{1}{\sqrt{\lambda}} = -2\lg\left(\frac{\varepsilon}{7,4} + \frac{2,51}{\mathrm{Re}\sqrt{\lambda}}\right)$$

If the second term in the parentheses is neglected, we obtain the Nikuradze formula for the quadratic friction law. However, if the first term is neglected, we derive the Prandtl formula for the smooth friction region:

$$\frac{1}{\sqrt{\lambda}} = 2\lg\mathrm{Re}\sqrt{\lambda} + 0,8.$$

The results of computations of λ using the Colebrook and White formula coincide well with experimental data obtained for industrial pipelines. But this formula has a significant shortcoming: in computing λ it is necessary to have recourse to the successive approximations method.

This shortcoming is absent in similar formulas (giving virtually the same results) proposed by:

N. Z. Frenkel'

$$\frac{1}{\sqrt{\lambda}} = -2\lg\left[\frac{\varepsilon}{7,4} + \left(\frac{6,81}{\mathrm{Re}}\right)^{0,9}\right];$$

I. A. Isayev

$$\frac{1}{\sqrt{\lambda}} = -1,8\lg\left[\left(\frac{k}{3,7D}\right)^{1,11} + \frac{6,8}{\mathrm{Re}}\right]$$

The A. D. Al'tshul' formula is characterized by particular simplicity

$$\lambda = 0{,}11\left(\frac{k}{D} + \frac{68}{Re}\right)^{0{,}25}.$$

With Re k/D < 10 it virtually coincides with the Blasius formula, and with Re k/D > 500 -- with the Shifrinson formula.

The Re k/D = 10 value can be considered the limit between the regions of smooth and mixed frictions and Re k/D = 500 is the limit between regions of mixed and completely rough friction.

Some k values are given in Table 5.5.

Table 5.5

A. D. Al'tshul' Equivalent Roughness Values

1 Материал и вид труб	2 Состояние труб	k, мм
3 Бесшовные стальные	5 Новые и чистые	$\frac{0{,}01-0{,}02}{0{,}014}$
	6 После нескольких лет эксплуатации	$\frac{0{,}15-0{,}3}{0{,}2}$
4 Сварные стальные	7 Новые и чистые	$\frac{0{,}03-0{,}10}{0{,}05}$
	8 С незначительной коррозией после очистки	$\frac{0{,}10-0{,}20}{0{,}15}$
	9 Умеренно заржавленные	$\frac{0{,}30-0{,}70}{0{,}50}$
	10 Старые заржавленные	$\frac{0{,}80-1{,}5}{1{,}0}$
	11 Сильно заржавленные или с большими отложениями	$\frac{2{,}0-4{,}0}{3{,}0}$

KEY:

1. Material and type of pipes
2. Condition of pipes
3. Seamless steel
4. Welded steel
5. New and clean
6. After several years of use
7. New and clean
8. With insignificant corrosion after cleaning
9. Moderately rusted
10. Old rusted
11. Severely rusted or with great deposits

Generalized L. S. Leybenzon Formula

The Stokes, Blasius and Nikuradze formulas (and also the Shifrinson formula) have the following general form:

$$\lambda = \frac{A}{\mathrm{Re}^m}, \qquad (5.6)$$

where A and m are constant values (m is the index of the liquid motion regime). Substituting (5.6) into the Darcy-Weisbach equation (5.5) and taking into account that Re = $4Q/\pi D\nu$, we obtain the generalized Leybenzon formula:

$$h_\tau = \beta \frac{Q^{2-m}\nu^m}{D^{5-m}} L,$$

where

$$\beta = \frac{8A}{4^m \pi^{2-m} g}$$

The Leybenzon formula is used extensively in those cases when the dependence of h_τ on Q must be expressed in explicit form.

The values of the parameters m, A and β are given in Table 5.6.

On the graph lg λ = f(lg Re) the dependence (5.6) for the flow regimes indicated in Table 5.4 is represented in the form of straight lines, the tangent of whose slope to the lg Re axis is equal to m. In the region of mixed friction, where λ is dependent not only on Re, but also on the relative roughness k/D, the line lg λ = f(lg Re) is a smooth curve. The index m of the flow regime in this region is a variable value.

Table 5.6

Values of Coefficients Entering into Leybenzon Formula

Наименование 1	m	A	β, с²/м 2
3 Ламинарный режим	1	64	$\frac{128}{\pi g} = 4{,}15$
4 Турбулентный режим в зоне Блазиуса	0.25	0.3164	$\frac{0.242}{g} = 0{,}0247$
5 Область квадратичного закона трения	0	λ	$\frac{8\lambda}{\pi^2 g} = 0{,}0826\lambda$

KEY:

1. Name
2. sec^2/m
3. Laminar regime
4. Turbulent regime in Blasius zone
5. Region of quadratic friction law

The latter circumstance virtually excludes the possibility of use of the Leybenzon formula in the mixed friction region. This is a major inadequacy because the region of mixed friction occupies a broad range of Reynolds numbers in which the pumping of low-viscosity petroleums and light petroleum products is usually accomplished.

However, at the price of some loss in the accuracy of computations this shortcoming can be eliminated.

On the graph (Fig. 5.2) $\lg \lambda = f(\lg Re)$ we note by the figure 1 the point on the "Blasius straight line" where $Re_1 = 10\ (k/D)^{-1}$, and by the figure 2 the point on the "Shifrinson straight line," where $Re_2 = 500\ (k/D)^{-1}$ (limits of the region of mixed friction). Substituting Re_1 into the Blasius formula, and Re_2 into the Shifrinson formula, we find $\lg \lambda_1$ and $\lg \lambda_2$ -- the ordinates of the points 1 and 2.
Now we will pass a straight line through the points 1 and 2. Its equation is reduced to the form

$$\lg \lambda = 0{,}127 \lg \frac{k}{D} - 0{,}027 - 0{,}123 \lg Re.$$

Assuming

$$10^{0{,}127 \lg \frac{k}{D} - 0{,}027} = A,$$

we obtain

$$\lambda = \frac{A}{Re^{0{,}123}}. \tag{5.7}$$

It is obvious that for the region $Re_1 < Re < R_2$ the replacement of the curve $\lg \lambda = f(\lg Re)$ by the straight line 1-2 is equivalent to a replacement of the Alt'shul' formula by formula (5.7). This makes it possible to apply the Leybenzon formula also to the region of mixed friction.

For this region in accordance with (5.7) $m = 0.123$ and the β coefficient must be computed for each specific case, since A for the mixed friction region is dependent on k/D.

#5.3. Hydraulic Slope. Losses of Head in Pipelines with Loopings and Inserts

From the initial and final points of the profile of a line drafted with identical horizontal and vertical scales we plot the heads $H_1 = p_1/\gamma$ and $H_2 = p_2/\gamma$ (Fig. 5.3). The ends of the determined segments H_1 and H_2 are connected by a straight line.

The tangent of the slope of this straight line is known as the hydraulic slope i (assuming that the diameter of the pipeline along its entire length is identical, there are no local resistances and discharge along the length does not change).

It can be seen from Fig. 5.3 that

$$i = \frac{H_1 - H_2 - \Delta z}{L}.$$

But in accordance with (5.4) $H_1 - H_2 - \Delta z = h_\tau$. Accordingly, the physical sense of the hydraulic slope -- the head loss on friction, assignable to a unit length of pipeline is

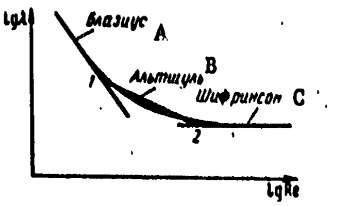


Fig. 5.2. Replacement of curve lg λ = f(lg Re) by straight line.
A) Blasius; B) Al'tshul'; C) Shifrinson

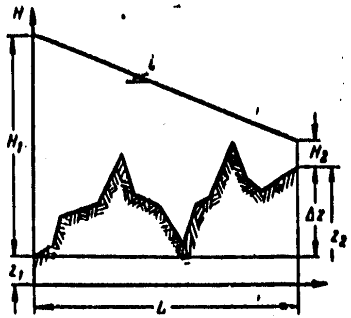


Fig. 5.3. Diagram explaining determination of hydraulic slope.

$$i=\lambda\frac{1}{D}\cdot\frac{w^2}{2g}$$

or according to Leybenzon

$$i=\beta\frac{Q^{2-m}\nu^m}{D^{5-m}}.$$

It is convenient to use the following compact formula:

$$i=fQ^{2-m},$$

where f is the hydraulic slope when Q = 1,

$$f=\beta\frac{\nu^m}{D^{5-m}}.$$

The straight line connecting the ends of the segments H_1 and H_2 is called the hydraulic slope line. It shows the distribution of heads (and accordingly pressures) along the length of the pipeline.

If a parallel pipeline ("looping") or a pipeline with a different diameter ("insert") is laid in some section of the route, the hydraulic slope in this section will differ from the hydraulic slope of the main line.

We will find the relationships between the hydraulic slopes of the looping, insert and main line. We will assume that the regimes of petroleum movement in them are identical.

Using the notations in Fig. 5.4 we have:

hydraulic slope of the main line

$$i=\beta\frac{Q^{2-m}\nu^m}{D^{5-m}},$$

hydraulic slope of the looping sector

$$i_{\text{л}}=\beta\frac{Q_1^{2-m}\nu^m}{D^{5-m}}=\beta\frac{Q_2^{2-m}\nu^m}{D_{\text{л}}^{5-m}}.$$

taking into account that $Q_1 = Q_2 = Q$, we obtain

$$i_{\text{л}}=i\omega, \tag{5.8}$$

[л = "looping"; В = insert]

where

$$\omega = \frac{1}{\left[1+\left(\frac{D_л}{D}\right)^{\frac{5-m}{2-m}}\right]^{2-m}}.$$

If $D_{loop} = D$, then

$$\omega = \frac{1}{2^{2-m}}.$$

In this case in a laminar regime $\omega = 1/2$, in the case of a turbulent regime in the Blasius zone $\omega = 0.297$, for the quadratic region $\omega = 0.25$.

Similarl. ιor the insert

$$i_в = i\Omega,$$

where

$$\Omega = \left(\frac{D}{D_в}\right)^{5-m}.$$

The head losses in friction for a pipeline with a looping will consist of the head losses in the single and double (with looping) sectors:

$$h_τ = i(L-x)+i_л x,$$

where x is the length of the looping.

Taking (5.8) into account, it can also be written that

$$h_τ = i[L-x(1-\omega)].$$

The total head loss for a pipeline with a looping is

$$H = i[L-x(1-\omega)]+\Delta z. \qquad (5.9)$$

For a pipeline with an insert the expression for head loss has a similar form.

If the head loss must be expressed in dependence on Q, we will use the formula

$$H = \beta\frac{Q^{2-m}\nu^m}{D^{5-m}}L+\Delta z \qquad (5.10)$$

or

$$H = fQ^{2-m}L+\Delta z. \qquad (5.11)$$

#5.4. Characteristics of Pipeline, Pump and Pumping Station

The dependence of the head loss on flow is expressed by the pipeline characteristic curve. Equation (5.10) or (5.11) is an analytical expression of this dependence. A graphic representation of the pipeline characteristic curve is shown in Fig. 5.5. The initial point of the characteristic curve is the end of the segment Δz, plotted upward from the H axis, if $z_2 > z_1$, or downward, when $z_2 < z_1$. If the pipeline operates with the counterpressure p_2 at the final point, then to Δz we add p_2/γ.

The values ν , L and D determine the steepness of the characteristic curve. The greater the viscosity of the pumped fluid, the extent of the pipeline, and the lesser its diameter, the steeper is the characteristic curve.

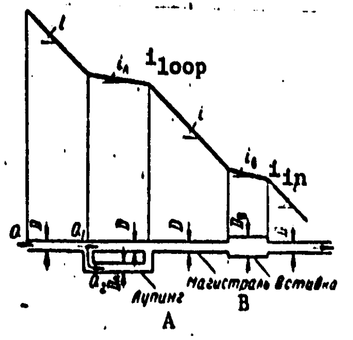


Fig. 5.4. Hydraulic slope in different pipeline sectors. A) looping, B) main line

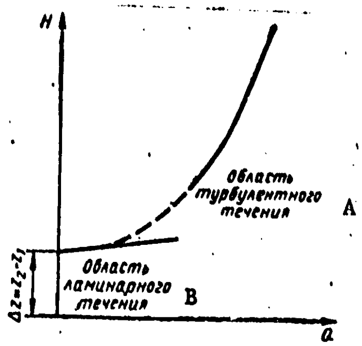


Fig. 5.5. Characteristic curve of pipeline. A) region of turbulent flow, B) region of laminar flow

In the case of small flows in the zone of laminar flow the dependence of H on Q is linear and in the region of turbulent flow -- the dependence is parabolic.

However, in the equation for the pipeline characteristic curve there is no reflection of transition from the linear part to the parabolic part. Assuming, for example, that $m = 0.25$, we obtain a parabolic curve for any Q values, including with values corresponding to laminar flow. In Fig. 5.5 this is shown by a dashed line.

In practical computations there is no need to draw the characteristic curve from the initial point corresponding to $Q = 0$. It is entirely sufficient to construct the characteristic curve of the pipeline on the basis of three or even two points situated in the narrow range of flows anticipated in the operation of the computed pipeline.

The head characteristic curve for the pump is a representation of the dependence of the developed head H on flow quantity Q.

For piston pumps the Q-H characteristic curve has the same shape as the dependence of torque on rpm for an engine. In particular for a special case for a pump with drive from a synchronous electric motor the characteristic curve is a straight line parallel to the H axis.

For centrifugal pumps used on main pipelines the characteristic curves have the shape of gently sloping curves. The sector of the characteristic curve corresponding to the highest efficiency values is the working region. For it the dependence of H on Q is approximated very successfully by the expression

$$H = a - bQ^2, \qquad (5.12)$$

Frequently there is a need for joint solution of the equations for the characteristic curves of a pump (pumping station) and a pipeline. In these cases in place of (5.12) it is desirable to assume

$$H = a - bQ^{2-m}. \qquad (5.13)$$

In formulas (5.12) and (5.13) a and b are constant values determined by the processing of the coordinates of points taken in the working region of the characteristic curve. According to the sense of (5.12) or (5.13) a is the head with $Q = 0$ and the b coefficient is evidence of the steepness of the characteristic curve. In formula (5.13) the m value is the same as in the Leybenzon formula for head loss in the pipeline. The characteristic curves of the pumps are obtained experimentally when working with water.

When working with very viscous petroleum the Q-H characteristic curve is reduced and becomes steeper. The method for the scaling the characteristic curve "from water` to petroleum" can be found in special manuals. The density of the pumped fluid exerts no influence on the Q-H characteristic curve; the head developed by the pump remains constant with a change in the density of the pumped fluid.

An increase or decrease in the diameter D of the wheel pump, and also the frequency of rotation n, changes the characteristic curve. It is known that

$$\frac{D^*}{D} = \frac{Q^*}{Q}; \qquad \frac{D^*}{D} = \sqrt{\frac{H^*}{H}}. \qquad (5.14)$$

Here the asterisk denotes the new, changed conditions. With a change in the frequency of rotation the equations are similar. With cutting down of the wheels ($D^* < D$) or with a decrease in the frequency of rotation ($n^* < n$) the Q-H characteristic curve decreases.

The characteristic curve for the pump after cutting down of the wheel to the diameter D^* can be obtained on the basis of the former characteristic using formulas (5.14). It is impossible to restructure the characteristic curve using only one of these formulas.

If it is necessary that the pump characteristic curve passes through the point with the coordinates Q^*, H^*, situated under the characteristic curve corresponding to the wheel diameter D, the wheel diameter after cutting down can be found using the formula

$$D^* = D\sqrt{\frac{H^* + bQ^{*2}}{a}} \qquad (5.15)$$

This formula is derived from (5.12) and (5.14). The parameters a and b entering into it must be computed using formula (5.12), proceeding on the basis of the given Q-H characteristic curve data with the diameter D.

The characteristic curve of the group of interconnected pumps (total characteristic curve) is obtained by adding together the characteristic curves of the pumps entering into this group.

In the case of pumps connected in series we add the heads for identical flows, and in the case of connection in parallel -- the flows with identical heads (Fig. 5.6, a,b).

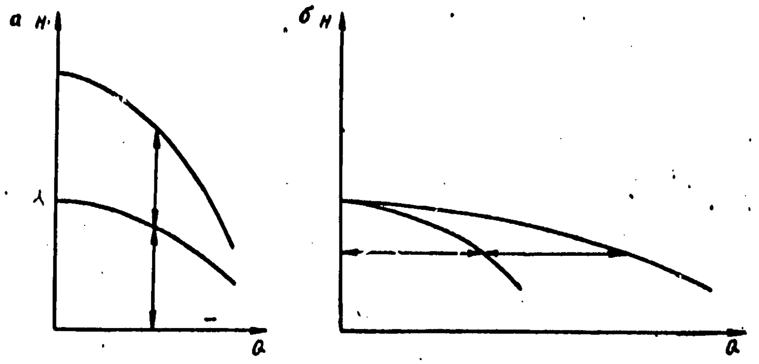


Fig. 5.6. Plotting of total characteristic curve for two (identical) pumps: a) connected in series; b) connected in parallel.

The equation for the total characteristic curve is the same as (5.12) or (5.13).

With the in-series connection of pumps

$$a = \sum a_i$$

$$b = \sum b_i.$$

With in-parallel connection of k identical pumps with the characteristic curve $H = a - b_1 Q^{2-m}$ the total characteristic curve will be as follows:

$$H = a - b_1 \left(\frac{Q}{k}\right)^{2-m}.$$

Assuming here that $b_1/k^{2-m} = b$, we arrive at the earlier expression (5.13).

The total characteristic of the pumps, operating at the pumping station, is called the characteristic curve of the pumping station.

#5.5. Head Balance Equation. Integrated Characteristic Curve

If the flow of liquid in the pipeline must overcome not only the resistance caused by friction, but also rising by the height Δz, and also perform mechanical work bringing into motion, for example, a turbine, then equation (5.2) must be supplemented by the term N/M (where N is the power; M is the mass flow).

However, if along the path of the flow there is a pump, rather than a turbine, the term N/M must be assigned a minus sign.

Thus, when we consider a system consisting of a pipeline and a pumping station,

$$\frac{p_1-p_2}{\rho}=\lambda\frac{l}{l}\cdot\frac{w^2}{2}+g\,\Delta z-\frac{N}{M}.$$

Converting to heads and taking into account that

$$M=Q\rho=Q\frac{\gamma}{g}$$

and

$$N=Q\gamma H_{\text{ст}},$$

[CT = station] where H_{st} is the head developed by the pumping station, we obtain

$$\frac{p_1}{\gamma}+H_{\text{ст}}=h_\tau+\Delta z+\frac{p_2}{\gamma}. \qquad (5.16)$$

For a main pipeline, along whose route there are n petroleum pumping stations, in equation (5.16) in place of H_{st} it is necessary to write nH_{st}. The head p_1/γ is created by a special (supporting) pumping station.

If from p_1/γ we subtract the head loss in the system of pipelines in the suction direction of the main pumping station (h_{sd}) [sd = suction direction], we obtain the head in the suction pipe of the first main pump, called the "backup" (ΔH_1).

The parameter h_τ includes the head loss in friction in the main line (iL) and in the communicating lines (nh_{st}) of all n pumping stations. In turn, the head loss in the communicating lines (of one) station is

$$h_{st}=h_{sd}+h_{pd},$$

where the subscript "sd" is for the "suction direction" and the subscript "pd" is for the "pumping direction."

The head at the final point of the petroleum line p_2/γ will be designated h_{fp} (fp = final point). This is the head loss in the connecting lines at the final point, including the height of the level in the receiving tank.

For the main pipeline with n identical pumping stations equation (5.16) can now be represented in the following form:

$$\Delta H_1+nH_{\text{ст}}=iL+\Delta z+nh_{\text{ст}}+h_{\text{к.п}}. \qquad (5.17)$$

[CT = st; K.П. = fp = final point]

Henceforth for brevity we will write:

$$\Delta H_1+nH_{\text{ст}}=iL+\Delta z. \qquad (5.18)$$

Equations (5.16), (5.17) and (5.18) are called the head balance equations.

The left-hand side of these equations gives the head developed by the pumping stations and the right-hand side gives the head loss.

The sense of the head balance equations is similar to the sense of Newton's third law.

Expressing the head developed by one station in the form $H_{st} = a - bQ^{2-m}$ and the hydraulic slope in the form $i = fQ^{2-m}$, we obtain the head balance equation

$$\Delta H_1 + n(a - bQ^{2-m}) = fQ^{2-m}L + \Delta z. \tag{5.19}$$

This equation has one unknown. Here Q is a specific value.

Assuming ΔH_1 to be a constant value, from (5.19) we obtain

$$Q = \sqrt[2-m]{\frac{\Delta H_1 + na - \Delta z}{nb + fL}}. \tag{5.20}$$

After determining Q, using formula (5.13) it is possible to compute the head developed by the stations, and using formula (5.11) the head loss in the pipeline. Both these values are equal to one another (head balance).

These same flow and head values can be found graphically (Fig. 5.7), in the same diagram plotting the characteristics of the pipeline and the pumping stations (integrated characteristic curve).

The point of intersection of the H(Q) curves on the integrated characteristic curve is called the working curve. The coordinates of this point are the flow in the pumping station - pipeline system and the head developed by the pumping stations (head loss in the pipeline).

In Fig. 5.7 the Q axis can be shifted upward by the value ΔH_1 (dashed horizontal line). In this case the backup before the head station ΔH_1 must be taken into account by the pipeline characteristic curve:

$$H = fQ^{2-m}L + \Delta z - \Delta H_1.$$

Integrated characteristic curves can also be plotted for individual pumping stations with corresponding segments of the pipeline (runs). For identical stations the coordinates of the working points of these characteristics will be one and the same if the backups before the stations are related to the characteristic curves of the runs. In other words, any of the pumping stations situated on the route develops one and the same head, regardless of the length and difference in the elevations at the end and beginning of the run connected to it.

In contrast to this, the heads developed by stations with piston pumps are dependent on the lengths and the differences in heights of the end and beginning of the corresponding runs (drive from synchronous electric motors, pumping with connected tanks).

The head balance and the equality of delivery by the pumps to flow in the pipeline (material pumping balance) give basis for the following important conclusion: the pipeline and the pumping stations constitute a unified hydraulic system.

This principle is the point of departure in solving any problems in the pumping of petroleum (petroleum products) along the main pipelines. The change in the operating regime of any one pumping station (such as shutdown of part of the pumps) impairs the regime of the remaining stations and simultaneously leads to a change in the operating regime of the pipeline, and vice versa, a change in pipeline resistance exerts an influence on the operating regime of the pumping stations.

The operation of the pipeline and pumping stations always must be regarded as a joint operation.

Hydraulic computations of any (not only the main) pipeline cannot be considered finished if only the head loss is computed for a stipulated flow and selected pumps. As a result of the computations, it should be possible to determine the actual flow which is established in the system pump (pumping stations) - pipeline, that is, the flow corresponding to the working point on the integrated characteristic curve.

#5.6. Pass Point and Computed Length of Petroleum Pipeline

A rise on the route along which the petroleum flows to the terminal point of the pipeline by gravity is called a pass point.

There can be several such points (Fig. 5.8). The distance from the initial point on the petroleum pipeline to the closest of them (π) is called the computation length of the petroleum pipeline.

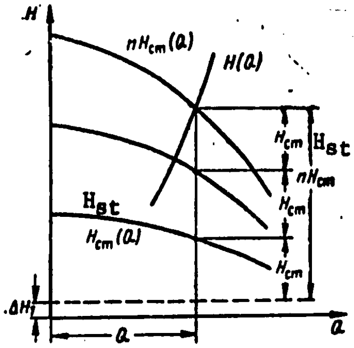


Fig. 5.7. Integrated characteristic curve of pipeline and pumping stations.

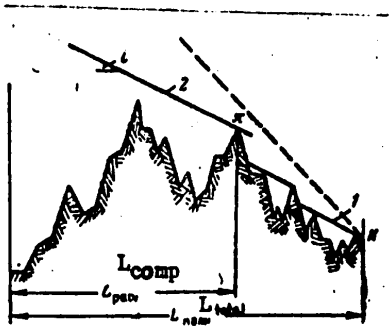


Fig. 5.8. Finding pass point and computation length of petroleum pipeline.

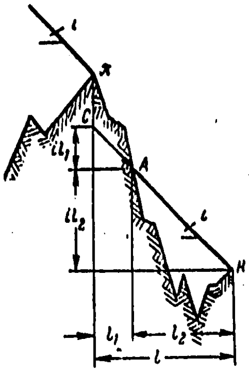


Fig. 5.9. Line of hydraulic slope beyond pass point.

In hydraulic computations the length of the petroleum pipeline is assumed to be equal to the computation length; the difference in elevations Δz is assumed to be equal to the excess of the pass point over the initial point on the route.

In order to find the pass point, from the final point on the route K we will draw the hydraulic slope line 1 to its intersection with the profile. Then we will draw the parallel line 2 in such a way that it touches the profile, not intersecting it in any place. The point of contact of the line of the hydraulic slope 2 with the profile of the route is the pass point π, determining the computation length of the petroleum pipeline.

If the hydraulic slope line drawn from the final point on the route nowhere intersects with the profile and is not in contact with it (the dashed line in Fig. 5.8), the pass point is absent and the computation length is equal to the total length of the pipeline. We will examine the movement of the petroleum beyond the pass point.

We define two segments in the route interval from the pass point to the terminal point: πA with the length ℓ_1 and AK with the length ℓ_2 (Fig. 5.9). In the latter of these the gravitational movement of the petroleum is ensured by the difference in elevations of the points A and K: $i\ell_2 = \Delta z_{A-K}$. In the segment πA, as can be seen from Fig. 5.9, $\Delta z_{\pi-A} > i\ell_1$ by the value πC. But this contradicts the balance condition of the lost ($i\ell_1$) and active ($\Delta z_{\pi-A}$) heads. Accordingly, in the segment πA the hydraulic slope must be greater than i. This is possible only in the case of an increase in the velocity of movement of the petroleum in the segment πA. From the continuity equation

$$Q = wF$$

it can be seen that with an increase in velocity the cross section F of the flow should decrease. Accordingly, beyond the pass point (to the point A) the petroleum moves with partial filling of the pipeline cross section. The pressure in this segment is lower than at any other point in the pipeline: it is equal to the pressure of saturated vapor of the pumped petroleum. In this case $(\Delta z_{\text{П}-\text{K}} - i\ell)Q\gamma$ is the power nonproductively lost beyond the pass point.

#5.7. Computation Values of Discharge and Viscosity of Pumped Petroleum

The viscosity of the pumped petroleum does not remain constant during the course of the year. It changes in accordance with the seasonal variations of ground temperature at the depth at which the pipeline is laid. With a change in the viscosity of the pumped petroleum, as already mentioned above, there is a change in the characteristic curves for the pipeline and the pumps (centrifugal): with an increase in viscosity it increases, whereas with a decrease it decreases. Accordingly, the throughput capacity of the petroleum pipeline, determined by the point of intersection of the characteristic curves for the pipeline and pumping stations (working point), in the course of the year changes from a minimum value (March-April) to a maximum value (August-September), as shown in Fig. 5.10.

The movement of the working point in the field Q-H is determined primarily by a change in the steepness of the pipeline characteristic curve. In most cases the "deformation" of the characteristic curve for the centrifugal pumps is insignificant and it can be neglected.

From the point of view of the saving of energy expended on the pumping of petroleum, it is advantageous that the mentioned movements of the working point not exceed the limits on the zone of high efficiencies of the pumping plant characteristic curves.

This requirement is satisfied by the proper choice of the pumps for pumping petroleum.

In accordance with the norms for technological planning, the computed hourly throughput capacity is assumed equal to

$$\frac{Q_{\text{год}}}{8400\rho},$$

[ГОД = an(nual)]

The computed viscosity must also correspond to the computed temperature.

The computed temperature is that which the oil flow assumes in the pipeline in the cold season of the year. It is determined by the ground temperature at the depth of the pipeline and the self-heating of the petroleum flow in the pipeline as a result of friction.

#5.8. Determination of Number of Petroleum Pumping Stations

Neglecting the value ΔH_1 in the head balance equation, we obtain

$$n_0 H_{\text{ст}} = iL + \Delta z, \qquad (5.21)$$

Using this equation we find the number of stations. The head developed by one station (H_{st}) is logically taken corresponding to the computed flow (using the Q-H characteristic curve).

The number of stations n_0 is usually a mixed fraction. It is rounded off to a whole number n.

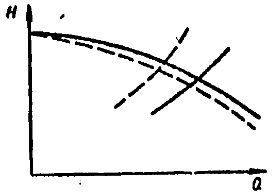


Fig. 5.10. Change in characteristic curves of pipeline and pumping station with change in viscosity. Note. The solid curves are for a summer regime and the dashed curves are for a winter regime.

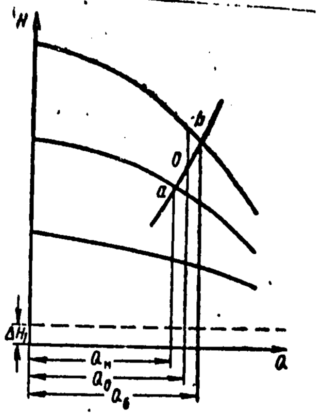


Fig. 5.11. Graph of change in output of pumping stations with change in their number. ($Q_б = Q_g = Q$ greater)($Q_M = Q_{less(er)}$)

The throughput capacity of a petroleum pipeline with a rounded-off number of stations will be called the planned throughput.

If n_0 is rounded off in the greater direction, the planned output Q_g ($б$ = greater) will be greater than the computed level Q_0, and vice versa, with the rounding off of n_0 in the lesser direction the planned flow Q_{less} is less than the computed value. This can be seen from formula (5.20) and from the graph in Fig. 5.11.

The output Q_{less} or Q_{more} in the pumping stations - pipeline system is established automatically.

However, the planned output can be left equal to the computed output. For this it is necessary that the working point on the integrated curve for the pipeline and pumping stations be situated on the segment ab (see Fig. 5.11). With the rounding off of n_0 in the lesser direction the characteristic curve for the pipeline must pass through the point a, that is, the head loss in the pipeline must be decreased by the value $0a = (n_0 - n)H_{st}$. This can be accomplished by laying a looping (or an insert with a large diameter).

A looping with the length x decreases the hydraulic resistance by the value $ix - i_{loop}x = ix(1 - \omega)$. Accordingly, the length of the looping ensuring maintenance of the computed throughput capacity with rounding off of the number of stations in a lesser direction can be found from the equation

$$(n_0 - n) H_{\text{ст}} = ix(1 - \omega),$$

[CT = sta]

It is also possible to use equation (5.21) and the equation

$$nH_{\text{ст}} = i[L - x(1 - \omega)].$$

The result will be the same, that is, we obtain

$$x = H_{\text{ст}} \frac{n_0 - n}{i(1 - \omega)}.$$

With the rounding off of n_0 in the greater direction the head developed by the stations with the computed discharge Q_0 will be greater than necessary (that is, greater than the head loss in the pipeline) by the value H' (see Fig. 5.11, segment Ob).

The head balance equation with the rounding off of n_0 in the greater direction will be as follows:

$$nH_{\text{ст}} - H' = iL + \Delta z.$$

It is obvious that

$$H' = (n - n_0) H_{\text{ст}},$$

where H' is the value by which the head developed by the stations must be decreased.

The head can be reduced by means of a decrease in the number of pumping plants or cutting down of the pump wheels.

After a decrease in the number of pumping plants the characteristic curve of the pumping stations is reduced, as a result of which the gap between the head developed by the pumping stations and the head losses in the pipeline is reduced.

A final balancing of the heads can be obtained by cutting down the pump wheels. The diameter of the cut-down wheel can be determined using formula (5.15).

#5.9. Optimum Parameters of Petroleum Pipeline

Sequence of Technical Computations

The parameters of a petroleum pipeline, characterizing it from both the economic and technical points of view, are the pipeline diameter D, pressure p developed by the pumping stations, number of petroleum pumping stations and the pipeline wall thickness δ (the throughput capacity Q of the petroleum pipeline is stipulated).

All four parameters are interrelated: a change in one of them leads to a change in all the others. The greater the diameter of the pipeline or the greater the pressure, the fewer is the number of necessary petroleum pumping stations and vice versa. The thickness of the pipeline wall, with the selected grade of steel, is determined by the p and D parameters.

Thus, for pumping a stipulated quantity of petroleum it is possible to propose a number of variants of the plan, differing with respect to the parameters D, p, n and δ . The problem involves finding the economically most advantageous variant.

The capital expenditures K on construction of the main pipeline can be broken down into two parts: the cost of the petroleum pumping stations K_{st} and the cost of the pipeline (pipes, welding, insulation, digging of trenches, etc.) K_{pipe}. With an increase in D or p the capital expenditures on a pipeline increase, whereas on the petroleum pumping stations they decrease. Since K_{st} and K_{pipe} change in dependence on D or p in opposite directions, the functions $K = K(D)$ and $K = K(p)$ have a minimum. The operating expenses Op change similarly. Accordingly, there is a minimum also for the reduced expenditures Red = KE + Op.

The values of the pipeline parameters D, p, n and ρ for which the reduced expenditures are minimum are optimum.

The finding of the pipeline parameters from the minimum of the reduced expenditures does not take into account such factors as the short supply of different materials or equipment, simplicity, convenience and safety of servicing, requirements of a special nature, etc.

It is obvious that with these indices different variants of the plan for one and the same pipeline cannot differ significantly from one another.

For solving the problem of the optimum pipeline parameters it is necessary:
1) to write an equation for the reduced expenditures;
2) to express the capital expenditures K and the operational expenditures Op entering into the reduced expenditures Red in dependence on the parameters D, p, n and δ , that is, obtain the equation

$$\text{Red} = K(D, p, n, \delta)E + Op(D, p, n, \delta)$$

where E is the standard coefficient of effectiveness of capital investments;
3) to find the minimum of the function Red. Here it must be taken into account that the parameters of the petroleum pipeline are related to one

another. The correlation conditions are:

pressure balance equation

$$\frac{np}{L}=\beta\frac{Q^{2-m}\nu^{m}}{D^{5-m}}\gamma+\frac{\Delta z}{L}\gamma$$

and the strength equation

$$\delta=\frac{pD}{2\sigma},$$

where σ is the computed stress of metal in the pipes.

The minimum of the Red function is found using the Lagrange rule. For this we write the new function

[Π= Red]

$$\Phi=\Pi+\lambda\left(\frac{np}{L}-\beta\frac{Q^{2-m}\nu^{m}}{D^{5-m}}\gamma-\frac{\Delta z}{L}\gamma\right),$$

where λ is an indeterminate Lagrange factor.

Then we obtain the partial derivatives of Φ relative to D, p and n and equate them to zero.

The joint solution of the equations

$$\frac{\partial\Phi}{\partial D}=0;\quad\frac{\partial\Phi}{\partial p}=0;\quad\frac{\partial\Phi}{\partial n}=0$$

with the correlation equations makes it possible to derive formulas for determining the optimum parameters of the pipeline.

In order to express Red as a function of the petroleum pipeline parameters, capital expenditures and operational expenditures are represented in the form of a sum in which each term is related to the different parameters.

For this purpose the capital expenditures on pumping stations are represented in the form of two terms: in the form of expenditures proportional to power and expenditures not dependent on power (power is proportional to pQ). The capital expenditures on the linear part of the pipeline are expressed as expenditures proportional to the diameter of the pipeline and proportional to the mass of the pipes (the mass of the pipes is linearly dependent on pD^2).

The operational expenditures relating to pumping stations consist of expenditures proportional to power and not dependent on power, and also allocations for amortization and current repair. The allocations for amortization and current repair can be regarded as the operational expenditures for the linear part of the pipeline.

The expenditures not dependent on the pipeline parameters can be neglected. If any of the parameters are stipulated, that is, are known in advance, the problem is solved in the same way with the single difference that it is not necessary to take the first derivative for this parameter.

In preparing a list of expenditures or in clarifying the technical-economic indices necessary for determining the capital expenditures and operating costs there will inevitably be errors which can exert an influence on the numerical values of the sought-for parameters. In addition, the considered method for determining the optimum parameters does not take into account many circumstances dependent on planning and construction conditions. It is therefore not surprising if the optimum parameters, computed by this method, in some cases will be far from reality. Accordingly, the optimum pressure can be lower than that which is developed by the pumps produced by factories and the optimum thickness of the pipeline wall will be less than the limiting admissible thickness.

But this does not mean that the analytical method for determining the optimum parameters of a pipeline is useless. It makes it possible to trace both the interrelationship between the parameters and the influence exerted on them by pumping conditions. An investigation of the equations determining the optimum parameters of a pipeline made it possible to draw a number of important conclusions. The most important of them are:
1) with an increase in the pipeline throughput capacity the optimum pressure developed by the pumping stations decreases, the number of stations increases and the optimum diameter of the pipeline increases;
2) with increase in the computed stress of the pipe material there is an increase in the optimum pressure and a decrease in the optimum number of pumping stations;
3) with an increase in the viscosity of the pumped petroleum there is a decrease in the pressure which the pumping stations must develop and the number of stations and the diameter of the pipeline increase;
4) with an increase in pressure there is a decrease in the diameter of the pipeline and the number of pumping stations and also an increase in the thickness of the pipeline wall;
5) with an increase in the pipeline diameter the relative thickness of the wall, pressure and number of stations decrease.

Usually the optimum parameters of the pipeline are determined by a comparison of variants.

The sequence of technological computations can be as follows:
1) approximate determination of pipeline diameter from the table given in #5.1;
2) selection of the three closest diameters from the State Standard;
3) selection of the pumps for the pumping (delivery) of petroleum. Then, in accordance with the pressure recommended in this same table, the number of working plants (usually three or two) is determined and the pumping station characteristic curve is constructed. This characteristic curve is used used in finding the head H_{st} developed by the station for the computed flow and then the computed pressure is determined:

$$p(H_{st} + \Delta H)\gamma;$$

[CT = st]

4) determining the wall thickness and the interior diameter of the pipeline from the ascertained p and D values for all three variants;
5) determination of the Reynolds number, the hydraulic resistance coefficient, hydraulic slope, pass point (computed length L) and the corresponding difference in the geodetic readings Δz, and finally, the total head loss

$$H = iL + \Delta z;$$

6) determination of the number of petroleum pumping stations;
7) computation of capital expenditures and operating costs using consolidated technical-economic indices;
8) comparison of variants with respect to reduced expenditures and selection of the economically most advantageous of them;
9) determination, for the selected variant, of the planned delivery (if it is not assumed equal to the computed value) and the corresponding head developed by the pumping stations;
10) siting of the stations on the route profile.

***

#5.10. Positioning of Petroleum Pumping Stations

The siting method was proposed by V. G. Shukhov for pipelines with piston petroleum pumping stations. The siting is accomplished graphically on the route profile.

The head H_{st} developed by the station is plotted along the vertical from the initial point on the route where the head station must be situated at the scale of profile elevations. After this, the hydraulic slope line is drawn from the end of the determined segment. The point of its intersection with the route profile is the site for positioning of the second station. The head developed by the station is again plotted from this point, the hydraulic slope line is again drawn, etc. The hydraulic slope line running from the last station must run to the pass point (or final point) on the route.

The siting of the petroleum pumping stations, accomplished by the described method, must not always be regarded as strictly obligatory. The siting of stations can vary in certain limits.

Assume that the theoretical number of stations n_0, determined by computations, is rounded off in the greater direction. Then the site, for example, of the second station (Fig. 5.12) can be shifted to the right, that is, forward, by the distance at which the head H_{st} attains the admissible value H_{ad}. With movement of the station to the left there is a decrease in the head developed by the preceding station. Since the total head developed by all the stations should remain constant, at least one of the remaining stations must operate with an increased head.

The position of the station at which it and all the subsequent stations are forced to develop the limiting admissible head H_{ad} determines the limit to which it can be moved to the left. As already mentioned, the limit to the right is determined by the admissible head H_{ad} at the preceding station. In Fig. 5.12 these limits are denoted by the points a and b. The sector of the route between these points is called the zone of possible siting of a petroleum pumping station.

When the number of stations is rounded off in the lesser direction, and accordingly, computations call for the laying of a looping, from the end of the vertical segment H_{st} two hydraulic slope lines are drawn (Fig. 5.13): for the main line i and the looping i_{loop}. The length of the segment i_{loop} corresponds to the length of the looping x obtained by computations. We draw a second line i from the end of the segment i_{loop}. The points of intersection of the hydraulic slope lines with the profile (a and b) determine the zone of the possible siting of the next station. A station can be put in any place between these points.

Assume that the point c is a convenient site for the second station. From this point we draw the hydraulic slope line of the looping to the intersection with the hydraulic slope line for the main line. The projection of the resulting segment cd onto the horizontal will be equal to the length of the looping x_1 used on the segment (run) between the first and the second stations. Then from the point c we plot the head H_{st} and then again draw the lines i_{loop} and i; the length of the segment i_{loop} here corresponds to the not further used length of the looping $x - x_1$. The lines i emanating from the ends of the segment i_{loop} intersect with the profile at the new points a and b (not shown in Fig. 5.13). A new point c can be selected between these points -- the site for the third station. Subsequent constructions are made in the same way.

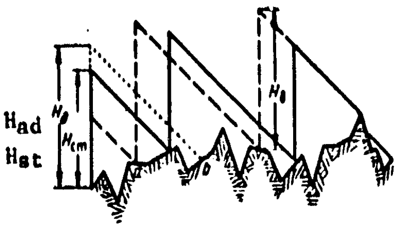


Fig. 5.12. Determination of limits of zone of possible positioning of petroleum pumping stations with rounding off of their number in the greater direction.

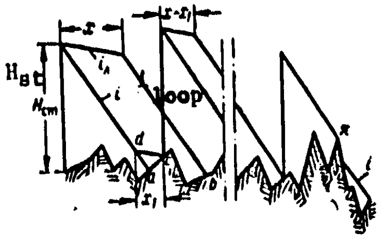


Fig. 5.13. Positioning of petroleum pumping stations with rounding off of their number in the lesser direction.

There can be cases when in the zone of possible positioning there is no site convenient for the siting of a petroleum pumping station. The siting of a station outside the zone of possible positioning (points e or f in Fig. 5.14) leads to the necessity for laying an additional looping x^* and at the same time to the underloading (work with incomplete head) of at least one of the stations.

Loopings on the lines between stations can be laid where it is advantageous to do so. The effect from a looping (decrease in hydraulic resistance of the pipeline) run at the beginning, at the middle or at the end of the segment is one and the same. However, in order to decrease the stresses arising in the pipeline from the petroleum pressure it is desirable that the loopings be laid at the end of the segments. But in some cases the decrease in the load on the pipeline can be achieved by the laying of a looping in the middle of the segment (Fig. 5.15). In the neighborhood of point A it is desirable to lay a looping and not construct a station there since in this case the pressure in the lowered segment of the route will be considerably less.

The following conclusion can be drawn: with siting of the petroleum pumping stations, regardless of the type of pumps (piston or centrifugal) it is necessary to "press" the hydraulic slope line to the profile. This reduces the stresses in the pipeline.

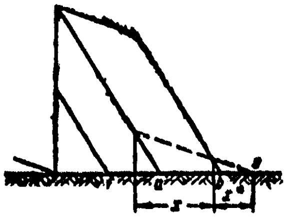


Fig. 5.14. Siting of station outside zone of possible positioning.

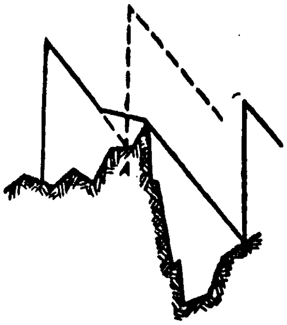


Fig. 5.15. Laying of looping in middle of segment.

When using the principle described above, by which is found the site for positioning of the petroleum pumping stations, the type of pump is not taken into account. However, the siting of stations with centrifugal pumps has peculiarities caused by the following:

1) mainline centrifugal pumps can normally operate only with a backup, that is, only when the suction pipe is under pressure. The backup before the station must not be less than the minimum admissible value Δh, since otherwise the operation of the pumping station will be accompanied by cavitation;

2) the backup consists of the head H_{st} developed by the pumping station. Their sum (head on the force side of the station) must not exceed the admissible value H_{ad} determined by the strength of the pump and the pipeline.

For stations with centrifugal pumps the limits of the zone of possible positioning are not determined by the points of intersection of the hydraulic slope lines with the profile but by the admissible backup values. The right limit is determined by the minimum backup ΔH_{ad}, whereas the left limit is the maximum backup $\Delta H_{ad} = H_{ad} - H_{st}$ (Fig. 5.16).

The zone of possible positioning of the centrifugal station also exists in a case when there is no looping (see Fig. 5.16, right part).

Now we will examine a case when any station must be sited outside the zone of possible positioning (coincidence with a populated place, more favorable geological-soil characteristics of the terrain, closeness to sources of electric power, water, etc.).

Assume that this station has the number c + 1. The extent of the pipeline segment from the head station to the considered station is denoted ℓ_{c+1}. The length of the segment from the station c + 1 to the end of the pipeline will be equal to $L - \ell_{c+1}$.

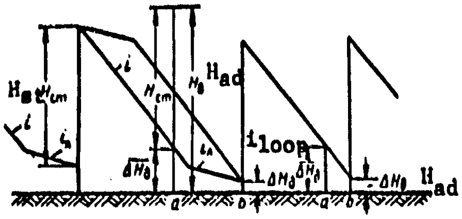


Fig. 5.16. Limits of zones of possible positioning of stations equipped with centrifugal pumps.

We will place the station c + 1 beyond the right boundary of the zone of possible siting. Then the backup before this station ΔH_{c+1} will be less than ΔH_{ad}. In order to ensure cavitation-free operation of the station c + 1 it is necessary to raise the backup ΔH_{c+1} to ΔH_{ad}. This can be done by laying the looping in the segment between the stations c and c + 1 or at any other desirable site in the segment ℓ_{c+1}. Its length x^* can be found from the following head balance equation for the segment ℓ_{c+1}:

$$\Delta H_1 + cH_{\text{ст}} = i\,[l_{c+1} - x(1-\omega) - x^*(1-\omega^*)] + \Delta z_{c+1} + \Delta H_{\text{д}},$$

[CT = st(ation); Д = ad(missible)] where x is the length of the looping obtained from hydraulic computations with rounding off of the number of stations n_0 in the lesser direction; c is the number of stations situated in the segment ℓ_{c+1}.

The need for laying the looping x^* does not follow from hydraulic computations of the pipeline. Therefore, after laying the looping x^* the head balance which is common for the entire pipeline will be impaired. In order to restore this balance in the segment $L - \ell_{c+1}$ it is necessary to reduce the head developed by the stations.

The H' value by which the head developed by the stations in the segment $L - \ell_{c+1}$ must be decreased is determined from the following head balance equation:

$$\Delta H_{\text{д}} + (n-c)\,H_{\text{ст}} - H' = i\,(L - l_{c+1}) + \Delta z_{\text{к}}.$$

[CT = st(ation); Д = ad(missible)]

A decrease in the head by H' can be achieved by a decrease in the number of pumping plants (if H' is greater than or equal to the head developed by one pump) and by cutting down the pump wheels. The diameter of the cut-down wheel can be determined using formula (5.15). The head H^* entering into this formula is found from the obvious equality

[HAC = pump]

$$kH_{\text{нас}} - H' = kH^*,$$

where k is the number of pumps whose wheels it is proposed be cut down; H_{pump} is the head developed by a pump whose wheel has not been cut down.

From the hydraulic point of view it makes no difference whether the decrease in head occurs at one (and specificially which) or at several stations. It is desirable to do this, that is, use pumps with cut-down wheels or decrease the number of pumps at those stations where the propulsion head is high.

Now we will site the station c + 1 without going as far as the left boundary of the zone of possible positioning. We will assume that the problem of positioning of all c + 1 stations in the segment l_{c+1} is already solved and the operating regimes of the pumping plants up to station c have been determined.

In order for the propulsion head at the station c + 1 not exceed the admissible value H_{ad} it is evidently necessary to decrease the head developed either by the station c + 1 or by the station c (decrease in the number of pumps, cutting down of wheels). In the latter case there is a decrease in the backup before the station c + 1 and accordingly there is a decrease in the head on the propulsion side of this station.

A decrease in the head H' is determined from the head balance equation for the segment between stations c and c + 1:

[c = prop]

$$H_{\text{с}} - H' = il + \Delta z + \overline{\Delta H_{\text{Д}}},$$

where H_{prop} is the head on the propulsion side of the station (is determined by preceding computations); ΔH_{ad} is the maximum admissible backing.

The sense of this equation is as follows: in order that the backup before the station c + 1 not exceed ΔH_{ad} at station c it is necessary to reduce the head by the value H'.

If the decrease in head is accomplished at the station c + 1, the head balance equation for determining H' is logically written in the following form:

$$H_{\text{с}} = il + \Delta z + H_{\text{Д}} - (H_{\text{ст}} - H'),$$

[c = prop; Д = ad; CT = st]

where $H_{ad} - (H_{st} - H')$ is the backup before the station c + 1; H_{st} is the head developed by the station without a decrease in the number of working pumps and without cutting down the wheels.

It is easy to see that this equation is identical to the preceding one.

With a decrease in head at the station c + 1 the segment between stations c and c + 1 will obviously be under a greater pressure. Therefore, from the point of view of a stressed state of the pipeline the decrease in head at station c is more desirable than at station c + 1.

If provision is made for the laying of an "insert" of a lesser diameter in the segment between stations c and c + 1, its length x_{in} can be determined from the equation

$$H_{prop} = i[\ell - x_{in}(1 - \Omega)] + \Delta z + H_{ad} - H_{st}.$$

A decrease in head or an increase in hydraulic resistance in the segment ℓ_{c+1}, as in the already considered case of going beyond the right boundary of the zone of possible positioning, impairs the head balance common for the entire pipeline. For compensating this impairment it will be necessary to decrease the hydraulic resistance of the segment $L - \ell_{c+1}$. For determining the length of the looping x^* ensuring such a decrease in hydraulic resistance we can use the following head balance equation for the segment $L - \ell_{c+1}$

$$H_{п} + (n - c - 1) H_{ст} = i\,[(L - l_{c+1}) - x(1 - \omega) - x^*(1 - \omega^*)] + \Delta z_n,$$

where x is the length of the looping obtained in hydraulic computations due to rounding off of the number of stations in the lesser direction and falling in the segment $L - \ell_{c+1}$.

#5.11. Change in Backups Before Stations With Change in Viscosity of Pumped Petroleum

The backup before the pumping station c + 1 is determined from the head balance equation for the segment ℓ_{c+1} (between the first and the c + 1st stations):

$$\Delta H_1 + c(a - bQ^{2-m}) = fQ^{2-m} l_{c+1} + \Delta z_{c+1} + \Delta H_{c+1}.$$

Taking into account that from the head balance equation for the entire pipeline

$$Q^{2-m} = \frac{\Delta H_1 + na - \Delta z}{nb + fL},$$

we obtain

$$\Delta H_{c+1} = \Delta H_1 + ca - \Delta z_{c+1} - (\Delta H_1 + na - \Delta z)\,\frac{c}{n}\,\frac{b + f\,\dfrac{l_{c+1}}{c}}{b + f\,\dfrac{L}{n}}.$$

In this equation only

$$f = \beta\,\frac{\nu^m}{D^{5-m}}.$$

is dependent on viscosity.

Thus, a change in the backup ΔH_{c+1} with a change in viscosity is determined by the value

$$\frac{b + f(l_{c+1}/c)}{b + f(L/n)},$$

where ℓ_{c+1}/c is the mean distance between the petroleum pumping stations in the segment ℓ_{c+1}, and L/n is the mean distance between the pumping stations for the entire pipeline.

If $\ell_{c+1}/c > L/n$, with an increase in petroleum viscosity the fraction

$$\frac{b + f(l_{c+1}/c)}{b + f(L/n)}$$

increases and therefore the backup ΔH_{c+1} decreases.

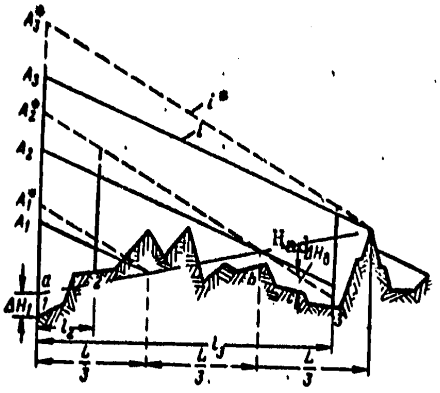


Fig. 5.17. Change in backups before stations with a change in viscosity of pumped petroleum.

For the case $\ell_{c+1}/c < L/n$, on the other hand, with an increase in petroleum viscosity the backup before station c + 1 increases.

Finally, if $\ell_{c+1}/c = L/n$, a change in petroleum viscosity exerts no influence on the magnitude of the backup, since with any f value in this case

$$\frac{b+f\frac{l_{c+1}}{c}}{b+f\frac{L}{n}}=1.$$

The change in backups before stations with a change in viscosity is illustrated in Fig. 5.17.

The vertical dashed lines on the route profile cut off identical distances L/n (in the figure L/3): L is the computed length of the petroleum pipeline.

The solid and dashed hydraulic slope lines i and i^* correspond to the viscosities ν and ν^*; $\nu^* > \nu$. The segments $aA_1 = A_1A_2 = A_2A_3$ and $aA_1^* = A_1^*A_2^* = A_2^*A_3^*$ represent the heads H_{st} and H_{st}^* developed by the pumping stations with petroleum viscosities ν and ν^*; the segment 1a is the backup before the first station ΔH_1.

We will use the point 1 as the origin of coordinates. Then the hydraulic slope lines emanating from the points A and A^* will be described by the equations

$$H=\Delta H_1+cH_{\text{ст}}-il \quad \text{and} \quad H^*=\Delta H_1+cH_{\text{ст}}^*-i^*l,$$

where ℓ is the distance from the initial point on the route 1; H and H^* are the ordinates corresponding to ℓ.

At the points of intersection of the mentioned lines H = H*, that is

$$cH_{\text{ст}} - il = cH^*_{\text{ст}} - i^*l.$$

[CT = st] Taking into account that

$$i = \frac{\Delta H_1 + nH_{\text{ст}} - \Delta z}{L}$$

and

$$i^* = \frac{\Delta H_1 + nH^*_{\text{ст}} - \Delta z}{L},$$

it is easy to confirm that the hydraulic slope lines with the viscosities ν and ν^* intersect at the distances

$$l = c\frac{L}{n},$$

where c is a whole number, that is, c = 1, 2, 3, etc.

If the third station is situated at the point b, over which the lines i and i* intersect, that is, at a distance which is a multiple of L/n, with any increase or decrease in petroleum viscosity the backup would remain unchanged (condition $l_{c+1}/c = L/n$).

However, this station was situated beyond the point of intersection of the hydraulic slopes i and i* and for it

$$\frac{l_{c+1}}{c} > \frac{L}{n}.$$

Therefore, the backup before the third station with an increase in viscosity is reduced (see Fig. 5.17). The second petroleum pumping station is situated to the left of the point of intersection of the lines i and i*.

For it

$$\frac{l_{c+1}}{c} < \frac{L}{n}.$$

Therefore, the backup before it with the viscosity ν^* is greater than with the viscosity ν.

A change in the backups with a change in petroleum viscosity must be taken into account when siting petroleum pumping stations: the limits of the zones of their possible positioning are dependent on viscosity. If the nature of the profile is such that $l_{c+1} > c\,(L/n)$, the right limit of the zone of possible positioning of the station c + 1 will be determined by the point of intersection of the hydraulic slope line i* with a maximum viscosity of the petroleum ν^* with the line drawn equidistantly to the profile at the height which is equal to the minimum admissible backup ΔH_{ad}. In Fig. 5.17 the third station has been placed incorrectly: the right limit of its zone of possible positioning must be at the point c, where the distance from the profile to the hydraulic slope line is equal to ΔH_{ad}.

The second station in Fig. 5.17 can be situated at a distance $\ell_2 < L/3$. Therefore, the right limit of the zone of its possible positioning is determined by the hydraulic slope line i with the minimum viscosity ν.

The left limit of the zone of possible positioning of the station c + 1, where the backup has the greatest value, must be determined from this same hydraulic slope line (i or i^*), which passes above.

#5.12. Planning of a Petroleum Pipeline with a Stipulated Positioning of Pumping Stations. Planning of "Short" Pipelines

It is advantageous to place petroleum pumping stations at places situated close to villages, railroads and highways, to sources of electricity supply and water supply. Favorable topogeological characteristics of the areas around petroleum pumping stations are of great importance. In addition, the areas should be situated in such a way that the propulsion pressure at the stations will be identical as possible.

With the placement of stations by the Shukhov plan there is always a guaranteed satisfaction of only the last of these requirements. The selection of sites around petroleum pumping stations free of restrictions, dictated by the Shukhov method (zones of possible positioning) sometimes most reasonably makes possible satisfaction of the mentioned requirements.

Assume that all the computations up to the choice of the optimum variant have been made, the number of stations has been rounded off in the greater direction and the sites of the petroleum pumping stations have been selected.

Then it is necessary to ensure that the heads on the propulsion and suction sides of the stations will not exceed the limits of the admissible values.

The sequence of the computations can be as follows.

We will begin with the first segment (head station and the segment adjacent to it).

1. Using the Q-H characteristic curves we find the heads developed by the backup ΔH and main H_{st} stations. Adding them, we obtain the head on the propulsion side of the station (propulsion head H_{prop}):

$$\Delta H + H_{\text{ст}} = H_{\text{н}}.$$

[CT = station; H = prop(ulsion)]

2. Using the head balance equation for the segment we find the backup ΔH before the second station. Taking into account the losses in the station connecting lines this equation will be as follows:

$$H_{prop} = il + \Delta z + h_{\text{ст}} + \Delta H,$$

where ℓ and Δz are the length and difference in elevations of the end and beginning of the line segment between stations (found from the route profile); h_{st} is the head loss in the station connecting lines.

Computations for subsequent segments are similar: we will determine the propulsion head H_{prop} and then the backup ΔH before the next station.

If at any station the head H_{prop} is higher than the admissible level, in order to reduce it to H_{ad} it is possible to use the measures mentioned above: a decrease in the number of working pumps, cutting down the pump wheels (interchangeable rotors), and also throttling.

The first method is the most economical. With the second method there is some reduction in pump efficiency (a cutting down of the wheels by not more than 10% is admissible). Throttling, that is, an artificial increase in hydraulic resistance, involves an expenditure of energy and therefore it must be used only when it is the only possible means for reducing head.

It must be remembered that a decrease in propulsion head inevitably causes a decrease in the backup before the next station. If the backup is above the admissible level, in order to increase it to ΔH_{ad} in the considered segment it is necessary to lay a looping (large-diameter insert). Its necessary length x^* is determined from the equation

$$H_{\text{д}} = i\,[l - x^*(1 - \omega)] + \Delta z + h_{\text{ст}} + \Delta H_{\text{д}}.$$

[Д = ad; CT = st]

Computations of the heads H_{prop} and ΔH at stations can also be made in a different way, beginning with the last segment.

1. We will determine the head H_{prop} which much exist on the propulsion side of the last station (required head) using the formula

$$H_{prop} = i\ell + \Delta z + h_{cl},$$

where h_{cl} is the head loss in the connecting lines at the final pipeline station (including the level height in the receiving tank).

If there is a pass point, it must be considered the final point. In this case the required head at the last station is

$$H_{\text{н}} = il + \Delta z.$$

[H = prop]

2. Using the Q-H characteristic curve we find the head H_{st} and then we find what backup should exist before the last station:

$$\Delta H = H_{\text{н}} - H_{\text{ст}}.$$

[H = prop; CT = st]

3. We will determine the required head at the next-to-the-last station using the formula

$$H_{\text{н}}=H+\Delta z+h_{\text{ст}}+\Delta H,$$

[Н = prop; СТ = st]

Then we find the backup before this station, etc.

If it appears for any segment that $H_{prop} > H_{ad}$ or $\Delta H < \Delta H_{ad}$, the measures used for decreasing H_{prop} or for increasing ΔH_{ad} are the same as considered above.

The construction of integrated Q-H characteristic curves and also the hydraulic slope lines, when the positioning of the stations is stipulated, evidently loses independent importance. They must be constructed only for checking the correctness of the computations.

For the segments where the propulsion pressures differ considerably from the computed level it is necessary to refine (again determine) the thickness of the pipeline wall. Then the problem of "breakdown" of the pipes is solved.

Petroleum pipelines with one or two petroleum pumping stations will be called short.

For computing such pipelines there is no need for performing all the operations indicated in #5.9. The computations are reduced to a determination of the diameter of the pipeline with two values of the number of stations (n = 1 and n = 2) and to the selection of the most advantageous variant.

First we will find the computed length of the pipeline and the Δz value. For this (Fig. 5.18) from the initial point of the route we lay out the backup ΔH_1 and twice the head H_{st} and we draw the lines i_1 and i_2 (with another route profile there can be two pass points -- for the lines i_1 and i_2 or there may be no pass point).

Then from the head balance equation

$$\Delta H_1+nH_{\text{ст}}=\beta\frac{Q^{2-m}\nu^{m}}{D^{5-m}}L+\Delta z$$

we find the values of the pipeline diameters D_1 and D_2 with n = 1 and n = 2. Then, adopting D_1 and D_2 from the State Standard, we determine the capital expenditures for both variants and select the best of them.

The head H_{st} is determined from the Q-H characteristic curve, first selecting the make and number of pumps operating at the station.

The positioning of the second station (with n = 2) can be found by the usual Shukhov method. However, if the site for the second station is stipulated, as before the computations must be ended by determining the propulsion heads at both stations and the backup before the second station.

§5.13. Increase in Throughput Capacity of Petroleum Pipeline

An increase in the need for petroleum products in the considered economic region, caused by the peculiarities of its development, leads to an increase in the capacity of the petroleum refinery (refineries) servicing the region and the means for delivering the refined petroleum products to consumers.

An increase in the capacity of the plant in turn involves a need for increasing the handling capacity of the transportation facilities delivering petroleum from the fields to the petroleum refinery.

Thus, the problem arises of increasing the throughput capacity of an existing petroleum pipeline.

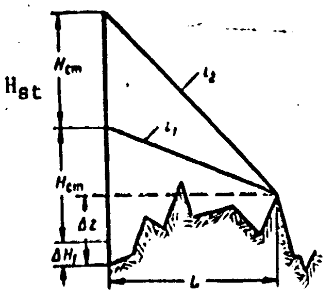


Fig. 5.18. Diagram explaining computation of short petroleum pipeline.

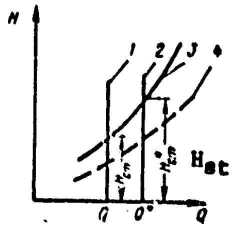


Fig. 5.19. Increase in throughput capacity of petroleum pipeline with piston pumps: 1) characteristic curve of pumping station; 2) characteristic curve of pumping station after increasing number of pumping plants; 3) characteristic curve of pipeline (run between stations); 4) characteristic curve of pipeline after doubling number of stations or after laying looping.

Frequently in the planning process the condition is imposed that the throughput capacity of the pipeline must be increased gradually and attain the maximum value only by a definite time. The diameter of such a pipeline is selected corresponding to the maximum throughput capacity. Petroleum pumping stations are constructed and put into operation as required.

An increase in the petroleum pipeline throughput capacity from Q to Q* can be achieved by a change in the characteristic curve for the pipeline or pumping stations for which the working point on the integrated characteristic curve is moved to the right.

The ratio

$$\frac{Q^*}{Q}=\chi$$

is called the coefficient of increase in throughput capacity.

The problem is solved most simply in the case of a very great steepness of the characteristic curves of the pumping stations (vertical line for piston pumps). In this case an increase in the throughput capacity is accomplished by installing at each station additional pumping plants which are connected in parallel, and if at each station there were k working pumps, and if after the installation of the additional pumps there were k^*, the coefficient of increase in throughput capacity (under the condition that the pumps are identical) is

$$\chi = \frac{k^*}{k}$$

An increase in flow after the additional pumps are put into operation leads to an increase in head loss. The working point on the integrated characteristic curve Q-H is moved not only to the right, but also upward (Fig. 5.19). In this case the head H^*_{st} which the stations will develop may be above that which is admissible from strength conditions.

The head H_{st} can be decreased by the following methods:

by the construction of additional stations on the runs between existing stations (doubling the number of stations). In this case a decrease in the head occurs due to a decrease in the lengths of the runs serviced by the stations;
by laying additional loopings.

Now we will examine these methods. The heads H_{st} developed by the stations before and after the increase in the throughput capacity will be considered identical.

Doubling of Number of Stations

Before an increase in throughput capacity

$$nH_{ст} = fQ^{2-m}L + \Delta z.$$

After doubling the number of stations and installing additional pumping plants ensuring an increase in flow we obtain

$$2nH_{ст} = fQ^{*(2-m)}L + \Delta z.$$

Dividing the second equation by the first, we obtain

$$\chi = \left(\frac{2nH_{ст} - \Delta z}{nH_{ст} - \Delta z}\right)^{\frac{1}{2-m}}. \qquad (5.22)$$

Formula (5.22) shows that for pipelines running uphill (with $\Delta z > 0$) the χ coefficient is greater than for "horizontal" or (even moreso) for pipelines for which $\Delta z < 0$.

The Δz value is frequently neglected. Then

$$\chi = 2^{\frac{1}{2-m}}. \qquad (5.23)$$

Accordingly, if it is necessary to increase the throughput by a factor of

$$2^{\frac{1}{2-m}}$$

(in the case of a turbulent regime in the zone of operation of the Blasius law

$$2^{\frac{1}{2-m}} = 1.485),$$

then it is desirable to double the number of stations. In this case the pressure developed by the stations does not change.

Laying of Additional Loopings

This method is effective when $\chi < 2^{\frac{1}{2-m}}$.

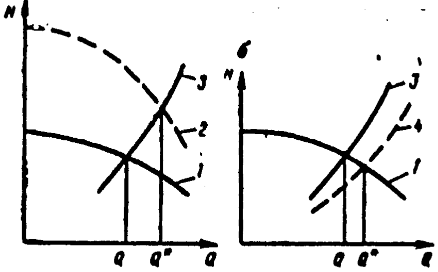


Fig. 5.20. Increase in throughput capacity of petroleum pipeline with centrifugal pumps: a) after doubling number of stations; b) after laying loopings; 1) characteristic curve of pumping station; 2) characteristic curve of pumping stations after doubling number of stations; 3) characteristic curve of pipeline; 4) characteristic curve of pipeline after laying looping

The length of the looping x ensuring retention of the former pressure after installing additional pumping plants at the stations is determined from the equations

$$nH_{\text{ст}} = fQ^{2-m}L + \Delta z$$

and

$$nH_{\text{ст}} = fQ^{*\,(2-m)}\,[L - x\,(1-\omega)] + \Delta z,$$

[CT = st] Hence

$$x = \frac{L}{1-\omega}\left(1 - \frac{1}{\chi^{2-m}}\right). \qquad (5.24)$$

If it is necessary to increase the throughput capacity by a factor greater than

$$2^{\frac{1}{2-m}}$$

the doubling of the number of stations can be supplemented by the laying of loopings (combined method). In this case the necessary length of the looping (without taking Δz into account) is

$$x = \frac{L}{1-\omega}\left(1 - \frac{2}{\chi^{2-m}}\right).$$

Finally, the problem of doubling the number of stations or the laying of a looping is solved by an economic comparison. Whereas on a petroleum pipeline with piston pumps a doubling of the number of stations and the laying of loopings serve for reducing the head developed by the pumping stations, on pipelines with centrifugal pumps a doubling of the number of stations and the laying of loopings serve as a means for increasing their throughput capacity. It is easy to confirm this by comparing the graphs in Figures 5.19 and 5.20, a, b. The first of these requires no clarification. The second gives a determination of the throughput capacity of a pipeline with centrifugal pumps after doubling the number of stations (see Fig. 5.20, a) and after the laying of loopings (see Fig. 5.20,b). It can be seen from these graphs that an increase in throughput capacity can also be accomplished without the installation of additional pumps connected in parallel. The latter are necessary in those cases when after an increase in throughput capacity the working point on the Q-H characteristic curve goes beyond the limits of the working zone (having a sufficiently high efficiency).

With a doubling of the number of stations we obtain a fixed value of the coefficient of increase in throughput capacity. With an increase in the throughput capacity by the laying of a looping the coefficient χ can have different values in dependence on the length and diameter of the looping.

The combined method also makes it possible to ensure a set of χ values (due to the looping).

Since the characteristic curves for the pumping stations are "dropping off" curves, the head developed by the stations, after increasing the throughput capacity, decreases. Therefore, with a doubling of the number of stations outfitted with centrifugal pumps the coefficient of increase in throughput capacity will be less than determined by formula (5.22) or (5.23). The length of the looping for this same reason will be greater than the length determined using formula (5.24).

We will examine what increase in the throughput capacity will be given by a doubling of the number of stations and what the length of the looping should be for obtaining a stipulated χ value.

Doubling of Number of Stations

From the head balance equations before and after doubling the number of stations

$$\Delta H_1 + n\left(a - bQ^{2-m}\right) = fQ^{2-m}L + \Delta z$$

and

$$\Delta H_1 + 2n\left(a - bQ^{*2-m}\right) = fQ^{*(2-m)}L + \Delta z$$

we have

$$Q^{2-m} = \frac{\Delta H_1 + na - \Delta z}{fL + nb}$$

and

$$Q^{*(2-m)} = \frac{\Delta H_1 + 2na - \Delta z}{fL + 2nb}.$$

Dividing the second equation by the first, we derive a formula showing that for centrifugal pumping stations, the same as for piston pumping stations, the coefficient of increase in throughput capacity is the greater the greater is the Δ z value:

$$\chi^{2-m} = \frac{(\Delta H_1 + 2na)(fL + nb) - \Delta z(fL + nb).}{(\Delta H_1 + na)(f + 2nb) - \Delta z(fL + nb) - \Delta z nb}$$

For those cases when the Δ z and ΔH_1 values can be neglected,

$$\chi^{2-m} = 2\frac{fL + nb}{fL + 2nb}. \qquad (5.25)$$

It follows from this formula that:

1) with centrifugal pumps the coefficient of increase in throughput capacity is less than

$$2^{\frac{1}{2-m}},$$

that is, is less than for piston pumps (as was mentioned above);

2) the steeper is the pipeline characteristic curve (the greater the fL value), the greater is the effectiveness in doubling the number of stations;

3) the χ value decreases with an increase in nb, that is, with an increase in the steepness of the total characteristic curve of the pumping stations.

Laying of Loopings

Solving jointly the equations

$$\Delta H_1 + n(a - bQ^{2-m}) = fQ^{2-m}L + \Delta z$$

and

$$\Delta H_1 + n(a - bQ^{*(2-m)}) = fQ^{*(2-m)}[L - x(1-\omega)] + \Delta z,$$

we obtain a formula for determining the length of a looping necessary for increasing the throughput capacity by a factor of χ:

$$x = \frac{L}{1-\omega}\left(1 - \frac{1}{\chi^{2-m}}\right)\left(1 + \frac{nb}{fL}\right). \qquad (5.26)$$

Formula (5.26) shows that the necessary length of the looping is not dependent on Δz (the same as is true of piston pumps); with one and the same coefficient of increase in throughput capacity for petroleum pipelines with centrifugal pumps it is necessary to have a greater length of the looping than for petroleum pipelines equipped with piston pumps; the effectiveness of laying of the looping is increased with an increase in the steepness of the pipeline characteristic curve and with a decrease in the steepness of the characteristic curve for the pumps.

If we substitute into formula (5.26) the χ value determined by formula (5.25) we obtain

$$x = \frac{L}{2(1-\omega)}.$$

This is the length of a looping giving the same effect as a doubling of the number of stations.

Adopting x = L in formula (5.26), we find the maximum value of the coefficient of increase in throughput capacity possible when laying a looping:

$$\chi=\left(\frac{1+\frac{nb}{fL}}{\omega+\frac{nb}{fL}}\right)^{\frac{1}{2-m}}.$$

If measures are taken at stations for maintaining the former pressure (installation of additional plants, replacement of existing ones by others), then formulas (5.25) and (5.26) are transformed into the formulas derived above (5.23) and (5.24).

The siting of additional petroleum pumping stations (with centrifugal pumps) is determined as before: from the initial point of the route we plot the backup ΔH_1 and the head H^*_{st} developed by the main pumps of the station with the flow Q^*; then the hydraulic slope line i^* corresponding to the flow Q^* is drawn and the site for an additional station is selected. The necessary (that is, not exceeding the admissible limits) backup before the additional station is always ensured if the station site is located in the "zone of possible location." The backup before the next station, that is, before an existing station in the first plan, by no means always will remain in the necessary limits (it may be both excessively great and excessively small).

Now we will consider how it is possible to determine the backups before stations in the first plan and how it is possible to keep them within the framework of the admissible values.

We will write equations for the lines of hydraulic slopes for the segment ℓ_{c+1} before an increase in capacity and after a doubling of the number of stations:

$$H=\Delta H_1+cH_{\text{ст}}-il \quad \text{and} \quad H^*=\Delta H_1+2cH^*_{\text{ст}}-i^*l.$$

[CT = st(ation)]

Here H and H^* are the ordinates; ℓ is the abscissa. The origin of coordinates is at the point of siting of the head station.

When $\ell = \ell_{c+1}$ $H^* - H$ represents the additional backup δH_{c+1} carried to station c + 1 from the preceding additional station:

$$\delta H_{c+1}=c\,(2H^*_{\text{ст}}-H_{\text{ст}})-(i^*-i)\,l_{c+1}.$$

Since

$$i^*=\frac{\Delta H_1+2nH^*_{\text{ст}}-\Delta z}{L} \quad \text{and} \quad i=\frac{\Delta H_1+nH_{\text{ст}}-\Delta z}{L},$$

the δH_{c+1} value can be represented in the following form:

$$\delta H_{c+1} = c\frac{L}{n}(2H^{\circ}_{ct} - H_{ct})\left(\frac{L}{n} - \frac{l_{c+1}}{c}\right).$$

This formula makes it possible to draw the conclusions:
1) if station c + 1 is situated at a distance l_{c+1} less than c (L/n) (from the initial point on the route), then $\delta H_{c+1} > 0$, that is, the backup before station c + 1 increases after an increase in the throughput capacity,

$$\Delta H^{\circ}_{c+1} = \Delta H_{c+1} + \delta H_{c+1};$$

2) if

$$\frac{l_{c+1}}{c} > \frac{L}{n},$$

then $\delta H_{c+1} < 0$ and $\Delta H^{\circ}_{c+1} < \Delta H_{c+1};$

3) with $\frac{l_{c+1}}{c} = \frac{L}{n}$ $\delta H_{c+1} = 0.$

In the latter case the backup before station c + 1 does not change.

The change in the operating regime of stations in the first plan after the construction of additional stations is shown in Fig. 5.21.

The lines of hydraulic slope i emanating from stations in the second plan, A, B and C, intersect at points lying on the aл line. These points divide the route into equal segments with the length L/n (in Fig. 5.21 L/3). The distance of station 2 from the initial point on the route $l_2 < L/3$; therefore, after stations A, B and C are put into operation, the backup in front of station 2 increased by δH_2. This led to an increase in head at the station. The third station was situated at the distance $l_3 > 2L/3$ and therefore the backup before it was decreased ($\delta H_3 < 0$). If station 3 was situated at point D, distant from the beginning of the pipeline by the distance 2L/3, the backup in front of it would not change.

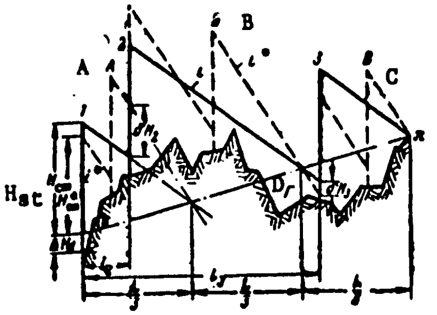


Fig. 5.21. Operating regime of pipeline after construction of second-plan stations.

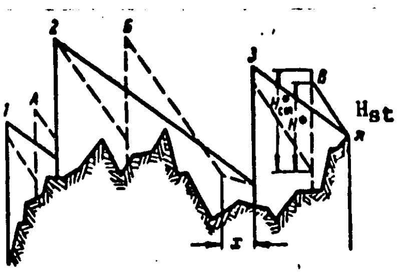


Fig. 5.22. Diagram explaining doubling of number of stations.

If after doubling the number of stations the head at station 2 is greater than the admissible level H_{ad} (due to the strength condition) or the head before station 3 is less than ΔH_{ad} (cavitation), the throughput capacity of the segment λ_2 will be greater than the throughput capacity of the segment limited by stations 2 and 3.

Figure 5.22 shows that for evening out the throughput capacities in these segments at the additional station A there was a decrease in the number of pumps and on the line between stations B and 3 there was a looping with the length x which compensates the decrease in head developed by station A and ensures an increase in the backup in front of station 3 to the former level ΔH_3. In order to pump petroleum from station B to the pass point π it is necessary to have a head somewhat less than H^*_{st} (the run between station 3 and the point π is less than L/3). The excess head can be eliminated by cutting down the wheels of the pumps installed at station B. As before, the degree to which the wheels is modified is determined, as before, using formula (5.15), in which the head H^* can be found using the head balance equation or by a construction on the profile, as is shown in Fig. 5.22.

#5.14. Petroleum Pipelines with Withdrawals and Additions of Petroleum Along Line

In many cases for supplying consumers located along a route there is a withdrawal of the pumped petroleum from the petroleum pipeline. The withdrawals can be continuous and periodic. Continuous withdrawal can be organized, for example, for supplying petroleum to a petroleum refinery located near the route of the petroleum pipeline. Periodic withdrawals are into auxiliary pipelines (supplementing the reserves at near-lying petroleum bases).

If at any place a petroleum pipeline passes close to a producing region, petroleum can be pumped into the passing line. The petroleum produced in these fields is carried in the same main petroleum pipeline. Depending on the productivity of the deposit the delivery can be either continuous or periodic.

The technological computations for a pipeline with continuous withdrawals or with continuous additions of petroleum can be made for the segments limited by the points of withdrawal or addition.

In the case of insignificant withdrawals or additions the pipeline is designed without taking them into account. However, it must be remembered that in the case of periodic withdrawals (additions) the technological pumping regime changes: this usually leads to a necessity for regulating the operation of pumping stations.

Now we will examine the operating regime of a pipeline with periodic withdrawals and additions.

The pipeline segment from the initial point to the point of withdrawal (addition) will be called the left segment and the segment from the withdrawal (addition) point to the final or pass point will be called the right segment.

In the case of a withdrawal the flow for the left segment will increase, whereas for the right segment it will decrease. The backups before all intermediate stations will be reduced.

This is confirmed by the following considerations. Assume that the point of withdrawal is situated at the distance l_{c+1} from the initial point on the route, that is, near the station c + 1. From the head balance equations:

For the left part of the petroleum pipeline

$$\Delta H_1 + c\left(a - bQ^{*(2-m)}\right) = fl_{c+1}Q^{*(2-m)} + \Delta z_{c+1} + \Delta H_{c+1} \tag{5.27}$$

and the right part of the pipeline

$$\Delta H^*_{c+1} + (n-c)\left[a - b\,(Q^* - q)^{2-m}\right] = f\,(L - l_{c+1})\,(Q^* - q)^{2-m} + \Delta z_n,$$

where q is the withdrawal, a* is an index denoting "with withdrawal"; it is easy to derive the expression

$$(cb + fl_{c+1})\,Q^{*(2-m)} + \left[(n-c)\,b + f\,(L - l_{c+1})\right](Q^* - q)^{2-m} = \Delta H_1 + na - \Delta z, \tag{5.28}$$

which shows that with an increase in withdrawal there is an increase in flow for the left part of the pipeline.

From equation (5.27) and the head balance equation for pumping without withdrawal

$$\Delta H_1 + c\left(a - bQ^{2-m}\right) = fl_{c+1}Q^{2-m} + \Delta z_{c+1} + \Delta H_{c+1}$$

we find that the decrease in backup before the station c + 1 (where the withdrawal point is situated) is

$$\delta H_{c+1} = \Delta H_{c+1} - \Delta H^*_{c+1} = (cb + fl_{c+1})\left(Q^{*(2-m)} - Q^{2-m}\right).$$

Using this same formula we determine the change in the backup before station c' + 1, situated to the left of station c + 1,

$$\delta H_{c'-1} = (c'b + fl_{c'+1})\left(Q^{*(2-m)} - Q^{2-m}\right),$$

where Q* has its former value.

Since c' < c, then $\delta H_{c'+1} < \delta H_{c+1}$. Accordingly, in accordance with the length of the left segment of the petroleum pipeline the backups before the stations (beginning with the second) decrease; the minimum backup is at station c + 1, where a withdrawal is made. The backups along the right segment of the pipeline increase; this can be demonstrated by similar reasonings. The change in backups before the stations in the case of withdrawal is illustrated in Fig. 5.23.

In the case of an addition along the line, in the left part of the pipeline $Q^* < Q$; the flow in the right part $Q^* + q > Q$. With an increase in the added quantity q the flow Q* decreases. This can be confirmed by placing a "+" sign in front of the q value in formula (5.28).

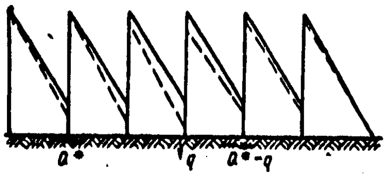


Fig. 5.23. Change in operating regime of petroleum pipeline with withdrawal.

The backup before station c + 1 increases with an increase in the volume of petroleum added to the line. This can be seen from the formula

$$\delta H_{c+1} = \Delta H^{*}_{c+1} - \Delta H_{c+1} = (cb + fl_{c+1})(Q^{2-m} - Q^{*(2-m)}).$$

The distribution of backups before stations will be as follows: for a station situated near the point where petroleum is added -- the maximum backup; with increasing distance from it (in both directions) the backups decrease.

Withdrawal and flow in the left part of the pipeline, for which the backup before the station is c + 1 (at the withdrawal point), attaining the minimum admissible value ΔH_{ad}, will be designated the critical value q_{cr} and Q_{cr}.

We will write the head balance equation for the left part of the pipeline in the case of critical withdrawal:

$$\Delta H_1 + c\left(a - bQ^{2-m}_{\text{кр}}\right) = fl_{c+1}Q^{2-m}_{\text{кр}} + \Delta z_{c+1} + \Delta H_{\text{Д}}.$$

[KP = cr(itical); Д = ad(missible)]

Hence we find the critical flow

$$Q_{cr} = \left(\frac{\Delta H_1 + ca - \Delta z_{c+1} - \Delta H_{\text{Д}}}{cb + fl_{c+1}}\right)^{\frac{1}{2-m}}.$$

From the head balance equation for the right part of the pipeline

$$\Delta H_{\text{Д}} + (n-c)\left[a - b(Q_{\text{кр}} - q_{\text{кр}})^{2-m}\right] = f\,(L - l_{c+1})(Q_{\text{кр}} - q_{\text{кр}})^{2-m} + \Delta z_{n}$$

[KP = cr; Д = ad] we obtain a formula determining the critical withdrawal:

$$q_{\text{кр}} = Q_{\text{кр}} - \left[\frac{\Delta H_{\text{Д}} + (n-c)a - \Delta z_{n}}{(n-c)b + f(L - l_{c+1})}\right]^{\frac{1}{2-m}}.$$

If the withdrawal $q > q_{cr}$, there is then a need for artificially increasing the backup before station c + 1; for ensuring cavitation-free operation it must not be less than ΔH_{ad}.

The backup can be increased by an increase in the hydraulic resistance of the right part of the pipeline or a decrease in the head developed by the stations situated there (after the withdrawal point). This is accomplished by regulation.

Now we will clarify what should be the increase in resistance, or (which is the same) what head H' must be extinguished by regulation.

Since by means of regulation before station c + 1 the backup ΔH_{ad} is maintained, the flow in the left part of the pipeline is equal to Q_{cr}; in the right part it will be equal to $Q_{cr} - q$.

The head H' which must be absorbed by the regulating device can be determined using the equation

$$\Delta H_{\text{Д}}+(n-c)\left[a-b\left(Q_{\text{кр}}-q\right)^{2-m}\right]=f\left(L-l_{c+1}\right)\left(Q_{\text{кр}}-q\right)^{2-m}+\Delta z_{\text{к}}+H'.$$

[Д = ad; KP = cr] If

$$H'=kH_{\text{нас}}+h',$$

[HAC = pump] where H_{pump} is the head developed by one pump with the flow $Q_{cr} - q$; k is a whole number and $h' < H_{pump}$, then it is desirable to cut out k pumps and the head h' is extinguished by throttling.

We will call the critical addition of petroleum to the line q_{cr} that addition with which the head at station c + 1 attains the maximum admissible value H_{ad}.

The flow in the right part of the pipeline in the case of a critical addition of petroleum will also be called critical Q_{cr}.

We will find the critical flow from the head balance equation for the right part of the petroleum pipeline (with the addition of petroleum, as before, before the station c + 1)

$$H_{\text{Д}}+(n-c-1)\left(a-bQ_{\text{кр}}^{2-m}\right)=f\left(L-l_{c+1}\right)Q_{\text{кр}}^{2-m}+\Delta z_{\text{к}}.$$

We obtain

$$Q_{\text{кр}}=\left[\frac{H_{\text{Д}}+(n-c-1)\,a-\Delta z_{\text{к}}}{(n-c-1)\,b+f\left(L-l_{c+1}\right)}\right]^{\frac{1}{2-m}}.$$

Now we will write the head balance equation for the left part of the pipeline in the case of a critical addition of petroleum:

$$\Delta H_1+c\left[a-b\left(Q_{\text{кр}}-q_{\text{кр}}\right)^{2-m}\right]=fl_{c+1}\left(Q_{\text{кр}}-q_{\text{кр}}\right)^{2-m}+\Delta z_{c+1}+H_{\text{Д}}-\left(a-bQ_{\text{кр}}^{2-m}\right).$$

Hence we find that the critical addition of petroleum is

[KP = cr]

$$q_{\text{кр}}=Q_{\text{кр}}-\left\{\frac{\Delta H_1+ca-\Delta z_{c+1}-\left[H_{\text{Д}}-\left(a-bQ_{\text{кр}}^{2-m}\right)\right]}{cb+fl_{c+1}}\right\}^{\frac{1}{2-m}}.$$

With the addition of petroleum $q > q_{cr}$ it is necessary to have regulation. The purpose of the regulation is to reduce the flow in the left part of the petroleum line to the value $Q_{cr} - q$. This is achieved in the same way: by cutting out some of the pumps or increasing the hydraulic resistance.

The head H' which must be eliminated by regulation in the left part of the pipeline is determined from the equation

$$\Delta H_1+c\left[a-b\left(Q_{\text{кр}}-q\right)^{2-m}\right]=fl_{c+1}\left(Q_{\text{кр}}-q\right)^{2-m}+\Delta z_{c+1}+H_{\text{Д}}-\left(a-bQ_{\text{кр}}^{2-m}\right)+H'.$$

[KP = cr]

#5.15. Operating Regime of Pipeline With Shutting Down of Pumping Stations

The temporary shutdown of any station can be caused by malfunctions in the electric supply system, damage, the need to do repair work, etc.

The shutdown of a pumping station greatly changes the operating regime of the pipeline (flow, pressure, backups before stations). Such a change in the operating regime is characterized by a transient process with a duration of up to several tens of minutes and a new steady-state operating regime of the pipeline which sets in after attenuation of the transient process.

When there are transient processes in pipelines with intermediate pumping stations there are sharp changes in pressure and flow. The pressure at individual points on the route can exceed the admissible values.

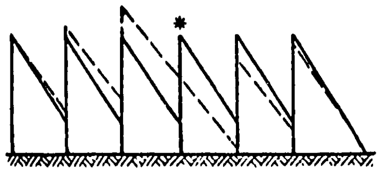


Fig. 5.24. Change in operating regime of petroleum pipeline with shutdown of station.

Methods for protecting pipelines against excessively high pressures and methods for computing fluctuations of pressure and flow during transient processes have been examined in detail in Chapter 9. Now we will examine the method for computing the regime for a pipeline which is established in it after shutdown of one of the pumping stations and attenuation of oscillations. In order to understand better the change in the pumping regime we will assume for the time being that the petroleum pipeline can operate with any heads and pressures arising as a result of shutdown of the station.

Regardless of what station has malfunctioned -- the second, third, etc. or last, from the head balance equation for the entire pipeline it follows that

$$Q^{*(2-m)}=\frac{\Delta H_1+(n-1)a-\Delta z}{(n-1)b+fL}. \tag{5.29}$$

The flow Q^* is established automatically, as a result of self-regulation. It is obviously less than the flow Q which prevailed prior to shutdown of the station.

We will clarify how the backups change before the stations with shutdown of station c.

From the head balance equations for the left part of the petroleum pipeline (segment L_{c+1}):

with shutdown of station c

$$\Delta H_1+(c-1)\left(a-bQ^{*\,(2-m)}\right)=fl_{c+1}Q^{*\,(2-m)}+\Delta z_{c+1}+\Delta H^{*}_{c+1},$$

with operation of all stations

$$\Delta H_1+c\left(a-bQ^{2-m}\right)=fl_{c+1}Q^{2-m}+\Delta z_{c+1}+\Delta H_{c+1}$$

we find that with a shutdown of the station the backup before station c + 1 is reduced by the value

$$\delta H_{c+1}=\Delta H_{c+1}-\Delta H^{*}_{c+1}=\left(a-bQ^{*\,(2-m)}\right)-\left(cb+fl_{c+1}\right)\left(Q^{2-m}-Q^{*\,(2-m)}\right). \qquad (5.30)$$

It can be seen from formula (5.30) that the closer the shut-down station is situated to the head station, the greater will be the decrease in the backup before station c + 1.

Similarly, from the equations

$$\Delta H_1+(c-2)\left(a-bQ^{*\,(2-m)}\right)=fl_{c-1}Q^{*\,(2-m)}+\Delta z_{c-1}+\Delta H^{*}_{c-1}$$

and

$$\Delta H_1+(c-2)\left(a-bQ^{2-m}\right)=fl_{c-1}Q^{2-m}+\Delta z_{c-1}+\Delta H_{c-1}$$

it follows that before station c - 1 the backup increases to

$$\delta H_{c+1}=\Delta H^{*}_{c-1}-\Delta H_{c-1}=\left[(c-2)\,b+fl_{c-1}\right]\left(Q^{2-m}-Q^{*\,(2-m)}\right).$$

It is obvious that the backup before station c - 2 also increases, but to a lesser degree, before station c - 3 -- to a still lesser degree, etc.

It can also be demonstrated that in the right part of the petroleum line the backups will increase from station to station, but will remain less than they were prior to the shutdown of station c.

The change in backups before the stations with a shutdown of one of them is shown in Fig. 5.24.

On the basis of formula (5.30) it is possible to write the pumping condition for a self-regulating regime:

$$\left(a-bQ^{*\,(2-m)}\right)-\left(cb+fl_{c+1}\right)\left(Q^{2-m}-Q^{*\,(2-m)}\right)\leqslant\varepsilon,$$

where ε is the backup reserve,

$$\varepsilon=\Delta H_{c+1}-\Delta H_{g}.$$

Usually the head reserves will be small: at the station following the shutdown station, with a decrease in ΔH below the admissible level the appearance of cavitation can be observed. The backup before the station c + 1 can be raised to the admissible value ΔH_{ad} by regulation of operation of stations situated in the right part of the petroleum pipeline. The head H' which must be extinguished by regulation is found from the head balance equation for the right part of the pipeline

[Д = nd] $$\Delta H_{\text{д}} + (n-c)\left(a - bQ^{*(2-m)}\right) = f(L - l_{c+1})Q^{*(2-m)} + \Delta z_{\text{к}} + H',$$

where the flow Q^* is determined from the head balance equation for the left part of the pipeline

$$\Delta H_1 + (c-1)\left(a - bQ^{*(2-m)}\right) = fl_{c+1}Q^{*(2-m)} + \Delta z_{c+1} + \Delta H_{\text{д}}.$$

This flow will be less than the flow determined by formula (5.29).

Since the backups before the stations in the left part of the pipeline increase, the propulsion pressure at station c - 1 can be greater than the admissible level H_{ad}. A decrease in the heads to H_{ad} is attained by regulation at the stations in the left part of the pipeline. In this case the flow Q^* will be determined by the equation

$$H_{\text{д}} = flQ^{*(2-m)} + \Delta z + \Delta H_{\text{д}}, \tag{5.31}$$

where ℓ is the distance between stations c - 1 and c + 1; Δz is the difference in the leveled elevations of the end and beginning of the segment.

The value H' by which the head developed by the stations in the left part of the pipeline must be reduced can be found from the equation

$$\Delta H_1 + (c-1)\left(a - bQ^{*(2-m)}\right) = fl_{c-1}Q^{*(2-m)} + \Delta z_{c-1} + H_{\text{д}} + H'$$

or

$$\Delta H_1 + (c-1)\left(a - bQ^{*(2-m)}\right) = fl_{c+1}Q^{*(2-m)} + \Delta z_{c+1} + \Delta H_{\text{д}} + H'.$$

If H' exceeds the head H_{pump} developed by one pump, then, rounding off H'/H_{pump} to a whole number k (in the lesser direction), we find the number of pumps k subject to shutdown. The head $H' - kH_{pump}$ must be extinguished by throttling.

The operating regime of the pipeline when any station breaks down can be computed graphically, using the profile of the route and the characteristic curve for the pumping station. We will demonstrate this in the following example.

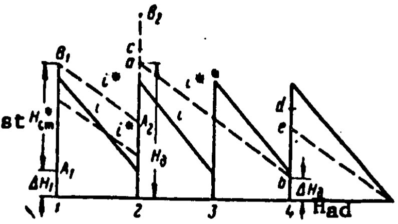


Fig. 5.25. Diagram explaining computations of the operating regime of a petroleum pipeline with shutdown of station.

On a petroleum pipeline with a horizontal profile of the route there are four stations, at each of which there are three working pumps. The lines of the hydraulic slope in the case of a normal operating regime are represented by solid lines (Fig. 5.25).

Assume that the third station has malfunctioned.

From the point on the profile where the second station is situated we plot the head H_{ad} and from the point where the fourth station is situated -- the head ΔH_{ad}. By connecting the ends of these segments (a,b) we obtain the line of the hydraulic slope i^* corresponding to the equation (5.31) and determining the flow Q^* with which the pipeline should operate after shutting down of the third station.

Now on the basis of the characteristic curve for the pumping station we find the head H^*_{st} for the flow Q^* and we plot it from the initial point on the profile after ΔH_1 (segment A_1B_1). From the point B_1 we draw the line of the hydraulic slope i^* (segment B_1A_2). By plotting the head H^*_{st} from the point A_2 (segment A_2B_2) we see that at station 2 it is necessary to shut down one pump and the excess head ac is eliminated by throttling. But it is better to shut down one pump at the first station and at the second to extinguish the head ac; in this case the run between the first and second stations will experience lesser pressure (see the line of hydraulic slope i^* below the line B_1 A_2).

Then, drawing the line i^* for the last run, we find that at the fourth station it is necessary to shut down one pump (the segment bd is equal to the head developed by the two pumps with the flow Q^*) and by throttling eliminate the head ed.

In a graphic method it is convenient to use analytical computation of the regime for monitoring.

#5.16. Regulation of Operating Regime of Pumping Stations

Changes in pumping conditions in the course of operation (change in flow, temporary malfunctioning of any station) can lead to an impairment of the normal operating regime of the pipeline: to cavitation at some stations and to pressures exceeding the limiting pressure at others. This means that the throughput capacities of individual segments of the pipeline will be dissimilar. The matching of the operation of the pumping stations (or, which is the same thing, the evening-out of the throughput capacities of pipeline segments) is achieved by regulation. As a result of regulation, the backups before the stations should not be less than the admissible levels ΔH_{ad} and the heads must not exceed the limiting value H_{ad}.

With regulation there is a change in the head at the pumping station and at the same time, the flow. The regulation can be step-by-step (shutting down of the pumping plants) and smooth, accomplished by a change in the frequency of rotation of the engine or pump, by transfer of part of the petroleum flow from the pressure collector into the suction collector and by throttling of the flow.

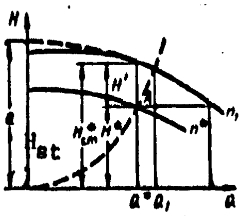


Fig. 5.26. Diagram explaining computation of pumping station regulation.

Regulation by the shutting down of one or more plants is the most economical method. It is used in those cases when it is necessary to decrease the head by a value close to the head developed by at least one pump. In order to establish precisely the necessary heads and flows, step-by-step regulation must be supplemented by smooth regulation.

Regulation by a change in the frequency of engine rotation has not come into wide use since for the time being the existing schemes are still complex, unwieldy and expensive (reference is to electric motors).

The regulation of the change in the frequency of pump rotation is accomplished using special magnetic or hydraulic clutches.

Now we will examine regulation by means of clutches, transfer and throttling. comparing these methods with respect to efficiency.

Assume that as a result of regulation the flow and head are equal to Q^* and H^* (Fig. 5.26), which are the coordinates of the point A, lying on the characteristic curve of the pipeline (the latter is not shown in Fig. 5.26). Then with regulation by throttling the pumping station will develop the head H^*_{st}; the head H' must be extinguished by throttling. The useful power is equal to $Q^*H^*\gamma$, and the expended power — to $Q^*H^*_{st}\gamma$. Hence

$$\eta_{throt} = H^*/H^*_{st}$$

or

$$\eta_{throt} = 1 - H'/H^*_{st}. \quad (5.32)$$

With regulation by transfer (bypassing) the delivery by the pumping station is equal to Q_0; the petroleum flow with the volume $Q_0 - Q^*$ must circulate through the bypass line.

Accordingly, in the case of transfer (bypassing)

$$\eta_{by} = Q^*/Q_0.$$

We will express η_{by} through the values H' and H^*_{st}.

If the equation for the characteristic curve for the pumping station is written in the form $H = a - bQ^2$, then

[CT = st(ation)] $Q^* = \sqrt{\frac{a - H^*_{ст}}{b}}$ and $Q_0 = \sqrt{\frac{a - H^*}{b}}$.

Also taking into account that $H^* = H^*_{st} - H'$, we obtain

$$\eta_{by} = \sqrt{\frac{a - H^*_{ст}}{a - (H^*_{ст} - H')}}$$

or

$$\eta_{by} = \sqrt{1 - \frac{H'}{a - (H^*_{ст} - H')}}. \qquad (5.33)$$

In the case of regulation using a clutch the torque on the engine shaft is transmitted to the pump shaft without a change, that is

$$N_{mot}/n_{mot} = N^*/n^*$$

where N_{mot} and n_{mot} are the power and frequency of rotation of the motor shaft; N^* and n^* are the power and frequency of rotation of the pump shaft.

Accordingly, the efficiency with this regulation method is equal to n^*/n_{mot}.

It is obvious that the efficiency for the entire pumping station is equal to this same value if identical pumping plants are installed in the station.

The value n^*/n_{mot} is the total efficiency ($\eta_{clutch\ total}$); it includes the efficiency of regulation and the efficiency with a shutdown regulating device of the clutch $\eta_{clutch\ max}$ (the maximum efficiency when the driven shaft rotates with the greatest frequency of rotation n_1).

Thus, $\eta_{clutch\ comp} = \eta_{clutch\ max}\eta_{clutch}$, where

$$\eta_{clutch\ max} = n_1/n_{mot}; \quad \eta_{clutch} = n^*/n_1.$$

The maximum efficiency for magnetic clutches is 0.93-0.95, and for hydraulic clutches -- 0.97-0.98. The efficiency of regulation η_{clutch} is determined by the frequency of rotation, that is, by the limits of regulation.

For centrifugal pumps

$$\frac{n^*}{n} = \frac{Q^*}{Q} \quad \text{and} \quad \frac{n^{*2}}{n^2} = \frac{H^*}{H}.$$

From these expressions we have

$$\eta_{clutch} = Q^*/Q_1$$

and

$$H = \frac{H^{*}}{Q^{*2}} Q^{2}. \tag{5.34}$$

Equation (5.34) is a parabolic equation for similar pump operating regimes (in Fig. 5.26 — the dashed line). The flow Q_1, corresponding to the frequency of rotation n_1, is found by the joint solution of equation (5.32) and the equation for the pumping station characteristic curve, which is represented in this same form

$$H = a - bQ^{2}.$$

As a result, we will have

$$Q_1 = \sqrt{\frac{a}{b + \frac{H^{*}}{Q^{*2}}}}.$$

Then, making the replacement

$$Q^{*2} = \frac{a - H^{*}_{\text{ст}}}{b} \qquad \text{and} \qquad H^{*} = H^{*}_{\text{ст}} - H',$$

[CT = st(ation)] we obtain

$$\eta_{\text{м}} = \sqrt{1 - \frac{H'}{a}}. \tag{5.35}$$

[M = clutch]

It follows from formulas (5.33), (5.34) and (5.35) that $\eta_{\text{clutch}} > \eta_{\text{throt}}$ and $\eta_{\text{clutch}} > \eta_{\text{by}}$. However, this does not mean that regulation by clutches is always more advantageous.

In comparing regulation by means of clutches and remaining methods it is necessary to use not the coefficient η_{clutch}, but the total efficiency $\eta_{\text{clutch comp}}$), which takes into account the energy losses in regulation and the constant losses. The latter exist not only during the time of regulation, but also during the operation of the pipeline, when there is no regulation. The lesser the frequency and duration of the period of regulation, the less advantageous is the regulation by means of clutches.

Now we will compare methods of regulation by throttling and transfer (bypassing).

From the formulas

$$\eta_{\text{др}} = \frac{Q^{*}H^{*}}{Q^{*}H^{*}_{\text{ст}}} \qquad \text{and} \qquad \eta_{\text{п}} = \frac{Q^{*}H^{*}}{Q_{0}H^{*}}$$

[π = by; CT = station = st; ДP = throt(tling)]

it follows that if $Q_0H^{*} > Q^{*}H^{*}_{st}$, then $\eta_{\text{by}} < \eta_{\text{throt}}$; accordingly, if the power used by the pump (pumping station) increases with an increase in the flow, regulation by throttling is more advantageous than regulation by bypassing, and vice versa.

The pumps used on main pipelines have sloping Q-H characteristic curves; for them the dependence $N = N(Q)$ is an increasing function. Therefore, on main pipelines regulation by throttling is more advantageous than regulation by bypassing.

5303
CSO: 8344/0811

PUMPING OF HIGHLY VISCOUS AND HIGHLY CONGEALING PETROLEUM

Moscow TRUBO-PROVODNYY TRANSPORT NEFTI I GAZA in Russian 1978 pp 322-374

[Chapter 8 by V. D. Belousov, E. M. Bleykher, A. G. Nemudrov, V. A. Yufin and Ye. I. Yakovlev (also participating in the writing of this chapter were Candidates of Technical Sciences V. A. Kulikov and V. M. Agapkin and Engineers V. M. Mikhaylov and S. N. Chelintsev) from the book TRUBO-PROVODNYY TRANSPORT NEFTI I GAZA edited by V. A. Yufin, Izdatel'stvo "Nedra," 7,700 copies, 408 pages]

[Text] At the present time in our country and abroad there is a considerable production of both highly viscous petroleums and petroleums containing a great quantity of paraffin and accordingly congealing at relatively high temperatures. The pumping of these petroleums by the usual method is irrational because at the ambient temperatures the hydraulic resistance of the pipelines is great. A decrease in the hydraulic resistance of the pipelines is ensured by different methods for increasing the flowability of petroleums: the mixing of viscous and congealing petroleums and petroleum products with those having a low viscosity and their joint pumping, mixing and pumping with water, thermal processing of congealing paraffinic petroleums and petroleum products and their subsequent pumping, pumping of preheated petroleums and petroleum products, use of additives and depressants in the petroleum, etc. In each case the choice of the pumping method must be backed up by technical and economic computations.

#8.1. Rheological Properties of Viscous and Congealing Petroleums

Rheology is a science concerned with study of the flowability of liquid, gaseous and plastic substances, as well as processes associated with residual deformations of solid bodies. The properties of the liquid on which the nature of their flow is dependent are called rheological properties.

In pipeline transport the rheological characteristics of petroleums are evaluated using the following parameters: viscosity (Newtonian), plastic viscosity, effective viscosity, initial (static) shearing stress, limiting dynamic shearing stress and congealing point.

The nature of liquid flow is determined by the the form of the dependence of the frictional forces on the surface of contact of the liquid layers or shearing stress τ on the velocity gradient along the radius or shearing velocity dw/dr. The graphic expression of this dependence is called the liquid flow curve.

For light petroleum products, petroleums with a low paraffin content and paraffinic petroleums at a high temperature a dependence obtained by Newton is correct; he formulated it in the following way: "the resistance which arises due to inadequate slipping of liquid particles, all other conditions being equal, is proportional to the velocity with which the liquid particles move relative to one another," or

$$\tau = -\mu \frac{dw}{dr},$$

where μ is the dynamic viscosity coefficient,

The liquids for which the cited dependence of τ on dw/dr is correct for a constant μ value are known as Newtonian liquids or fluids, and the viscosity of such liquids is called Newtonian.

The behavior of many liquids, especially paraffinic petroleums and petroleum products at temperatures close to their congealing point, does not conform to the Newton law. Such liquids are called non-Newtonian.

There are several classes of non-Newtonian liquids differing with respect to the shape of the flow curve (Fig. 8.1).

The flow curves describe the behavior of liquids: plastic or Bingham (1), pseudoplastic (2), Newtonian (3) and dilatant (4).

Figure 8.1 shows that the flow curves of pseudoplastic, Newtonian and dilatant liquids pass through the origin of coordinates and accordingly their flow begins with the minimum pressure differentials. The flow of Bingham liquids begins only after the creation of a definite stress τ_0. In the case of stresses less than τ_0, such liquids behave as solid bodies, whereas with greater stresses -- as fluids. The rheological equation for a Bingham fluid is derived from a combination of two equations -- the Newton equation (8.1) and the rheological equation for a plastic body ($\tau = \tau_0$) -- and can be written in the following form:

[пл = pl(astic)]

$$\tau = \tau_0 - \eta_{пл} \frac{dw}{dr}.$$

It contains two coefficients: yield stress τ_0 and viscosity η_{pl}, which is called plastic viscosity.

For pseudoplastic and dilatant liquids in a wide range of change in shear velocity in the technical computations it is possible to use a power dependence of stress on shear velocity

$$\tau = -k \left| \frac{dw}{dr} \right|^{n-1} \frac{dw}{dr},$$

where $|dw/dr|$ is the dimensionless shear velocity modulus; n and k are constant coefficients for the particular liquid. The n coefficient is known as the flow index and k is a characteristic of consistency. For a Newtonian liquid $n = 1$ and $k = \mu$; for pseudoplastic liquids $n < 1$ and for dilatant liquids $n > 1$.

The flow of paraffinic petroleums and petroleum products at temperatures close to their congealing point or below can be described by curves 1 or 2 (see Fig. 8.1). In other words, they can be related to plastic or pseudoplastic liquids, and in the case of sufficiently high temperatures -- to Newtonian liquids.

This peculiarity is associated with the high content of paraffin in such petroleums. At a high temperature the main quantity of paraffin present in the petroleum is in a dissolved state. Under these conditions the petroleum is a Newtonian liquid.

With a temperature decrease the paraffin begins to crystallize out of the petroleum. The process of crystallization of paraffin as the first stage includes a change in structure of the liquid phase of the petroleum with a decrease in temperature. The essence of these changes is an ordering in the arrangement of molecules of the dissolved substance due to a decrease in the energy of their thermal motion. As the solution is cooled the capacity of the molecules of the solvent to hold paraffin molecules in a dispersed and isolated state is reduced, that is, the dissolving power of the solvent is reduced. With a further temperature decrease the paraffin concentration in the hydrocarbon medium attains a level at which the solution becomes saturated.

However, in this case the crystallization of paraffin does not begin and there must be some supersaturation of the solution, which creates the possibility of appearance of quite large paraffin crystals with a size greater than the critical size of crystallization centers.

With approach of the cooling temperature to the congealing point t_{con} the number and size of the crystals increase to such an extent that they form a spatial lattice structure through the entire volume of the petroleum and immobilize the liquid phase of the petroleum. The petroleum acquires the properties of pseudoplastic and then plastic fluids.

Some highly parafinnic petroleums (such as those from the Mangyshlakskiye deposits) also have the properties of thixotropic liquids.

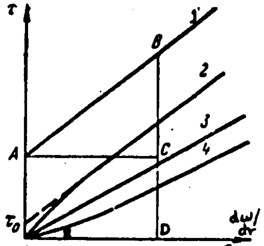


Fig. 8.1. Dependence of shearing stress τ on shearing velocity dw/dr for different liquids.

Thixotropy is a property of bodies as a result of which the ratio of the shearing stress to the deformation rate (shear) temporarily decreases due to the preceding deformations. In other words, thixotropy is the capacity of a liquid, as time passes, to restore the earlier destroyed structure.

Viscosity (Newtonian)

The movement of a flow of a real fluid is always accompanied by an energy loss. This occurs even during the movement of a fluid through pipelines with completely smooth walls. The reason for such losses is not so much friction against the pipeline wall as the internal friction of the fluid (viscosity).

It has been established that for the movement of a plate lying on a layer of fluid it is necessary to impart to it a tangential force which is directly proportional to the area of the plate S, the velocity of its movement w, and is inversely proportional to the thickness of the fluid layer x. This dependence is given more precisely by the Newton equation, in which, as mentioned above, μ is a proportionality factor, known as the dynamic viscosity coefficient.

During the pumping of viscous fluids the influence of viscosity on the hydraulic losses is extremely significant, and therefore in each real case it is necessary to determine viscosity with the greatest possible accuracy.

If in the laboratory there is no possibility of determining the petroleum viscosity-temperature curve, the viscosity at the temperature of interest can be computed using empirical formulas. The following formulas have come into widespread use: American Society of Testing Materials (ASTM)

$$\lg \lg (\nu + 0.8) = a + b \lg T;$$

Vogel-Fulcher-Tamman formula

$$\nu = \nu_{\infty} \exp\left(\frac{b_1}{t - \theta}\right);$$

Reynolds formula

$$\nu = \nu_0 \exp[-u(t - t_0)],$$

where ν is the coefficient of kinematic viscosity at the temperature t (in °C) or T (in K); ν_0 is the coefficient of kinematic viscosity at the temperature t_0; a, b, b_1, ν_{∞}, θ, u are determined using the formulas cited above if viscosity is known at three or two temperatures; in the ASTM formula the dimensionality ν is in centistoke.

Plastic Viscosity

Plastic (Bingham) viscosity characterizes the plastic properties of a fluid.

Usually plastic viscosity is determined from the curve of flow of a fluid using the Bingham equation

$$\eta_{\text{пл}} = \frac{\tau - \tau_0}{\frac{dw}{dr}}.$$

[пл = pl(astic)]

Graphically plastic viscosity can be expressed by the ratio of the segments BC to AC (see Fig. 8.1).

Effective Viscosity

Effective viscosity is the ratio of shearing stress to shear velocity

[∋ = eff]

$$\mu_{\text{э}}=\frac{\tau}{\frac{dw}{dr}}.$$

For Newton fluids this is a constant value, equal to the so-called Newton viscosity, whereas for non-Newton fluids it varies with a change in shear velocity.

Graphically the effective viscosity value can be represented as the ratio of BD to ED (see Fig. 8.1).

Initial Shearing Stress

A number of rheological parameters of paraffinic petroleums vary with time. Outwardly this is manifested in that under a mechanical influence (shaking, mixing) the system acquires mobility and flowability, but during prolonged rest under low-temperature conditions it solidifies and a paraffinic structure is formed whose strength increases with time.

It is necessary to create a definite initial pressure for the shear of paraffinic petroleums. This pressure corresponds to the initial shearing stress τ_{in}, whose value is dependent on the strength of the paraffinic structure forming under the given conditions during the time of presence at rest.

Figure 8.2 shows the characteristic curve of the dependence of the change in τ_{in} on the time of the presence of petroleum at rest.

It must be remembered that the operation of a main pipeline involves inevitable stoppages. It is necessary to take into account the capacity of τ_{in} to increase with time, since during the time of a standstill the τ_{in} value can attain a value at which the pressure developed by the pumping station may prove to be inadequate for moving the petroleum in the open line and then the petroleum pipeline will be "frozen."

Due to the multiplicity of different factors exerting an influence on the initial shearing stress of paraffinic petroleums, there are virtually no formulas for computing τ_{in}. Therefore, in each specific case the τ_{in} value is determined experimentally.

Limiting Dynamic Shearing Stress

One of the rheological parameters characterizing the plastic properties of paraffinic petroleums is the limiting dynamic shearing stress τ_0.

For determining τ_0 it is necessary to plot the petroleum rheological curve; the extension of the linear segment of the rheological curve to the τ axis cuts off on it a segment whose value characterizes the limiting dynamic shearing stress of the particular petroleum (see Fig. 8.1).

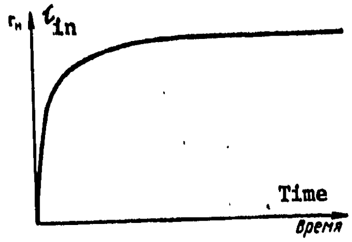


Fig. 2. Dependence of initial shearing stress on time of presence of petroleum at rest.

It should be noted that the temperature prehistory of the petroleum exerts a great influence on the rheological parameters of both Newton and non-Newton petroleums, that is, it is important to known to what temperature influence the petroleum was subjected prior to the determination of any particular rheological parameter.

#8.2. Methods for Pumping Highly Viscous and High Congealing Point Petroleums

Pumping Paraffinic Petroleums with Hydrocarbon Diluents

The introduction of a hydrocarbon diluent into paraffinic petroleum in some cases makes it possible to achieve a considerable improvement in its rheological properties.

Experience in the joint pumping of petroleum, petroleum liquefied gases and gas condensate has been gained in a number of foreign countries.

The pumping of mixtures of various petroleums with liquefied gases, gas benzine and distillates is accomplished in the United States through a pipeline with a diameter of 300 mm and a length of 1,080 km which connects a field in Oklahoma with East Chicago, Indiana.

A highly viscous petroleum with an asphaltic base is pumped through a petroleum pipeline between Lloydminister and Hardisty in Canada (ν_{50} = 2.9 stoke). With a temperature decrease its viscosity increases sharply. Lloydminister petroleum is pumped one-quarter diluted by condensate; in winter the mixture is heated. Despite the fact that a special pipeline of the same length as the main line was constructed for feeding the condensate to the deposit, this transport method was economically more advantageous than other pumping methods.

However, as a rule, the feeding of a light hydrocarbon diluent (benzene, kerosene, diesel fuel) to a petroleum producing area and the necessity for constructing additional open-line structures at the petroleum pipeline terminal involves great expenditures and makes it very expensive to employ this method for improving the rheological properties of paraffinic petroleums. Accordingly, the pumping of paraffinic petroleum with light diluents is frequently more expensive than other transport methods.

As the diluents it is best to use petroleums with a low viscosity. If the field produces paraffinic and low-viscosity petroleums, it is feasible to mix them in structures at the head of the petroleum pipeline and transport them together.

The mixing of highly paraffinic and low-viscosity petroleums makes it possible not only to lower the cost of pumping, but also to make more effective use of the produced petroleums. By mixing different petroleums in different ratios it is possible to obtain petroleum mixtures of a predetermined composition; this makes it possible to stabilize operation of the petroleum pipeline and the installations at petroleum refineries. In addition, the mixing of petroleums sometimes makes possible a considerable improvement in their quality. For example, the mixing of highly paraffinic, but low-sulfur petroleums with low-paraffin but high-sulfur petroleums makes it possible to obtain a petroleum mixture with a moderate paraffin and sulfur content. An example of this is the highly paraffinic petroleum which is pumped in a heated state from the Mangyshlak peninsula to the Kuybyshev area, where some of it is refined and some of it is mixed with low-viscosity sulfur petroleum from the Volga region and fed into the "Druzhba" petroleum pipeline system.

The mechanism of the effect of a hydrocarbon diluent can be explained in the following way. First, with the addition of a diluent to a paraffinic petroleum there is a decrease in the paraffin concentration in the mixture, and also a decrease in the saturation temperature of the solution and the appearance of paraffin crystals. Accordingly, the congealing point of the system is reduced. Second, when using as diluents low-viscosity petroleums containing asphalt-tar substances, the latter, being depressants, impede the formation of a paraffinic structure lattice in the petroleum and thereby reduce the congealing point and the effective viscosity of the mixture. It must be remembered that the solubility of the paraffins to a high degree is dependent on the properties of the diluent. As a rule, the lesser the density and viscosity of the diluent, the more effective is its action. In addition, the lower the temperature of the mixture, the greater is the improvement in the rheological properties of the paraffinic petroleum with addition of a diluent.

The rheological properties of the petroleum mixture are also influenced by the method of mixing of the petroleums. In order to obtain a homogeneous mixture the mixing of the petroleums must occur at a temperature 3-5° higher than the congealing point of the viscous component. Under unfavorable mixing conditions the effectiveness of the diluent is reduced to a considerable degree and there can even be a separation of the petroleums.

Pumping of Highly Congealing Paraffinic Petroleums With Additives for Stimulating Flow

In the pumping of petroleums and their refined products through pipelines at the present time use is made of petroleum-soluble chemical additives having different purposes. For the purpose of reducing head losses in friction during a turbulent flow regime of low-viscosity petroleums they are supplemented by some quantity of polymer having long and strong molecules. Such polymer additives retard the development of eddies in the flow when there are great discharges. As a result, the throughput capacity of the pipeline is increased. In a laminar regime these polymer additives do not lessen the losses in friction.

The use of additives capable of improving the pumpability of highly congealing paraffinic petroleums in the field of low temperatures is of great interest.

In the Soviet Union and abroad research is being carried on in selecting additives which, interacting with petroleum paraffins, could improve its rheological characteristics (static and limiting dynamic shearing stress, plastic, that is, Bingham viscosity). The use of such additives for stimulating flow is a further development of the principle of use of additives which long ago were employed for reducing the congealing points of oils.

Investigations indicate the pour-point depressants for oils do not exert an influence on the low-temperature properties of paraffinic petroleums; this is attributable to the extremely complex physicochemical composition of the latter.

At the present time there are already effective flow stimulators whose addition to highly congealing paraffinic petroleums imparts to their flow a Newtonian character at relatively low temperatures.

As the basis for stimulators controlling the process of crystallization of paraffins in the petroleum flow it is possible to employ such high-molecular compounds as polymethacrylates, polyisobutylene, ethylene polymers, polypropylenes, etc.

Ash-free ethylene-propylene polymer additives are now being produced abroad. Examples are additives designated Paramins-20, -25, -70 for medium distillate fuels, and also additives of the ECA type for heavy fuels and petroleums.

With respect to external form, these additives constitute a paraffin-like mass acquiring mobility only at 50-60°C.

The effectiveness of use of these additives is dependent on the physicochemical properties of the paraffinic petroleums or their mixtures with low-viscosity petroleums, and especially on their content of paraffins and natural surface-active substances -- tars and asphaltenes.

The necessary concentration of flow stimulator in the petroleum is dependent on the purpose and the specific conditions of its use. For example, for successful pumping of petroleum along a main pipeline it is sufficient to introduce an additive in a quantity 0.1-0.2%. In the case of transport of a mixture of high-congealing petroleum with low-viscosity petroleums this concentration can be reduced.

In the storage of petroleum containing paraffin a concentration of additive up to 0.03% to a considerable degree lessens paraffin deposition on equipment and can eliminate expensive manual cleaning of the tanks in petroleum tanks (tank farms), tankers, etc. At the present time there is no uniform opinion concerning the mechanism of the effect of both depressor additives to oils and flow stimulators.

It has been established that flow stimulators do not decrease the quantity of paraffin precipitated from the petroleum and do not change the temperature of onset of its mass crystallization.

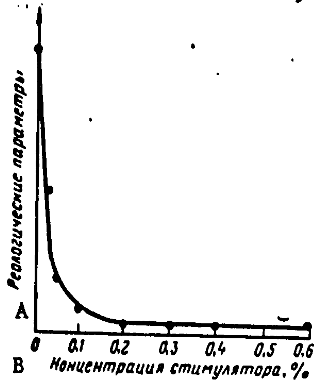


Fig. 8.3. Graph of dependence of rheological parameters on concentration of additive at constant temperature.

KEY:

A. Rheological parameters
B. Stimulator concentration

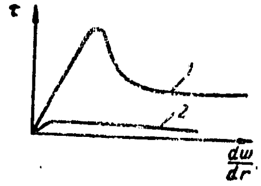


Fig. 8.4. Graph of dependence $\tau = \tau(dw/dr)$ with constant rate of deformation ε = const: 1) for initial petroleum containing paraffin at congealing temperature; 2) for petroleum processed with flow stimulator at this same temperature.

The first fractions of the additive are the most effective (Fig. 8.3). In this respect the action of flow stimulators is similar to the action of depressants for oils.

The possible mechanism of the action of additives for high-paraffin oils can be judged from the change in the deformation-strength properties of the structure of paraffin in dependence on the conditions of its formation (in the presence of additives or without them). A study of the kinetics of development of shearing stresses with a constant rate of deformation in disperse systems makes possible a deep investigation of the mechanism of appearance and nature of the structure. Any physicochemical processing of the system acting on the conditions of appearance of particles and also the number of contacts between them is manifested in a change in the course of the deformation process.

Figure 8.4 shows a diagram characterizing the development of flow in a high-congealing petroleum first heated to 50°C, that is, to the initial temperature in the case of "hot" pumping. The process of destruction of the paraffin structure includes not only the destruction of the crystal lattice proper, but also the setting free of the liquid medium immobilized within the structural lattice, a change in orientation of anisodiametric particles and other mechanisms for reducing resistance to deformation. The descending branch of curve 1 reflects completion of the complex process of change in the structure and transition to a steady-state flow regime.

On the basis of the nature of destruction of the structure of paraffin, high-congealing petroleums can be classified as elasticoplastic bodies. This is attributable to the fact that with cooling of the petroleum the paraffin crystals which separate out, joining with one another, form a structure lattice -- a gel. An increase in the mechanical strength and a decrease in plasticity of petroleums containing paraffin with a decrease in temperature is associated with the quantity of the solid phase crystallizing out and the presence of polydisperse crystals of paraffins expended on the strengthening of the phase contacts.

Asphalt-tar substances are of great importance in forming the paraffin gel; they can envelope the precipitating paraffin crystals, not allowing them to create a more solid crystalline lattice. In the presence of flow stimulators in a quantity of about 0.2% there is a radical change in the picture of development of the flow in petroleum containing paraffin. Here a plastic flow arises with stresses considerably less than in the initial petroleum.

A decrease in strength and an increase in plasticity, as capabilities of bodies for flow, that is, leading to extremely great residual deformations without apparent rupture under the influence of stresses exceeding the yield stress, must be attributed to the formation of complexes of the stimulator-paraffin molecule, creating a spatial obstacle to the formation of crystalline gel contacts and decreasing their ordering.

Considering the mechanism which is involved in the action of additives, they must be introduced into the petroleum at temperatures at which its paraffins are dissolved and it constitutes a true solution. The methods for introducing flow stimulators can be different. The principal condition is ensuring a high degree of mixing of the stimulator and the petroleum. This can be achieved by introducing the additive into the flow of heated petroleum in the pipeline through a nozzle. In order to ensure normal pumping of petroleum containing paraffin in the case of an isothermic regime in a pipeline of considerable length it is sufficient to introduce the additive only once, for example, at the head structures of a pipeline.

The experience in the use of additives improving the flow of petroleums with paraffin under industrial conditions during the pumping of African petroleums through the European pipelines Rotterdam - Rhine (D = 400-900 mm, L = 236 km), Ile de France (D = 500 mm, L = 150 km), Finnart-Grangemouth (Great Britain), and also use of the additive ECA-4242 during the starting-up of the pipeline Mangyshlak-Kuybyshev shows that using them it is possible to facilitate the startup of a pipeline and the pumping of petroleum in an isothermic regime at temperatures lower than its solidification point, and also reduce or completely exclude the deposition of paraffin in pipelines, tanks, etc.

Thus, this method for improving the rheological properties of petroleums with paraffin makes it possible to increase the throughput capacity of a pipeline and solve a number of specific problems in the transportation of such petroleums without additional capital investments on broadening the main equipment or on strengthening thermal insulation.

Additives of the type of flow stimulators can considerably simplify the operation of "hot" pipelines, especially in nonstationary operating regimes. Such regimes must include their starting-up after construction when the ground around the pipeline is not heated, reaching the planned throughput capacity under conditions of an increase in petroleum production in the fields, repeated startups after stoppages of pumping, etc.

Pumping of Thermally Processed Petroleums

With the heating of petroleum to a definite temperature with subsequent cooling the rheological parameters of the petroleum experience considerable changes. In some cases the values τ_0, τ_{in} and μ_e increase; in other cases they decrease. The thermal processing of petroleum for changing its rheological parameters is called the thermal processing of petroleum. [$\mu_e = \mu_{ef(fective)}$]

Thermal processing is one of the methods for improving the rheological properties of the petroleum for the purpose of increasing the effectiveness of pipeline transport of petroleums containing paraffin and petroleum products. Thermal processing makes it possible to obtain petroleum with a weak paraffin structure not capable of holding the entire volume of petroleum in its lattice elements.

The thermal processing process consists of the heating of petroleum to some temperature with subsequent cooling to its pumping temperature. With the heating of petroleum containing paraffin there is a total or partial dissolving of the paraffins present in the petroleum. With the cooling of the petroleum the paraffin is precipitated from solution in the form of crystals, the number and form of which are dependent on the temperature of the preliminary heating and on the cooling conditions.

In our country the problems involved in the thermal processing of petroleums with paraffin and petroleum products were already investigated in the 1930's. For example, we know of the studies of Zelinskiy and Sakhanov, in which the authors obtained positive results with the thermal processing of mazuts. The thermal processing of petroleum in the Romashkinskoye deposit made it possible to reduce the viscosity of petroleum by a factor of more than 2 and decrease the solidification point of petroleum to 20°C.

Investigations made it possible to detect a number of regularities associated with the thermal processing of petroleums containing paraffin:
1) the thermal processing of highly congealing paraffinic petroleums with a heating temperature 40-50°C (somewhat below the melting point of paraffins) greatly worsens the rheological properties of the petroleum;
2) for paraffinic petroleums there is a definite heating temperature at which the thermal processing effect is maximum. This temperature is always higher than the melting point of paraffins present in the petroleum;
3) the greater is the ratio of the content of paraffins to the content of asphalt-tar substances, the lesser is the thermal processing effect;
4) the conditions of petroleum cooling exert a great influence on the properties of thermally processed petroleums.

Accordingly, by changing the conditions for cooling of the petroleum and the temperature of the preliminary heating, it is possible to exert a significant influence on the strength of the paraffin lattice in the petroleum, that is, it is possible to select such a thermal processing regime in which its effect will be maximum.

The dependence of the rheological parameters of thermally processed high-paraffin petroleums on the rate of their cooling after heating is attributable to the conditions for crystallization of the paraffin present in the petroleum.

The process of crystallization (size, number and shape of the paraffin crystals in the petroleum) is influenced by the ratio of two rates: rate of appearance of centers of crystallization of paraffin and rate of increase of already precipitated crystals. If the rate of appearance of centers of crystallization is greater than the rate of crystal growth, a system is obtained with a great number of small crystals; otherwise, in the system there is formation of large unconsolidated crystals and the strength of such a structure is considerably less than that of a fine-crystal structure. For example, with a rate of cooling of thermally processed Mangyshlak petroleum equal to 10°C/hour, a favorable ratio of the rate of appearance of the centers of crystallization and the rate of increase of the forming paraffin crystals is created. Most of the paraffin goes to the formation of a small number of large crystals forming unconsolidated clusters.

It was noted earlier that the temperature of preliminary heating of the petroleum exerts a great influence on the crystallization of paraffin during the thermal processing of petroleums.

Figure 8.5 shows the dependence of petroleum viscosity on the temperature of thermal processing. Figure 8.5 shows that with an increase in the temperature of petroleum heating its viscosity at first increases, and then decreases, becoming minimum with a definite temperature of thermal processing. With a further increase in heating temperature the viscosity of the petroleum again increases.

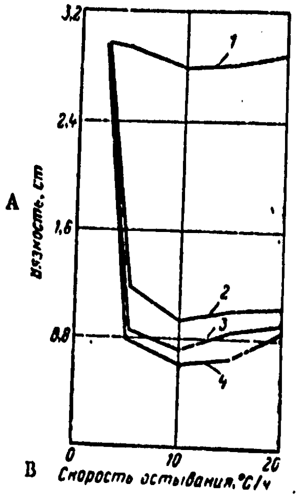


Fig. 8.5. Dependence of petroleum viscosity on thermal processing parameters: 1, 2, 3 and 4 -- heating temperature of 60, 80, 100 and 90°C respectively.

KEY:

- A. Viscosity, cm
- B. Cooling rate, °C/hour

These peculiarities of the influence of the temperature of thermal processing on rheological parameters can be explained in the following way. At the surface of the paraffin crystals there is adsorption of asphalt-tar substances present in the petroleum. With the heating of the petroleum to a low temperature some of the paraffin crystals are dissolved and the asphalt-tar substances released are adsorbed at the surface of the undissolved paraffin crystals. Subsequent cooling leads to the formation from the precipitating paraffin of a solid fine-crystal structure increasing the effective viscosity and solidification point of the petroleum. With an increase in the heating temperature there is an increase in the quantity of paraffin dissolved in the liquid phase of the petroleum, and in addition, the remaining crystals of paraffin with a high melting point adsorb an increasingly lesser quantity of asphalt-tar substances. During the cooling of the petroleum, due to the adequate quantity of the unadsorbed asphalt-tar substances, being surface-active substances, which favor dendritic crystallization, there is formation of a small number of large crystals of paraffin.

With heating to such a temperature when all the paraffin is dissolved, the most favorable conditions are created for the dendritic crystallization of paraffin with formation of the least solid structure.

With a still greater temperature of the thermal processing of the petroleum, the asphalt-tar substances present in it, which exert a favorable influence on the formation of a coarse-grained structure, are irreversibly destroyed, thereby reducing the thermal processing effect.

The rheological parameters of the petroleum t_{sol} (solidification or congealing point), τ_{in}, μ_e and τ_0, improving as a result of thermal processing, with time assume their initial values. The time required for restoration of the rheological parameters of the petroleum must be taken into account in the operation of pipelines pumping thermally processed petroleum.

Thus, if the thermal processing of high-paraffin petroleum gives good results and thermally processed petroleum has a long time of restoration of rheological properties, such a petroleum after thermal processing can be pumped as an ordinary low-viscosity fluid.

Hydraulic Transport of High-Paraffin and High-Viscosity Petroleums and Petroleum Products

A substantial improvement in the pumpability of viscous or high-congealing petroleums can be achieved by adding water to the petroleum flow.

With the joint pumping of water and petroleum the flow can be imparted different structures, such as coaxial, emulsion, separate, etc.

A coaxial structure is obtained when the water forms around the petroleum, along the inner surface of the pipe, in a concentric ring. In order for the petroleum not to float in the water and not stick to the upper surface of the pipe, a groove is made in the pipe which imparts a rotational motion to the flow. The water, being the heavier fluid, is propelled toward the pipe wall.

In an experimental pipeline with a diameter of 200 mm and a length of 40 km the throughput capacity was increased by a factor of 12.

In the case of hydraulic transport the flow increases with lesser expenditures of energy in comparison with the pumping of high-viscosity petroleum alone. The separation of the water and petroleum is accomplished at the final point in the pipeline by one of the well-known methods (standing, thermal method, etc.).

Hydraulic transport of highly viscous petroleums through pipelines with an internal groove has not come into wide use for the following reasons: 1) with the stoppage of pumping there will be a stratification of the water and petroleum. The latter sticks to the upper generatrix of the pipe and

packs the spiral, as a result of which there is a marked decrease in the effectiveness of hydraulic transport;
2) this method can only be used when pumping petroleum through a pipeline without intermediate pumping stations, since with the entry of water and petroleum into the pump a stable emulsion is formed which beyond the pumping station no longer separates and impedes the formation of the water ring along the pipe walls;
3) the complexity in producing the spiraling on the inner surface of the pipe.

With the formation of the pentroleum in water (p/w) emulsion there is a considerable decrease in system viscosity. Such a system consists of petroleum particles surrounded by a film of water and there is virtually no contact between the petroleum and the pipe surface. As a result, a water ring is formed along the entire internal surface of the pipe and the petroleum slides along it.

With the transport of water-petroleum emulsions through pipelines with some pumping rates, temperatures and water concentrations in petroleum there is formation of an emulsion of water in petroleum (w/p). The viscosity of such emulsions can be greater than the viscosity of pure petroleum.

In order to improve the conditions for formation and increase in the stability of emulsions of the type p/w different surface-active substances (SAS) are added to the water-petroleum mixture.

A surface-active substance, dissolved in water, hydrolyzes the pipeline walls, considerably decreases the forces of attachment of the petroleum to the walls and creates conditions for the formation of a disperse system of the p/w type. All this leads to a marked decrease in hydraulic resistance during pumping.

The technology of joint pumping of petroleum with a water solution of SAS is directed to the creation of a stable system of the p/w type in the pipeline and the prevention of a phase inversion, that is, a transition of the system from direct to reverse (w/p).

The stability of a system of the p/w system is influenced to a considerable degree by the form and concentration of the SAS, temperature, intensity of mixing and relationship of phases.

The SAS used in preparing water-petroleum emulsions must correspond to the following principal requirements: emulsify well (that is, create an envelope on the surface of the petroleum globules, mechanically sufficiently strong and capable of being easily restored when it breaks), must be nontoxic and not cause corrosion of the pipeline and tanks.

One of the SAS best corresponding to the above-mentioned requirements is NP-1 sulfanol.

An increase in the concentration of water in the mixture improves the stability of the emulsion but reduces the economic indices for this particular type of hydraulic transport. It has been established by experimental investigation that the minimum water content should be about 30% of the total volume of the mixture to be transported.

Pumping of Heated Petroleums and Petroleum Products

The pumping of highly viscous and high-congealing petroleums and petroleum products with heating is the most commonly employed method for the pipeline transport of these products. The pipelines through which heated petroleums are pumped are called "hot" pipelines.

The petroleum can be heated at stations or along the entire pipeline route.

In the first, most commonly used variant of "hot" pipelines there are three types of stations installed on the pipeline: pumping-heating stations (PHS), at which the product is both heated and pumped, heating stations (HS) at which only heating takes place, and pumping stations (PS) at which only the pumping of the product occurs. The heating of the product occurs both in tanks (at the head station), equipped with spiral or sectional steam heaters, and in heaters (at all stations), which can be steam operated or fired (furnaces).

In the second variant a heating satellite pipeline is laid alongside the pipeline through which the heat carrier (hot water or steam) is pumped. This same variant is possible using electric power.

A reduction in thermal losses in "hot" pipelines can be achieved by covering the pipes with heat insulation.

***

#8.3. Initial Data for Thermal Computation of "Hot" Petroleum Pipelines

When carrying out thermal computations of a petroleum pipeline it is necessary to have the following initial data: physical and thermophysical properties of the petroleum, thermal insulation, the ground (density, rheological characteristics, specific heat capacity, thermal conductivity, thermal diffusivity, moisture content), climatic data (mean monthly temperatures of the air and ground at the depth at which the pipeline is laid in a natural thermal state, level of solar radiation, depth of snow cover).

Data on temperature of the air and ground, snow cover depth and the level of solar radiation are taken from the climatic handbooks for the region through which the pipeline is to be laid.

The physical and thermophysical characteristics of the petroleum, thermal insulation, ground and others are determined experimentally or can be computed using the corresponding empirical formulas.

Specific heat capacity of petroleum [in kJ/kg·°C)] is determined using the Crego formula

$$c_{\text{м}}=\frac{1}{\sqrt{\rho_4^{15}}}\left(1,687+3,30\cdot 10^{-3}\, t\right),$$

where ρ_4^{15} is the relative density of petroleum relative to water at t = 15°C.

The specific heat capacity of petroleums and petroleum products falls in the range from 1.6 to 2.5 kJ/(kg·°C) and for approximate computations it can be assumed equal to 2.1 kJ/(kg·°C). The specific heat capacity of hydrocarbon steels and paraffin deposits is equal to 0.5 and 2.9 kJ/(kg·°C).

The thermal conductivity coefficient for petroleums λ, depending on the temperature in the range of change in pumping parameters, varies in the range from 0.1 to 0.16 W/(m·°C).

For refined computations use is made of the Crego-Smith formula

$$\lambda=\frac{0,137}{\rho^{15}}\left(1-0,54\cdot 10^{-3}\, t\right).$$

The mean values of the thermal conductivity coefficients for steel and paraffin are 46-50 and 2.5 W/(m·°C) respectively.

The thermal diffusivity coefficient is related to the thermal conductivity coefficient by the expression

$$a=\frac{\lambda}{c_{\text{м}}\rho}.$$

The total coefficient of heat transfer k from petroleum to the surrounding medium is dependent on the regime of movement of the fluid and its thermophysical properties, thermal resistance to heat transfer into the surrounding medium through the anticorrosion heat insulation, pipe wall, paraffin deposits and others:

$$\frac{1}{kD_0}=\frac{1}{\alpha_1 D_1}+\sum_{j=1}^{N}\frac{1}{2\lambda_j}\ln\frac{D_j}{D_{j-1}}+\frac{1}{\alpha_2 D_N}. \tag{8.1}$$

where α_1 is the internal heat transfer coefficient (from the petroleum to the internal surface of the deposits or pipe); λ_j is the thermal conductivity coefficient of the j-th cylindrical layer (deposits, pipe metal, insulation, etc.); D_0 and D_N are the internal and external diameters of the pipeline respectively; D_j is the external diameter of the j-th cylindrical layer; α_2 is the coefficient of heat transfer from the outer surface of the pipeline into the surrounding medium.

For pipelines with a great diameter ($D_N > 500$ mm) the k value can be determined approximately using the formula

$$\frac{1}{k}=\frac{1}{\alpha_1}+\sum_{j=1}^{N}\frac{\delta_j}{\lambda_j}+\frac{1}{\alpha_2}, \tag{8.1a}$$

where δ_j is the thickness of the j-th cylindrical layer.

The coefficient of heat transfer from the outer surface of an underground pipeline into the surrounding medium characterizes the thermal resistance of the ground and heat transfer from its surface into the atmosphere

[Γp = ground]

$$\alpha_2=\frac{2\lambda_{\text{гр}}\text{Bi}_2}{D_N\,(1+\alpha_0\text{Bi}_2)},$$

where

$$\text{Bi}_2=\alpha_{\text{в}}c/\lambda_{\text{гр}};\; c=\sqrt{h_0^2-(0{,}5D_N)^2};$$

$$\alpha_0=\ln\left[2h_0/D_N+\sqrt{(2h_0/D_N)^2-1}\right];$$

λ_{gr} is the coefficient of thermal conductivity of the ground; α_B is the coefficient of heat transfer from the ground surface into the atmosphere; h_0 is the depth of laying of the pipeline to its axis.

Under conditions of a high intensity of heat transfer from the ground surface (high Bi_2 values), and also with a considerable depth of pipeline placement, when $(h_0/D_N) > 2$, the α_2 coefficient can be computed using the F. Forchheimer formula

$$\alpha_2=\frac{2\lambda_{\text{гр}}}{D_N\alpha_0}.$$

The coefficient of heat transfer from the petroleum to the pipe wall is the ratio of the heat flux in the particular pipe section to the difference between the mean temperature of the petroleum and the temperature of the internal pipe wall.

For determining the coefficient of heat transfer from the moving petroleum (petroleum product) use is made of the M. A. Mikheyev criterial equations:

in the case of a laminar regime ($Re_f < 2000$)

$$Nu = 0{,}17 Re_f^{0{,}33} Pr_f^{0{,}43} Gr_f^{0{,}1} \left(\frac{Pr_f}{Pr_w}\right)^{0{,}25};$$

in the case of a turbulent regime ($Re_f \geqslant 10^4$)

$$Nu = 0{,}021 Re_f^{0{,}8} Pr_f^{0{,}43} \left(\frac{Pr_f}{Pr_w}\right)^{0{,}25}.$$

In the region $2000 < Re_f < 10^4$ the heat transfer coefficient is found by interpolation.

In the cited formulas the parameters with the subscript f are determined with the mean integral temperature of petroleum, whereas the parameters with the w subscript are determined with the mean integral temperature of the internal wall of the pipe. The mean integral temperature of the internal wall of the pipe is related to the mean integral temperature of the petroleum by the expression

[cp = mean]

$$t_{cp\,w} = t_{cp\,f} - \frac{(t - t_{cp\,f})\frac{1}{\alpha_1}}{\frac{1}{\alpha_1} + \sum_{j=1}^{N} \frac{R_0}{\lambda_j} \ln \frac{R_j}{R_{j-1}} + \frac{D_0}{\alpha_2 D_N}}.$$

The Reynolds (Re), Prandtl (Pr), Grashof (Gr) and Nusselt (Nu) parameters are equal, respectively, to:

$$Re = \frac{w D_0}{\nu}; \quad Pr = \frac{\nu c_H}{\lambda} \rho;$$

[H = pet(roleum)]

$$Gr = \frac{D_0^3 (t_{cp\,f} - t_{cp\,w})}{\nu^2} g \beta_H;$$

$$Nu = \frac{\alpha_1 D_0}{\lambda};$$

where ν is the coefficient of kinematic viscosity of petroleum; w is the mean velocity of petroleum flow in the section; g is the acceleration of free falling; β_{pet} is the coefficient of volume expansion of petroleum.

The coefficient of heat transfer from the petroleum to the pipe wall in a nonoperating pipeline (α_1^{stop}) is determined using the empirical formula $Nu^{stop} = c(Gr\,Pr_f)^n$, in which the coefficients c and n are taken from the data in Table 8.1.

Table 8.1

Values of Coefficients c and n

$Gr \cdot Pr$	c	n
10^{-3}—$5 \cdot 10^3$	1,18	0,13
$5 \cdot 10^3$—$2 \cdot 10^7$	0,54	0,25
$2 \cdot 10^7$—10^{13}	0,14	0,33

The coefficient of heat transfer from the ground surface is determined as the ratio of the heat flux directed into the atmosphere to the difference in the mean temperature of the ground and air. The value of the heat transfer coefficient includes values of the coefficients of convective ($\alpha_{B,\text{con}}$) and radiation heat exchange ($\alpha_{B,\text{ rad}}$): $\alpha_B = \alpha_{B,\text{con}} + \alpha_{B,\text{rad}}$.

The convective component $\alpha_{B,\text{con}}$ [in W/(m^2·°C)] is determined using the formula

$$\alpha_{B,\text{con}} = 6,15+4.18v,$$

where v is wind velocity, m/sec.

The value of the coefficient $\alpha_{B,\text{con}}$ falls in the range from 10 to 18 W/(m^2·°C) and for approximate computations is assumed to be equal to 11 W/(m^2·°C).

The value of the coefficient $\alpha_{B,\text{rad}}$ is determined using the formula

[П = surf]

$$\alpha_{\text{п.р}} = \frac{\varepsilon_1 c_s}{t_{\text{п.г}} - t_{\text{в}}} \left[\left(\frac{t_{\text{п.г}} + 273}{100} \right)^4 - \left(\frac{t_{\text{в}} + 273}{100} \right)^4 \right], \tag{8.2}$$

where $t_{\text{surf gr}}$ is the temperature of the ground surface, °C; ε_1 is the degree of blackness of the surface; c_s is the Planck constant [c_s = 5.68 W/(m^2·K^4)].

The radiation component $\alpha_{B,\text{rad}}$ is 70-80% less than $\alpha_{B,\text{con}}$ and on the average its value is equal to 4.0 W/(m^2·°C).

The coefficient of heat transfer from the pipe wall into the atmosphere when the pipeline is above the ground is related to the temperature difference between the outer surface of the pipes and the air. Its value is determined by the sum $\alpha_{B,\text{ con}} + \alpha_{B,\text{ rad}}$.

The convective component $\alpha_{B,\text{con}}$ when Re $>10^3$ is found using the criterial formula

$$\text{Nu}_{\text{в.к}} = 0,25\text{Re}_{\text{в}}^{0,6}\text{Pr}_{\text{в}}^{0,38} \left(\frac{\text{Pr}_{\text{в}}}{\text{Pr}_N} \right)^{0,25}, \tag{8.3}$$

[B, K = B, con] where the subscripts B and N mean that the corresponding dimensionless parameters are computed with the temperature of the outer air and the external surface of the pipeline. The latter is related to air temperature by the expression

$$t_N = t_{\text{в}} - \frac{(t_{\text{в}} - t_0) \left(\frac{1}{\alpha_1} + \sum_{j=1}^{N} \frac{R_0}{\lambda_j} \ln \frac{R_j}{R_{j-1}} \right)}{\frac{1}{\alpha_1} + \sum_{j=1}^{N} \frac{R_0}{\lambda_j} \ln \frac{R_j}{R_{j-1}} + \frac{1}{\alpha_{\text{в}}} \frac{R_0}{R_N}}$$

With an error not greater than 3% in the range of temperature change $-40 \leqslant t \leqslant 40$°C it can be assumed that:

$$\left(\frac{\mathrm{Pr}_{\text{в}}}{\mathrm{Pr}_N}\right)^{0,25} \approx 1,\ \mathrm{Pr}_{\text{в}} \approx 0{,}72,$$

simplifying in the corresponding way the form of the dependence (8.3)

[B,K = B,con]

$$\mathrm{Nu}_{\text{в.к}} = \frac{0{,}221\mathrm{Re}_{\text{в}}^{0,6}}{\nu_{\text{в}}^{0,6}}.$$

The coefficient $\alpha_{B,con}$ can also be determined using Table 8.2.

Table 8.2

The Values $\alpha_{B,con}$ [W/m$^2\cdot$°C)] for Pipelines With Forced Movement of the Surrounding Air

Скорость ветра, м/с 1	2 Наружный диаметр трубопровода, м						
	0,3	0,4	0,5	0,6	0,8	1,0	1,5
5	16,41	14,61	13,50	12,52	11,13	10,21	8,66
10	24,76	22,15	20,43	19,02	16,93	15,48	12,00
15	31,61	28,24	26,04	24,18	21,51	19,72	16,70
20	37,46	33,45	30,91	28,76	25,63	23,43	19,89

KEY:

1. Wind velocity, m/sec
2. External diameter of pipeline, m

In the case of a total calm ($v_B \to 0$) [Here, as elsewhere, B = air] and for pipelines protected against exposure to the wind, the coefficient of heat transfer by convection is determined using the free convection formula

$$\mathrm{Nu}_{\text{в.к}} = m\,(\mathrm{Gr}_{\text{в}}\mathrm{Pr}_{\text{в}})^{k}. \tag{8.3a}$$

For the conditions of main pipelines the complex $\mathrm{Gr}_B\mathrm{Pr}_B > 10^5$.

In this case the constant coefficients m and k are equal to m = 0.53 and k = 0.25.

Expanding the parameters $\mathrm{Nu}_{B,con}$, Gr_B and Pr_B, the coefficient $\alpha_{B,con}$ is represented in the form $\alpha_{B,con} = a(t_N - t_B)^{0.25}$,

$$\alpha_{\text{в.к}} = a\,(t_N - t_{\text{в}})^{0,25},$$

where

$$a = 0{,}53\left(\frac{\beta_{\text{г}}\rho_{\text{н}} g c_{\text{н}} \lambda_{\text{н}}}{2\nu_{\text{в}}/l_N}\right).$$

Table 8.3

Values of a Coefficient

D_N, m	a, $W/(m^2 \cdot {}^\circ C)^{1.25}$
0.05	2.25
0.1	2.09
0.2	2.01

Table 8.4

Physical Properties of Water on Saturation Curve

t, °C	$\rho_в$, кг/м³ 1	c_p, кДж/кг·°C 2	$\lambda_в$, Вт/(м·°C) 3	$a_в$, м²/ч 4	$\mu \cdot 10^6$, Нс/м² 5	$\nu_в \cdot 10^6$, м²/с 6	$Pr_в$ 7
0	999,87	4,216	0,559	13,3	1788	1,788	13,50
10	999,73	4,191	0,579	13,8	1305	1,306	9,45
20	998,23	4,183	0,598	14,3	1004	1,006	7,02

KEY:
1. kg/m^3
2. kJ/kg
3. $W/(m \cdot {}^\circ C)$
4. m^2/hour
5. Ns/m^2
6. m^2/sec
7. Pr_B

The coefficient a for approximate computations in a broad range of temperature change ($-40 \leqslant t \leqslant 40$) can be considered constant and be taken from the data in Table 8.3.

The coefficient of heat transfer by radiation is determined using formula (8.2), in which it is assumed that $t_{surf\ gr} = t_N$. The value $\alpha_{B,rad}$ in the case of forced convection is 3-4 times less than $\alpha_{B,con}$ and in this case it can be assumed approximately that $\alpha_B \approx \alpha_{B,con}$. However, in the case of free convection, which is possible during winter in the northern regions, the values $\alpha_{B,con}$ and $\alpha_{B,rad}$ are comparable and in the determination of α_B it is necessary to take into account the influence of radiation. It is admissible to assume that $\alpha_{B,rad}$ falls in the range 2-5 $W/(m^2 \cdot {}^\circ C)$.

The coefficient of heat transfer of underwater pipelines is the ratio of the heat losses of the pipeline averaged along the perimeter and the difference in the temperature of the pipe wall and the temperature of the surrounding water. Its value is found using formulas (8.3) and (8.3a), in which the corresponding thermophysical characteristics are taken for water using data from Table 8.4.

Table 8.5

Some Determined Values of Thermal Conductivity Coefficients of Ground in Thawed and Frozen States

Грунт 1	Влажность, % от массы сухого вещества 2	3 Коэффициент теплопроводности грунта, Вт/(м·°С)	
		4 талого	5 мерзлого
6 Песок крупный (1—2 мм):			
7 плотный	10	1,74/1,856	1,9836/1,3456
»	18	2,784	3,1088
8 рыхлый	10	1,276	1,4036
»	18	1,972	2,6796
9 Песок мелкий и средний (0,25—1 мм):			
7 плотный	10	2,436	2,5056
»	18	3,596	3,8048
8 рыхлый	10	1,74	1,9952
»	18	3,364	3,5032
10 Песок сухой различной крупности	1	0,2668—0,4756	0,2668—0,3828
11 Супеси, суглинки, пылеватые грунты, талая земля	15—20	1,392—1,624	1,74—2,32
12 Глина	20—5	0,928—1,392	1,392—1,74
13 Вода	—	—	—
14 Лед	—	0,6728	—
15 Снег неуплотненный	—	—	0,2668
16 Снег уплотненный	—	—	0,6728
17 Торф спрессованный и насыщенный водой	—	—	0,8004
18 Торф неспрессованный	270—235	0,3596—0,5336	0,3712—0,6612

KEY:
1. Ground
2. Moisture content, % of mass of dry matter
3. Ground thermal conductivity coefficient, W/(m·°C)
4. Thawed
5. Frozen
6. Coarse sand (1-2 mm)
7. Dense
8. Unconsolidated
9. Fine and medium sand (0.25-1 mm)
10. Dry sand of different granularity
11. Sandy loam, clayey loam, pulverized soil, thawed ground
12. Clay
13. Water
14. Ice
15. Uncompacted snow
16. Compacted snow
17. Pressed peat, water saturated
18. Unpressed peat

It is rather difficult to ascertain the thermophysical characteristics of the ground because their values vary both in the depth of the ground mass and along the length of the pipeline trajectory. In addition, the

Table 8.6

Values of Thermal Conductivity Coefficient for Different Types of Thermal Insulation

Изоляционный материал 1	Плотность, кг/м³ 2	Коэффициент теплопроводности, Вт/(м·°С) 3
4 Пенополиуретан	—	0,018—0,022
5 Пенополистирол	—	0,030
6 Стекловолокно	—	0,033
7 Пеностекло	—	0,051
8 Пенополистирол ПСБ-С (ГОСТ 15588—70)	20—40	$0{,}036 + 1{,}36 \cdot 10^{-4} t$
9 Пенополиуретан ППУ-3с (ТУ В-56-70)	50—60	$0{,}0384 + 1{,}42 \cdot 10^{-4} t$
10 Пенополиуретан ППУ-3н (ТУ ВНИИСС 67-66)	50—60	$0{,}0386 + 1{,}3 \cdot 10^{-4} t$
11 Пенополиуретан ППУ-307 (ТУ В-143-69)	30—40	$0{,}0371 + 1{,}36 \cdot 10^{-4} t$
12 Пенополиуретан ППУ-308н	50—70	$0{,}0384 + 1{,}42 \cdot 10^{-4} t$
13 Фенoформальдегидный пенопласт ФРП-1 (ВТУ ВНИИСС 56-65)	40—60	$0{,}0372 + 1{,}36 \cdot 10^{-4} t$

14 Примечание. t—температура, °С.

KEY:

1. Insulating material
2. Density, kg/m^3
3. Thermal conductivity coefficient, W/(m·°C)
4. Foam polyurethane
5. Foam polystyrene
6. Glass fiber
7. Foamglass
8. PSB-S foam polystyrene (GOST 15588-70)
9. PPU-3s foam polyurethane (TU V-56-70)
10. PPU-3n foam polyurethane (TU VNIISS 67-66)
11. PPU-307 foam polyurethane (TU V-143-69)
12. PPU-308n foam polyurethane
13. FRP-1 phenoformaldehyde foam plastic (VTU VNIISS 56-65)
14. Note: t is temperature in °C

thermophysical characteristics of the ground vary in the course of the year as a result of the seasonal migration of moisture in the ground, caused by spring high waters, rains and temperature variation. In addition, the properties of the upper soil layers can even vary during the course of 24 hours as a result of condensation of moisture in the ground pores during the nighttime hours and its evaporation with an increase in temperature during the daytime. In addition to these factors, the thermophysical properties of the ground are influenced considerably by the thermal effect of the pipeline itself. This is associated with the migration of moisture in the region of the thermal influence of the pipe, arising due to the temperature gradient between the wall of the pipeline and the near-lying ground layers. The thermophysical characteristics of the ground -- the thermal conductivity coefficient (λ_{gr}), the coefficient of thermal diffusivity (a_{gr}) and the specific heat capacity (c_{gr}) are determined as a result of special investigations. The measurements are made directly under field conditions or in the laboratory. In the latter case the ground samples are taken in special tight boxes retaining their natural moisture content and are transported to the laboratory. The number of points for measuring the thermophysical characteristics of the ground along the pipeline route and the frequency with which the measurements are made are determined by the requirements on the accuracy in finding λ_{gr}, a_{gr} and c_{gr} and are dependent on the degree of inhomogeneity of ground properties with depth and strike of the ground mass.

The λ_{gr}, a_{gr} and c_{gr} values, determined under laboratory conditions, must be corrected taking into account possible impairments in structure and changes in the temperature and moisture content of the samples arising in the process of their sampling, storage, transport and measurements. For this purpose use is made of empirical dependences of the thermophysical characteristics of the ground on the mentioned factors. The data from field measurements correspond to the natural conditions of ground bedding and therefore their correction is not necessary.

On the basis of the results obtained in the course of field investigations a summary is prepared of the thermophysical characteristics of the ground along the entire route of the pipeline, which serves as a basis for computing their mean values for the entire route or individual major segments.

Considerable expenditures of time and money are required for special field investigations for determining the thermophysical properties of the ground; therefore they are determined in the planning of a limited number of petroleum pipelines. In those cases when the plan makes no provision for determining the thermophysical properties of the ground, and also for approximate computations in the stage of technical-economic planning, their values, depending on ground types, are taken from the data in Table 8.5 or are computed using the formulas derived by I. Ye. Khodanovich and B. N. Krivoshein:

thawed sand $\ln \lambda_{rp} = -0{,}316 + 0{,}055w + 1{,}02\rho_{rp} - 0{,}055t_{rp} - 0{,}000636w^2;$

frozen sand $\ln\lambda_{rp}=-5{,}432+0{,}092w-0{,}0269\rho_{rp}+0{,}018t_{rp}-0{,}00297w^2;$

frozen clayey loam $\ln\lambda_{rp}=-1{,}642+0{,}019w-0{,}0396\rho_{rp}+0{,}0057t_{rp};$

clay $\ln\lambda_{rp}=-9{,}652+0{,}24w-0{,}92\rho_{rp}+0{,}06t_{rp}-0{,}011w\rho_{rp}-0{,}0007wt_{rp}-$
$-0{,}021\rho_{rp}^2+0{,}0015\rho_{rp}t_{rp}-0{,}0001t_{rp}^2,$

[Γ p = gr(ound)] where λ_{gr} is the coefficient of thermal conductivity of the ground, W/(m·°C); ρ_{gr} is ground density, tons/m^3; w is ground moisture content; t_{gr} is ground temperature, °C.

In order to take into account the thermal influence of a pipeline on the change in the coefficient of thermal conductivity of the ground, instead of its value, determined for the conditions of natural bedding of the ground, in the thermal computations use is made of the computed value, calculated using the formula

$$\lambda_{rp.\,p}=\frac{1}{t-t_0}\left[\int\limits_0^{t_N}\lambda_{rp}(t_{rp})\,dt_{rp}-\int\limits_0^{t_0}\lambda_{rp}(t_{rp})\,dt_{rp}\right], \tag{8.4}$$

[Γ p = gr(ound)] where t_0 is the ground temperature at the depth of laying of the pipeline in a natural thermal state; t_N is the temperature of the outer surface of the pipe. With a linear dependence of the thermal conductivity coefficient on temperature its computed value is equal to the half-sum of the λ_{gr} values, determined for conditions of natural bedding of the ground and near the pipe:

[Γ p = gr(ound)] $\lambda_{gr} = 0.5[\lambda_{gr}(t_N) + \lambda_{gr}(t_0)].$

The thermophysical characteristics of the thermal insulation are determined experimentally or are taken from certificate data. In the thermal computations use is made of the computed value of the thermophysical characteristics of the heat insulation, equal to the half-sum of the values, which correspond to the temperature of the inner and outer surfaces of the heat-insulating covering. The values of the thermal conductivity coefficient of some types of thermal insulation, used in constructing "hot" petroleum pipelines, are given in Table 8.6.

#8.4. Thermal Regime of Main Pipelines

Computations of the thermal interaction of pipelines with the surrounding medium are necessary for selecting the method for laying the line, the pumping method, determination of the power of pumping and thermal stations, etc. It is particularly important to take into account thermal processes for petroleum pipelines pumping petroleum in a heated state. The purpose of the thermal computations for the planning of a main pipeline is to determine the temperature distribution along its length and to estimate thermal losses. Taking into account the data from the thermal computations, it is possible to determine the throughput capacity of the pipeline, the intervals at which pumping (thermal) stations should be placed, the strength and stability of the pipeline can be computed and the type and thickness of the heat insulation are selected.

In the process of operation of pipelines the results of thermal computations are used for routine dispatcher control of its operation: finding the safe time for stopping the "hot" pumping of high-viscosity petroleums, selection of a method for expulsion of cooled petroleum from a stopped pipeline, estimating the optimum variant for starting up a "hot" pipeline and determining the safe time for shutting down the pumping stations.

The operating regimes for a "hot" pipeline under conditions of start-up and operation, stoppage of pumping, changes in volume and temperature of petroleum heating are called transition regimes. They are characterized by a change in volume and temperature of the petroleum with time from one stationary state to another. Under these conditions the process of flow of petroleum through the pipeline and its thermal regime are unsteady. The reason for the appearance of transition regimes in the operation of "hot" pipelines can be the planned or accidental shutdown of individual pumps or pumping stations, heating plants or heat exchangers at thermal stations, filling of the pipeline with petroleum during its startup, stoppage of pumping or its renewal, successive pumping of petroleums with different physical properties, connection or disconnection of petroleum inlets or outlets along the pipeline route, seasonal variation of air temperature and thermophysical properties of the ground. These factors lead to a change in pumping parameters: temperature, pressure and flow. A deviation of any of these parameters from a stationary state, if there is no special regulation of the system, leads to a corresponding change in all the others. For example, with the accidental shutdown of a heating station cold petroleum, having a higher viscosity in comparison with the heated petroleum, begins to enter into the pipeline. As a segment of the pipeline is filled with cold oil and the heated oil is expelled, there is an increase in head losses on friction. For a pipeline with pumping stations equipped with centrifugal pumps, this automatically leads to a reduction in the flow and an increase in pressure; the latter can exceed the admissible pressure set on the basis of pipe strength. Simultaneously changes in temperature and accordingly pressure and flow occur as a result of change in the heat losses of the pipeline into the surrounding medium arising in segments filled with cold petroleum. In addition, any change in the pumping rate in turn exerts an influence on the distribution of the temperature of the petroleum along the length of the pipeline and with time. The transient regime of pipeline operation continues until heat exchange in the "pipeline-ground" system attains a new steady state. The duration of the transient thermal processes can attain several months. Taking into account the seasonal variation in air and ground temperature, it must be noted that "hot" pipelines virtually always operate under conditions of variable regimes. However, since the number and nature of the transient processes are random, the planning of "hot" pipelines is carried out for stationary operation regimes. For these conditions the principal technical and economic indices are selected, as well as the construction and technological decisions. The data from computations of transient regimes of pipeline operation are taken into account in the operation process when determining safe deviation of the pumping parameters from the nominal values, in selection of the optimum conditions for the transport of petroleum in the case of breakdown of individual pumping plants and heating plants, etc.

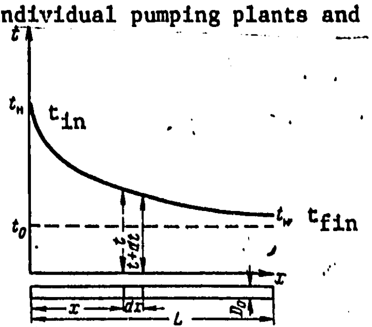


Fig. 8.6. Graph of decrease in temperature along length of pipeline.

In connection with the development and introduction of automated systems for control of operation of main pipelines, computations of transient regimes for the operation of "hot" pipelines are being carried out more and more extensively in the planning stage. The results of such computations are used in determining the parameters of the automation and telemechanical system of the pipelines, being a component part of the automated systems for control of operation of main pipelines and in formulating an algorithm for control of operation of pumping and heating stations.

Now we will examine the method for thermal computations of pipelines in stationary hydraulic and thermal regimes.

Assume that petroleum heated to the temperature t_{in} is fed into the pipeline through its initial section. Then at some distance x from the beginning of the pipeline, as a result of heat exchange with the surrounding medium, the temperature of the petroleum is reduced to t (Fig. 8.6). In order to determine the law of temperature decrease in the segment from the beginning of the pipeline to x we will define an elementary segment with the length dx and we will examine its thermal balance. According to the principal heat transfer laws, the quantity of heat lost by the petroleum enclosed in an elementary volume $0.25\pi D_0^2$ is directly proportional to the temperature drop $\Delta t = t - t_0$, the heat exchange surface $\pi D_0 dx$ and is inversely proportional to the thermal resistance of the surrounding medium. Accordingly, the heat losses of an elementary volume of petroleum into the surrounding medium with the temperature t_0 are

$$dq_1 = k\pi D_0 (t - t_0)\, dx.$$

The loss of part of the heat by the petroleum into the surrounding medium leads to a decrease in its heat content by the value

$$dq_2' = -Gc_м\, dt,$$

where G is the mass flow in the petroleum pipeline.

If the heat of friction is neglected and no allowance is made for the phase transitions associated with the crystallization of the paraffin in the petroleum, in accordance with the law of energy conservation, the dq1 and dq_2 values must be equal to one another, that is

$$k\pi D_0 (t - t_0)\,dx = -Gc_{\text{м}}\,dt.$$

Separating the variables and integrating, we obtain

[H = in]

$$\frac{k\pi D_0}{Gc_{\text{м}}}x = \ln\frac{t_{\text{н}} - t_0}{t - t_0}$$

or

$$t = t_0 + (t_{\text{н}} - t_0)\exp\left(-\frac{k\pi D_0}{Gc_{\text{м}}}x\right). \tag{8.5}$$

With x = L, from formula (8.5) we obtain the petroleum temperature at the end of the pipeline

[K = end]

$$t_{\text{к}} = t_0 + (t_{\text{н}} - t_0)\exp\left(-\frac{k\pi D_0}{Gc_{\text{м}}}L\right).$$

With a considerable length of the petroleum pipeline (theoretically with $x \to \infty$ in accordance with (8.5) the petroleum temperature approaches the ambient temperature, equal to the ground temperature at the depth of laying of the pipe in a natural thermal state in the case of placement underground or equal to the air temperature if the pipe is laid above the ground.

Equation (8.5) was derived for the first time by V. G. Shukhov and the equation has been given his name. It gives satisfactory results for a considerable range of operation of the pipelines and therefore these results are used extensively in thermal computations. The accuracy of the computations using formula (8.5) to a considerable degree is dependent on the reliability in determining the total heat transfer coefficient.

V. G. Shukhov proposed that the k value be determined experimentally in operating pipelines and that these results be applied to planned systems. We can allow such an approach if k is determined directly for an operating pipeline or for a pipeline for which the conditions are similar to an already operating pipeline, for example, when laying it parallel to the operating pipeline at a short distance from it. Then, using operational data, the heat transfer coefficient can be determined using an expression which follows from (8.5):

[K = end; H = in]

$$k = \frac{Gc_{\text{м}}}{\pi D_0 L}\ln\frac{t_{\text{н}} - t_0}{t_{\text{к}} - t_0}.$$

In a general case, however, k must be determined using formula (8.1) or (8.1a). When transporting petroleum with a high paraffin content it is necessary to take into account the paraffin crystallization effect. From the initial temperature t_{in} to the temperature of onset of paraffin crystallization $t_{in\ par}$ the cooling of the petroleum occurs in accordance with the V. G. Shukhov law. With further cooling the heat losses are partially compensated by the released heat of crystallization of the paraffin.

If it is assumed that the quantity of crystallizing paraffin is proportional to the temperature decrease, the quantity of heat released due to crystallization for the elementary segment dx is equal to

$$dq_{з} = \frac{G\varepsilon\varkappa}{t_{\text{н. п}} - t_{\varepsilon}} dt,$$

[H, П = in, par] where ε is the paraffin concentration (in fractions of unity), released from the petroleum with a decrease in temperature from $t_{\text{in, par}}$ to t_{ε} ; t_{ε} is any temperature for which ε is known; $\varkappa$ is the latent heat of paraffin crystallization.

Then, writing the heat balance for an elementary segment and solving the initial equation, for $l_1 \leqslant x \leqslant L$ we obtain

[H, П = in, par]

$$t = t_0 + (t_{\text{н. п}} - t_0) \exp\left[-\frac{k\pi D_0}{Gc_{\text{м1}}}(x - l_1)\right], \tag{8.5a}$$

where

$$c_{\text{м1}} = c_{\text{м}} + \varepsilon\varkappa/(t_{\text{н. п}} - t_{\varepsilon});$$

l_1 is the distance over which the petroleum temperature decreases from t_{in} to $t_{\text{in, par}}$, determined using the V. G. Shukhov formula.

With the pumping of viscous petroleums in a heated state there are cases possible when in the initial segment of the pipeline there will be a turbulent regime, whereas in the end segment, as a result of petroleum cooling there will be a laminar regime. As is well known, the regime of liquid movement is characterized by the Reynolds number. The transition from one regime to the other occurs at the so-called critical Reynolds number Re_{cr}. It has been established that for heated petroleums Re_{cr} = 1000-2000; for highly paraffinic petroleums Re_{cr} is closer to the lower value, whereas for viscous petroleums with a low paraffin content it is closer to the upper limit. Since $Re_{cr} = 4Q/\pi D_0 \nu_{cr}$, then $\nu_{cr} = 4Q/\pi D0Re_{cr}$. The ν_{cr} value determines the temperature t_{cr} at which there is a change in the flow regime. In this case t_{cr} can be estimated using both graphic and analytical dependences. For example, using the Filonov-Reynolds formula, we obtain

[KP = cr]

$$t_{\text{кр}} = t_0 + \frac{1}{u} \ln \frac{\nu_0 \pi D_0 \text{Re}_{\text{кр}}}{4Q}. \tag{8.6}$$

Substituting the t_{cr} value from (8.6) into the Shukhov formula and denoting the Shukhov parameter for a turbulent regime as $Shu_T = k_T \pi D_0 L/Q \rho c_M$, we obtain

$$x_{\text{кр}} = \frac{L}{\text{Шу}_{\text{т}}} \ln \frac{t_{\text{н}} - t_0}{t_{\text{кр}} - t_0}. \tag{8.7}$$

[KP = cr; T = T; H = in; Шy = Shu]

Accordingly, in the segment $0 \leqslant x \leqslant x_{cr}$ the regime of petroleum flow is turbulent, whereas with $x_{cr} \leqslant x \leqslant L$ it is laminar. Computations of temperature in both segments are made using formula (8.5), in which the k value is determined for the conditions of laminar and turbulent flow regimes respectively.

Knowing the lengths of segments with different liquid flow regimes, it is possible to estimate the total head losses in the pipeline by summing the head losses in both segments in the form $h_{\Sigma} = h_T + h_{lam}$.

With allowance for the release of heat due to friction the heat balance of a segment of the pipeline is written in the form

$$k\pi D\,(t-t_0)\,dx = Q\rho c\,dt + Q\rho i\,dx,$$

where i is the hydraulic slope.

Separating the variables, we obtain

[H = in(itial)]

$$\ln\frac{t_{н}-t_0-b}{t-t_0-b} = ax \qquad (8.8)$$

or

$$t = t_0 + b + (t_{н}-t_0-b)\exp(-ax),$$

where

$$a = \frac{k\pi D}{Q\rho c};\quad b = \frac{Q\rho i}{\pi k D}.$$

Comparing the derived expression with the V. G. Shukhov formula, we find that the increment in the petroleum temperature with allowance for the heat of friction is equal to

$$\Delta = b\,(1-e^{-ax}).$$

With $x \to \infty$ the maximum error is $\Delta_{max} = b$.

For a petroleum pipeline with different values of the heat transfer coefficients k_j in individual segments with the length l_j, on the basis of (8.5) it is possible to write:

[H = in; K = end]

$$\ln\frac{t_{н\,j}-t_0}{t_{к\,j}-t_0} = \frac{\pi D}{Q\rho c}\,k_j l_j.$$

Noting that $(t_{in})_{j+1} = t_{end\ j}$ and $t_{in\ j} = (t_{end})_{j-1}$, and adding by terms, we obtain

[H = in; K = end]

$$\ln\frac{t_{н1}-t_0}{t_{к\,n}-t_0} = \frac{\pi D}{Q\rho c}\sum_{j=1}^{n} k_j l_j,$$

where j is the sequence number of the segment; n is the number of segments.

If on a pipeline with heating stations the distance between the stations is L, the heat transfer coefficients k in the segments and the θ value by which the petroleum temperature is increased at the stations are identical, for the first segment between the thermal stations it is possible to write:

[H = in; K = end]

$$t_{к1} = t_0 + (t_{н1}-t_0)\exp(-aL).$$

For the second segment, taking into account that at the second station the petroleum temperature is increased by θ,

[K = end]

$$t_{к2} = t_0 + (t_{к1}+\theta-t_0)\exp(-aL).$$

Substituting into the latter expression the $t_{end\ 1}$ value from the preceding expression, we obtain

$$t_{к2} = t_0 + (t_{н1}-t_0)\exp(-2aL) + \theta\exp(-aL).$$

Similarly determining the temperature in successive segments, we find the temperature at the end of the pipeline

$$t_{\text{к н}}=t_0+(t_{\text{н}1}-t_0)\exp(-naL)+\theta[\exp(-aL)+\exp(-2aL)+\ldots+\exp(1-n)aL].$$

Since a geometric progression is written in brackets, then
[K = end; H = in]

$$t_{\text{к н}}=t_0+(t_{\text{н}1}-t_0)\exp(-naL)+\theta\frac{1-e^{(1-n)aL}}{e^{aL}-1}.$$

In the case of large n values

$$t_{\text{к н}}=t_0+\frac{\theta}{e^{aL}-1}.$$

[K = end]

#8.5. Hydraulic Regime of "Hot" Petroleum Pipelines

The hydraulic regime of a "hot" petroleum pipeline is determined to a conerable degree by the conditions for its heat exchange with the surrounding medium. With an increase in the temperature of the transported petroleum there is a decrease in its viscosity and a decrease in head losses. With a decrease in temperature the reverse picture is observed. The temperature regime of the petroleum pipeline in turn is dependent on the pumping volume, the conditions for the transfer of heat from the petroleum into the surrounding medium, meteorological conditions and other factors. In the preceding sections analytical dependences were obtained for taking into account the influence of these factors on the distribution of petroleum temperature along the length of the pipeline and its thermal losses. Using these dependences, it is possible to determine the distribution of pressure along the length of the pipeline transporting highly viscous petroleum in a heated state and estimate the head losses on its pumping.

Since the temperature, and accordingly, the viscosity in a "hot" pipeline operating under stationary conditions change with length, for finding losses in it one can use the Darcy-Leybenzon equation in differential form:

$$dH=\beta\frac{Q^{2-m}\nu^m}{D_0^{5-m}}\Delta_r dx+dh, \tag{8.9}$$

hence

$$H=\beta\frac{Q^{2-m}L}{D_0^{5-m}}\frac{1}{L}\int_0^L \nu^m(x)\Delta_r(x)\,dx+\Delta h, \tag{8.10}$$

where Δh is the difference in the geodetic readings of the beginning and end of the pipeline.

The Δ_r value is the correction for the nonisothermicity of the flow in a radial direction. If the Δ_r coefficient is considered constant along the entire length of the pipeline, the integral on the right-hand side of the latter expression has the sense of the mean integral petroleum viscosity:

[cp = mean]

$$\nu_{\text{cp}}^m=\frac{1}{L}\int_0^L \nu^m(x)\,dx.$$

Then the head losses on the pumping of a heated highly viscous petroleum are

$$H=\beta\frac{Q^{2-m}\nu_{\text{cp}}^{m}}{D_0^{5-m}}\Delta_r L+\Delta h.$$

This expression with $\Delta_r = 1$ coincides with the Darcy-Weisbach formula for determining the head losses on the pumping of petroleum with the viscosity ν_{mean} under isothermic conditions.

The ν_{mean} value is determined by the temperature conditions of transport and the viscosity-temperature dependence of the particular petroleum. We will assume a petroleum-temperature distribution using the V. G. Shukhov formula, and the dependence $\nu = \nu(t)$ using the Filonov-Reynolds formula. Then

$$\nu_{\text{cp}}^{m}=\frac{\nu_0^m}{L}\int_0^L \exp(-umt_0)\exp[-um(t_{\text{н}}-t_0)\exp(-ax)]\,dx.$$

[cp = mean; H = in]

After integration, taking into account that

$$\int_{x_1}^{x_2}\frac{e^y\,dy}{y}=Ei(x_2)-Ei(x_1),$$

we obtain

[cp = mean; H = in] $$\nu_{\text{cp}}^{m}=\frac{\nu_0^m}{aL}\exp[um(t_{\text{н}}-t_0)]\{Ei[-um(t_{\text{н}}-t_0)]-Ei[-um(t_{\text{н}}-t_0)\exp(-aL)]\},$$

where Ei(x) is an integral exponential function.

Multiplying the right-hand side of the latter expression by $\nu_{\text{in}}/[\nu_0 \exp(-ut_{\text{in}})] = 1$, we find

[cp = mean; H = in] $$\nu_{\text{cp}}^{m}=\frac{\nu_{\text{н}}^m}{aL}\exp[um(t_{\text{н}}-t_0)]\{Ei[-um(t_{\text{н}}-t_0)]-Ei[-um(t_{\text{н}}-t_0)\exp(-aL)]\}$$

or

$$\nu_{\text{cp}}^{m}=\frac{\nu_{\text{н}}^m}{aL}\exp[um(t_{\text{н}}-t_0)]\{Ei[-um(t_{\text{н}}-t_0)]-Ei[-um(t_{\text{н}}-t_{\text{к}})]\}.$$

We use the notation

[H = in; K = end] $$\Delta_l=\frac{\exp[um(t_{\text{н}}-t_0)]}{aL}\{Ei[-um(t_{\text{н}}-t_0)]-Ei[-um(t_{\text{н}}-t_{\text{к}})]\}.$$

Then

[cp = mean; H = in] $$\nu_{\text{cp}}^{m}=\nu_{\text{н}}^{m}\Delta_l$$

Thus, the Δ_l coefficient characterizes the deviation of petroleum viscosity, and accordingly, the hydraulic losses from the values corresponding to isothermic conditions when $t = t_{\text{in}}$. Taking the results into account, the head losses in the pumping of heated highly viscous petroleum are

$$H=\beta\frac{Q^{2-m}\nu_{\text{н}}^{m}}{D_0^{5-m}}\Delta_r\Delta_l+\Delta h. \qquad (8.11)$$

The head distribution along the length of the pipeline in this case is

$$H = H_{\text{н}} - \beta \frac{Q^{2-m} \nu_{\text{н}}^{m} \Delta_r}{D_0^{5-m}} \frac{\exp[um(t_{\text{н}} - t_0)]}{a} \{Ei[-um(t_{\text{н}} - t_0)] - Ei[-um(t_{\text{н}} - t_0)\exp(-ax)]\}. \quad (8.11a)$$

An analysis of the latter formula shows that the head distribution along the length of the pipeline has a parabolic nature, whereas under isothermic conditions it is linear. The deviation from a linear distribution is associated with an increase in the viscosity of the petroleum as a result of its cooling. The rate of head decrease increases in the final segments.

With high values $t_{in} - t_0$ and small $t_{end} - t_0$

[H = in] $$Ei[-um(t_{\text{н}} - t_0)] \approx 0,$$

that is, under these conditions the main resistance to movement of the flow is created by the "cold" end of the pipeline.

In droplet liquids not all the physical properties change identically with temperature. In the section there is the strongest change in viscosity μ_w/μ_f; density ρ_w/ρ_f changes far less, as do thermal conductivity $\lambda_w/\lambda f$ and heat capacity c_w/c_f. A change in the temperature heads $t_w - t_f$ in a section of the pipeline leads to a change in the velocity profile since the greatest change is in viscosity and as a result of this, leads to an additional change in the temperature profile. The changes in the velocity profile will be greater in laminar flows and less in turbulent flows. Usually the change in head in dependence on inhomogeneity of the flow in the diameter involves allowance for the change in viscosity and allowance for distortion of the temperature and velocity fields as a result of heat transfer by the factor Δ_r. For Δ_r we use the dependence $\Delta_r = \varepsilon \left(\frac{\nu_w}{\nu_f}\right)^{\zeta}$,

where ε and ζ are coefficients, for laminar flow $\varepsilon = 0.9$ and $\zeta = 1/3 - 1/4$, and for turbulent flow $\varepsilon = 1$ and $\zeta = 0$; ν_w is the viscosity of petroleum for the mean wall temperature of the pipeline $t_{w\ mean}$; ν_f is the viscosity of the petroleum with a mean flow temperature $t_{f\ mean}$,

[cp = mean; H = in; K = end] $$t_{f\,\text{cp}} = t_0 + \frac{t_{\text{н}} - t_{\text{к}}}{\ln[(t_{\text{н}} - t_0)(t_{\text{к}} - t_0)]},$$

where t_{end} is determined using formula (8.5).

The $t_{w\ mean}$ value is computed using the expression

[cp = mean] $$t_{w\,\text{cp}} = t_{f\,\text{cp}} - (t_{f\,\text{cp}} - t_0)\frac{\alpha_1}{k}.$$

Taking into account the change in petroleum temperature along the length of the pipeline by the V. G. Shukhov method, and the change in viscosity by the Reynolds method, we obtain

$$\Delta_r = \frac{\nu_{\text{CT}}}{\nu_{\text{cp}}} = \exp\left\{\frac{u}{8}\frac{k}{\alpha_1}(t_{\text{H}} - t_0)\,[1 + \exp(-aL)]\right\} =$$

$$= \exp\left\{\frac{u}{8}\frac{k}{\alpha_1}[(t_{\text{H}} - t_0) + (t_{\text{K}} - t_0)]\right\}.$$

[cp = mean; CT = st; H = in; K = end]

Earlier the Δ_r coefficient was determined for the mean temperature along the length of the pipeline. If the Δ_r value is assigned to an elementary segment, integration of (8.9) will give the following result:

$$\Delta = \Delta_l \Delta_r = \frac{\exp[um(t_{\text{H}} - t_0)]}{al}\left\{Ei\left[-u\left(m - \frac{1}{3}\frac{k}{\alpha_1}\right)(t_{\text{H}} - t_0)\right] - Ei\left[-u\left(m - \frac{1}{3}\frac{k}{\alpha_1}\right)(t_{\text{K}} - t_0)\right]\right\}. \quad (8.12)$$

[H = in; K = end]

In those cases when there are two flow regimes in the pipeline -- laminar at the beginning and turbulent at the end -- the losses for the two segments are determined separately. The lengths of the segments are found using the formulas cited earlier.

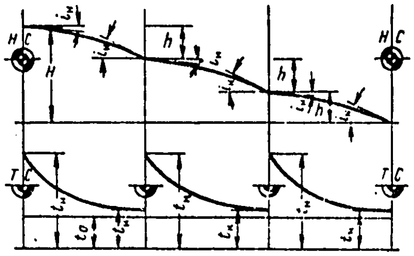
The reliability of the computed data is dependent to a considerable degree on the accuracy in approximating the viscosity-temperature dependence $\nu(t)$. Therefore, for more precise computations it is soundest to employ a numerical method for determining the head losses on the pumping of heated petroleums. In this case the pipeline is broken down into M segments (j = 1, 2,...,M), in the limits of which the petroleum viscosity with a stipulated accuracy is considered to be constant and equal to its mean value. Then it can be written

$$H = \sum_{j=1}^{M} \beta_j \frac{Q_j^{2-m} \tilde{\nu}_{\text{cp}\,j}^{m}}{d_j^{5-m}}\, l_j (\Delta_r)_j + \Delta h,$$

[cp = mean]

where the subscript j denotes that this parameter applies to the j-th segment with the length l_j.

TC = heating station
HC = pumping station



$t_{\text{H}} = t_{\text{in}}$
$t_{\text{K}} = t_{\text{fin}}$

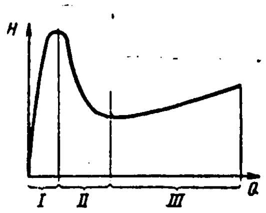


Fig. 8.7. Positioning of pumping and heating stations and also curves of decrease of head and temperature in open lines. [H = in; K = end]

Fig. 8.8. Head characteristic of "hot" pipeline.

PIPELINE TRANSPORT OF PETROLEUM

10 APRIL 1979 (FOUO 8/79) 2 OF 2

In the solution of technical and economic problems it is better to use analytical dependences, for example, for investigating the influence of different factors on the technological and energy indices of petroleum transport systems. With an identical number of pumping and heating stations the curves of decrease in temperature and head have the shape shown in Fig. 8.7. Each petroleum temperature corresponds to a very definite hydraulic slope. The number of pumping stations is limited by the maximum head which the pipes and pumps can withstand and the number of heating stations is limited by the maximum admissible heating temperature.

The graphic head characteristic curve for a "hot" pipeline describing the dependence Q-H, in accordance with the derived formula for head losses in friction, has the form shown in Fig. 8.8.

The head characteristic curve can be divided by vertical straight lines into three zones. In zone I of small flows the slowly moving petroleum can be cooled even in the initial segment of the pipeline to a temperature close to the temperature of the surrounding medium and in the remaining greater part of the pipeline there is movement of cold petroleum with a virtually constant high viscosity. Graphically in this zone the head characteristic curve has the shape of a straight line with a great slope to the x-axis due to the high viscosity. In zone III of great flows, the petroleum, moving with a great velocity, can pass through to the end of the pipeline, still retaining a high temperature. Since the mean temperature of the flow in this zone is high, the head characteristic curve has the shape of a straight line (laminar regime) with a far lesser slope to the x-axis than in the first zone due to the low viscosity of the petroleum. In zone II the head losses increase with a decrease in the flow. This is attributable to the fact that with a decrease of flow in this zone (zone of intermediate flows), and accordingly, with a decrease in the velocity of movement of the petroleum, each of its portions remains longer in the pipeline and can cool more. As a result, there is a decrease in the mean temperature and an increase in the mean viscosity of the petroleum; the relative increase in viscosity in this zone is greater than the relative decrease in flow and this leads to an increase in head losses with a decrease in the flow. Only zone III with relatively great flows is a working zone. Zone I is a nonworking zone, because with these same heads the flows here will be several times less than in zone III. If the head loss at the point of transition from zone I into zone II exceeds the maximum head developed by the pumping station, when the working point of the pumping station - pipeline falls in zone II, being unstable, the flow will be reduced spontaneously and finally the working point will enter into zone I. For practical purposes this means a stoppage of the pipeline because the flow becomes very small.

If for any reasons the working point of the "hot" pipeline has approached the boundary of zone II or has already passed into this zone, it can be returned to working zone III by one of the following methods:

1) by rapidly increasing the heating temperature of the petroleum;
2) by rapidly increasing the head at the stations by starting up additional pumps;
3) by beginning the pumping into the pipeline of a less viscous product without lowering the petroleum heating temperature.

If the pumping station can develop a head exceeding the maximum head losses at the boundary of zones I and II, these losses not exceeding the admissible head as governed by the strength of the pipeline and the equipment at the station, the return from zone I to zone III presents no difficulties.

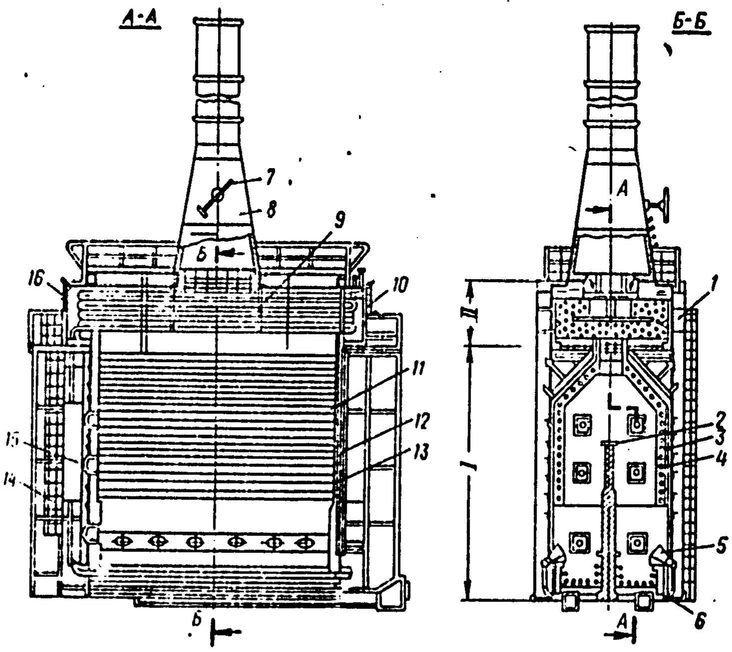


Fig. 8.9. Schematic diagram of radiant-convection network.

#8.6. Equipment for Heating Petroleum

Pumping-heating and heating (thermal) stations are outfitted with heaters of different designs for heating petroleum and petroleum products. In a case when at the head station on the pipeline the viscous product (such as mazut) is fed from the installations of a petroleum refinery in a hot state, at the head station it is possible to get by without heating plants. The tanks at the head station are heated by tubular heaters (coils or sections) for preliminary heating of the petroleum. The purpose of this heating is to reduce petroleum viscosity to the level adequate for its evacuation from the tank with a stipulated flow rate. The heating in the tank to the temperature of pumping through the pipeline is infeasible due to the great heat losses from the tank walls into the surrounding medium and an increase in the losses of light fractions due to intensified evaporation during heating. As the heat carrier use is made of ordinary water vapor. In order to lessen the heat losses the tank can be supplied with heat insulation.

Heating to a pumping temperature is accomplished in steam or fired heaters.

Multipass heat exchangers with a floating head are now increasingly coming into the widest use in steam heaters. In these the petroleum passes through pipes and the steam passes through the space outside the pipes. Such a distribution of flows increases the heat transfer coefficient and decreases the dimensions of the heat exchanger. Usually there are several heat exchangers at the station; they can be cut in either in series or in parallel. Most frequently they are used in-parallel, making it possible in broad limits to regulate the temperature of petroleum heating.

During the time of operation of the heat exchangers, in addition to monitoring the petroleum temperature it is necessary to monitor carefully the purity of the condensate emerging from the heaters. The entry of petroleum into a heat exchanger is evidence that the heat exchanger is malfunctioning. In this case the entry of petroleum into the heat exchanger must be stopped at once. On "hot" pipelines extensive use is also made of fired heaters (for the first time in the USSR on the Uzen'-Gur'yev-Kuybyshev pipeline). They constitute furnaces the fuel for which can be gas or the pumped product or petroleum.

Figure 8.9 shows a schematic diagram of a radiant-convection furnace for the heating of petroleum, the design of which was developed by the Giproneftemash combine. All the space in the furnace, mounted in the metallic housing 1, is divided into two zones: radiant I and convection II. The radiant zone in turn is divided into two parts by a wall 2 made of refractory brick, arranged along the axis of the furnace. In the lower part of the furnace there are six nozzles 5 with air spraying of fuel. On the Uzen'-Gur'yev-Kuybyshev pipeline the fuel is the petroleum which is transported. However, the nozzles are gas-mazut, which makes it possible to burn gaseous fuel with their assistance as well. The air is fed to the nozzles through the air line 6. In order to prevent destruction of the furnace from the "boom" occurring when fuel is fed again after a brief interruption, the furnace has air releases 3, whose covers 15 fly off when there is a shock wave.

In the radiant zone the pipes 11 of the coil through which the petroleum flows are laid on supports 4. In this zone the heating of the petroleum occurs for the most part due to the radiant energy of the flare. The combustion products then pass into the convective zone, where the transfer of heat to the petroleum flowing through the pipes is accomplished by means of convection. From the convective zone in the furnace the combustion products are ejected into the atmosphere through the stack 8. The regulation of rarefaction (draft) in the furnace is accomplished by means of a gate 7.

The coiled tubes are secured in the convective zone in the middle 9 and end 10 tube lattices. The furnace walls are covered on the inside by the refractory brickwork 13 and on the outside by the thermal insulation 12. There is a ladder 14 for servicing the furnace, whose height without the stack attains 10.5 m. In order to observe the condition of the convective pipes and for their cleaning when there is an accumulation of soot, which considerably reduces the heat transfer coefficient, provision is made for hatches with covers 16.

The system of monitoring and automation instruments enables the operator to watch over the process of heating of the petroleum and ensures automatic protection of the furnace when there is deviation from the stipulated technological regime. The presence of servicing personnel during operation of the furnace is mandatory. The throughput capacity of one furnace is 600 m^3/hour; the petroleum is heated from 30 to 65°C. The maximum working pressure of the petroleum upon entry into the coil must not exceed 6.5 MPa. The furnace heat productivity is 10 500 KW and the efficiency attains 0.77, evidence of its high thermal efficiency.

The heating of petroleum only at certain points (at pumping-heating stations and heating stations) imposes limitations on the design and operational flexibility of the "hot" pipelines. Thus, due to the limitation on the temperature of petroleum heating by the conditions for normal operation of the heat exchange apparatus, in a number of cases the calculated distance between the heating stations can be short, which forces an increase in their number and accordingly leads to an increase in the capital expenditures. A prolonged stoppage of pumping can result in a congealing of the petroleum in the pipeline and in this case a renewal of pumping involves great expenditures.

These shortcomings can be eliminated by the use of en-route heating of the "hot" pipeline. Such en-route heating by means of satellite pipelines has definitely begun to be used. These satellite pipelines are small in diameter and hot water is pumped through; these lines are laid parallel to the pipeline and adjacent to it (a common heat-insulating covering is applied to the petroleum pipeline and the hot water line). Such a system for en-route heating is employed, for example, in one of the pipelines for the transport of highly congealing petroleum in Indonesia.

Electric heating of the pipeline with use of the skin effect is promising. As is well known, when an alternating current is passed through a steel pipe the current is not distributed uniformly through the section of the pipe wall, but due to the skin effect is concentrated near the inner surface of the pipe. The intensity of current concentration is dependent on the frequency of the latter. However, due to the high conductivity of the steel the skin effect is manifested in it to a high degree even at industrial frequencies. For example, at a frequency of 50 Hz the depth of the skin effect (the fundamental index of intensity of this phenomenon, showing what thickness of the metal, measured from its surface, bounds the zone of current passage) in the case of steel is only 1 mm.

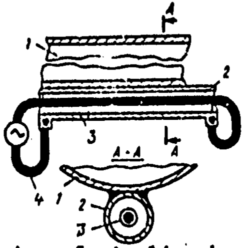


Fig. 8.10. Diagram of heating of pipeline by means of skin effect.

Figure 8.10 is a diagram of the system for heating a pipeline by means of the skin effect. A heating pipe 2 with a diameter of 6-40 mm lies flush against the petroleum pipeline 1. Within the heating pipe there is an internal copper cable 3 with a cross section of the conductors 8-60 mm^2. The cable has a heat-resistant insulation. A source of alternating current of an industrial frequency is connected at one end to the internal cable and at the other end to a second cable 4, whose other end is connected to the heating pipe. The second end of the internal cable is connected to the end of the heating pipe opposite the current source.

Since the electric current is concentrated in a very small cross-sectional zone in the pipe, its resistivity increases and a great quantity of heat is released. Usually 80-90% of the total quantity of heat released in the circuit is generated in the heating pipe, whereas the remaining quantity is generated in the internal cable. The petroleum pipeline and the heating pipe are covered by a common heat insulation. The heating line is welded to the pipeline and the heat generated in the heating line freely passes into the petroleum pipeline. At the same time, since the current passes only along the internal surface of the heating line it can be grounded.

Such a system of en-route heating has a high efficiency since the heat from both the heating pipe and from the internal cable is expended on the heating of the petroleum pipeline. According to test data, the difference in temperatures between the heating pipe and the petroleum pipeline does not exceed 10°C, the heat yield is 15-150 W per 1 m of length for one heating pipe. Several heating lines can be laid next to large-diameter pipelines.

#8.7. Heat-Insulated Pipelines

In some cases in order to increase the economy of operation of "hot" pipelines it can be desirable to cover them by heat insulation. The heat insulation reduces the heat loss by the pumped product; this makes it possible to reduce the number of heating stations. The proper choice of the material, design and thickness of the thermal insulation plays an important role in increasing the economy of a "hot" pipeline.

Usually the material and design of the thermal insulation are selected first and then the next step is determination of the thickness. The solution of the latter problem is dependent on the adopted optimality criterion or the condition which the decision must satisfy (economic criteria, inadmissibility of congealing of the product during stoppages of a definite duration, stipulated heat losses). The materials used for heat insulation must have the following properties: minimum heat conductivity coefficient, low moisture capacity and hygroscopicity, low density, absence of chemical interaction with the surface of the pipeline, incombustibility, biological inertia with respect to fungi, parasites and rodents, heat resistance, capacity for withstanding multiple coolings and heatings, strength, longevity and uniformity. In addition, when selecting the heat insulating material an effort must be made to satisfy a number of additional requirements. Thus, the expenditures on insulation must be low and pay for themselves quickly; the installation of the insulation must be convenient and reliable. Usually it is not possible to satisfy all the requirements mentioned above. Many of the requirements imposed on the insulation of pipelines are satisfied by insulation of foam polyurethane covered by synthetic films. The principal characteristics of the heat-insulating materials produced by Soviet industry are given in Table 8.6.

The determination of the optimum thickness of the insulation is a technical-economic problem and in a general case is extremely complex since it is necessary to optimize several parameters in addition to thickness: temperatures at the input and output from the heating stations, number of heating and pumping stations, etc. However, in actual practice, taking into account the experience in planning and operating "hot" pipelines, the optimization problem can be simplified.

In many cases the heating temperature t_{in} of the petroleum at the thermal stations is adopted on the basis of experience in operating similar pipelines or the maximum admissible temperature set by technological limitations (beginning of acceleration of petroleum, clogging-up of the pipes in heat exchange apparatus and others); the final temperature t_{end} at the end of the run between heating (thermal) stations is assumed for highly congealing petroleums to be 3-5°C above the congealing point, whereas for high-viscosity petroleums it is adopted on the basis of experience in operating similar pipelines. Accordingly, the heat losses are stipulated in the runs between heating stations. Investigations have shown that the minimum expenditure (mass) of insulation will be used in this case when the thickness of the insulation along the entire length of the run is constant. With an increase in the thickness of the insulation there is an increase in the capital and operational expenditures on insulation, but at the same time there is a decrease in heat losses and accordingly a decrease in the necessary number of heating stations and expenditures on these stations. With a decrease in the thickness of the insulation there is a corresponding decrease in the expenditures on insulation, but at the same time due to an increase in the heat losses there is an increase in the number of heating stations and the expenditures on them. The optimum variant will be one for which the sum of the reduced expenditures on heat insulation and heating stations will be minimum.

The necessary number of heating stations n for pipelines of the length L and the diameter D_0 in accordance with the V. G. Shukhov formula is

[Шу = Shu]

$$n = \frac{\pi k D_0 L}{Q \rho c_\text{м} \text{Шу}},$$

where, in accordance with (8.5) and (8.1)

[Шу = Shu; Н = in; К = end]

$$\text{Шу} = \ln \frac{t_\text{н} - t_0}{t_\text{к} - t_0},$$

and

$$\frac{1}{kD_0} = \frac{1}{\alpha_1 D_0} + \frac{1}{2\lambda_\text{м}} \ln \frac{D_N}{D_0} + \frac{1}{2\lambda_\text{из}} \ln \frac{D_\text{из}}{D_N} + \frac{1}{\alpha_2 D_\text{из}}, \qquad (8.12a)$$

[М = metal; ИЗ= insul(ation)]

where λ_M and λ_{insul} are the thermal conductivity coefficients for the metal in the pipeline and the insulation; D_0 and D_N are the internal and external diameters of the pipeline:

$$D_{insul} = D_N + 2\delta_{insul};$$

δ_{insul} is the insulation thickness.

For underground pipelines the external heat transfer coefficient can be determined with some simplifications using the formula

[Гр = gr(ound); ИЗ = insul]

$$\alpha_2 = \frac{2\lambda_\text{гр}}{D_\text{из}\left(\ln \frac{4H}{D_\text{из}} + \frac{\lambda_\text{гр}}{\alpha_0 H}\right)}, \qquad (8.13)$$

where λ_{gr} is the ground thermal conductivity coefficient; H is the depth of placement of the pipeline to its axis; α_0 is the coefficient of heat transfer from the ground surface into the air [α_0 = 10-18 W/(m$^2\cdot$°C)].

Since the thermal resistance at the petroleum-pipe discontinuity and the resistance of the pipe metal are insignificant in comparison with the thermal resistance of the insulation and ground, the first two terms in (8.12a) can be neglected and after substitution of (8.13) into (8.12a) we obtain

$$\frac{1}{kD_0} \approx A + B \ln D_\text{из},$$

[ИЗ = insul(ation)]

where

$$A=\frac{1}{2H\alpha_0}+\frac{1}{2\lambda_{\text{гр}}}\ln 4H-\frac{1}{2\lambda_{\text{из}}}\ln D_N;$$

[ИЗ = insul; гр = gr(ound)]

$$B=\frac{1}{2}\left(\frac{1}{\lambda_{\text{из}}}-\frac{1}{\lambda_{\text{гр}}}\right).$$

Then the necessary number of heating stations is

[Шу = Shu; ИЗ = insul]

$$n=\frac{\pi L}{Q\rho c_{\text{м}}\text{Шу}}\,\frac{1}{A+B\ln D_{\text{из}}}.$$

The heat expenditure on heating of the pumped petroleum at each heating station is

[T = heat; H = in; K = end]

$$Q_{\text{т}}=Q\rho c_{\text{м}}(t_{\text{н}}-t_{\text{к}}).$$

The heating surface of the heating plant is determined as

[T = heat; p = res(erve)]

$$F=\frac{Q_{\text{т}}}{q_{\text{т}}\eta_{\text{т}}}k_{\text{р}},$$

where q_T is the thermal stress of the heating surface; η_T is the efficiency of the heating plants; k_{res} is the coefficient of reserve of the heating equipment.

The cost of constructing the heating stations is

[CT = cost; Шу = Shu; H = in; T = heat; ИЗ = insul; K = end]

$$K_{\text{ст}}=\frac{\pi Lk_{\text{р}}(t_{\text{н}}-t_{\text{к}})C_{\text{т}}}{q_{\text{т}}\eta_{\text{т}}\text{Шу}}\,\frac{1}{A+B\ln D_{\text{из}}},$$

where C_{heat} is the cost of constructing the heating plants, related to a unit heating surface of the plant.

The operational expenditures for a heating station can be represented in the form

$$\text{Э}_{\text{ст}}=\alpha'K_{\text{ст}}+a_1n+a_2n\,\frac{Q\rho c_{\text{м}}(t_{\text{н}}-t_{\text{к}})}{\eta_{\text{т}}},$$

[CT = cost; H = in; K = end]

where α' are the annual costs for current maintenance and amortization in fractions of unity; a_1 are the annual wages allocated for one heating station; a_2 are the expenditures for water, fuel, lubricants, etc. per unit of station thermal power.

Then the reduced expenditures for heating stations are

[CT = cost; ИЗ = insul]

$$S_{\text{ст}}=EK_{\text{ст}}+\text{Э}_{\text{ст}}=\frac{M}{A+B\ln D_{\text{из}}},$$

where

$$M=\frac{\pi L(t_{\text{н}}-t_{\text{к}})}{\text{Шу}}\left[(\alpha'+E)\frac{k_{\text{р}}C_{\text{т}}}{q_{\text{т}}\eta_{\text{т}}}+\frac{a_1}{Q\rho c_{\text{м}}(t_{\text{н}}-t_{\text{к}})}+\frac{a_2}{\eta_{\text{т}}}\right];$$

[H = in; K = end; Шу = Shu; T = heat]

E is the standard coefficient of effectiveness of capital investments.

Next we take into account the expenditures on insulation. The capital expenditures are represented in the form

[из = insul]
$$K_{\text{из}}=V_{\text{из}}\rho_{\text{из}}C_{\text{из}}=\frac{\pi}{4}\left(D_{\text{из}}^2-D_N^2\right)L\rho_{\text{из}}C_{\text{из}},$$

where V_{insul} is the volume of insulation; ρ_{insul} is the density of insulation; C_{insul} is the cost of a unit mass of insulation, including expenditures on its installation.

The operational expenditures on the maintenance of insulation are

[из = insul]
$$Э_{\text{из}}=\beta_1 K_{\text{из}}+b_1,$$

where β_1 are the costs for amortization and current repair of the thermal insulation in fractions of unity; b_1 are expenditures not dependent on the pipeline parameters.

Then the reduced expenditures on thermal insulation are

$$S_{\text{из}}=(E+\beta_1)\frac{\pi}{4}\left(D_{\text{из}}^2-D_N^2\right)L\rho_{\text{из}}C_{\text{из}}+b_1.$$

The total reduced expenditures are

$$\sum S=\frac{M}{A+B\ln D_{\text{из}}}+M_1D_{\text{из}}^2+M_2,$$

where

$$M_1=\frac{\pi}{4}(E+\beta_1)\frac{\pi}{4}L\rho_{\text{из}}C_{\text{из}};$$

M_2 are the remaining terms, not dependent on the thickness of the insulation.

Equating $\partial\sum S/\partial D_{\text{insul}}$ to zero, we obtain an algebraic equation relative to D_{insul}

$$D_{\text{из}}(A+B\ln D_{\text{из}})=\left(\frac{MB}{2M_1}\right)^{0.5},$$

which is solved numerically or graphically.

It follows from an analysis of the equation that the optimum thickness of the thermal insulation is not dependent on the length of the pipeline and the viscosity of the pumped liquid; it decreases with an increase in the depth of laying the line, diameter, throughput capacity of the pipeline, cost of the insulation, and increases with an increase in the coefficients of thermal conductivity of the ground and insulation.

If we are considering the cyclic operation of "hot" pipelines, it is necessary to carry out checking computations in order to select insulation of such a thickness as would make it possible after stoppage for a stipulated time to resume pumping without complications or to estimate the time of possible stoppage of the pipeline having a particular thickness of the insulation for which the petroleum product along its entire length is not cooled below the stipulated temperature.

#8.8. Pumping of Petroleums Which are Non-Newtonian Liquids

As mentioned in #8.1, the flow of paraffinic petroleums and petroleum products can with some approximation be described by the equation

[пл = pl(astic)]

$$\tau = \tau_0 - \eta_{пл} \frac{dw}{dr}, \tag{8.14}$$

the so-called Bingham equation.

Such petroleums are non-Newtonian liquids and can be classified as Bingham fluids.

For a cylinder in a flow of liquid, whose axis coincides with the axis of the pipeline, we can write the following dependence between the force acting on the cylinder and the stress at the cylinder surface (Fig. 8.11):

$$\Delta p \pi r^2 = 2\pi r l \tau, \tag{8.15}$$

where Δp is the drop in pressures acting on the ends of the cylinder; r is cylinder radius; l is the length of the pipeline.

It follows from (8.15) that

$$\tau = \frac{\Delta p r}{2l}. \tag{8.16}$$

Substituting the τ value into (8.14), after transformation we obtain an expression for the velocity of the flow at the distance r from the axis of the pipeline

$$w = \int -\frac{1}{\eta_{пл}} \left(\frac{\Delta p r}{2l} - \tau_0 \right) dr = -\frac{1}{\eta_{пл}} \left(\frac{\Delta p r^2}{4l} - \tau_0 r \right) + C. \tag{8.17}$$

[пл = pl(astic)]

$$C = \frac{1}{\eta_{пл}} \left(\frac{\Delta p R^2}{4l} - \tau_0 R \right).$$

The integration constant C is determined from the condition of attachment of the liquid on the wall (absence of slipping), that is, when r = R and w = 0:

[пл = pl(astic)]

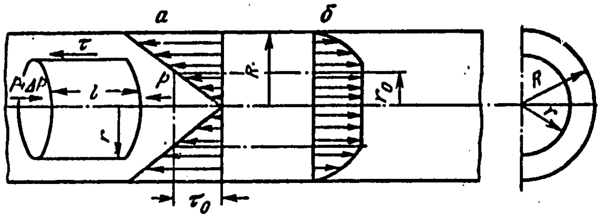


Fig. 8.11. Curves illustrating shearing stresses (a) and velocities (b) in cross section of Bingham liquid flow.

Substituting the C value into (8.17), we obtain

$$w = \frac{1}{\eta_{пл}} \left[\frac{\Delta p (R^2 - r^2)}{4l} - \tau_0 (R - r) \right]. \tag{8.18}$$

Figure 8.11 shows a shearing stresses curve constructed in accordance with (8.16) for the cross section of the flow. These stresses decrease from a maximum value on the pipeline wall to zero on the axis. When these stresses are equal to or less than the yield point τ_0 there is no shear between the concentric layers of flow and accordingly the "nucleus" of the flow moves as a solid body. The radius r_0 of this nucleus is determined by the substitution of $\tau = \tau_0$ into (8.16):

$$r_0 = \frac{2l\tau_0}{\Delta p}. \tag{8.19}$$

The velocity of the nucleus w_{nuc} is determined by the substitution of the r_0 value from (8.19) into (8.18):

[я = nuc]

$$w_{я} = \frac{\Delta p}{4\mu l}(R - r_0)^2.$$

Figure 8.11 shows the curve of flow velocities of a Bingham liquid in which the nucleus moves as a solid body and the liquid surrounding the nucleus flows in a laminar regime. Such a flow is called structured flow.

The discharge for a structured flow can be determined from the expression

[я = nuc]

$$Q = \int_{r_0}^{R} 2\pi r\,dr w + \pi r_0^2 w_{я}. \tag{8.20}$$

Substituting the w and w_{nuc} values found above into (8.20), after integration we obtain

[пл = pl(astic)]

$$Q = \frac{\pi R^4 \Delta p}{8\eta_{пл} l}\left[1 - \frac{4}{3}\frac{2l\tau_0}{R\,\Delta p} + \frac{1}{3}\left(\frac{2l\tau_0}{\Delta p R}\right)^4\right]. \tag{8.21}$$

This equation was derived by Buckingham in 1921.

It follows from (8.19) that the lesser the pressure drops in the pipeline, the greater is the radius of the nucleus r_0. With a definite pressure drop the radius of the nucleus becomes equal to the internal radius of the pipeline R -- this is the minimum pressure drop at which the liquid still moves. This pressure drop is equal to

$$\Delta p_0 = \frac{2l\tau_0}{R}. \tag{8.22}$$

From (8.21) and (8.22) we obtain another form of the Buckingham equation:

[пл = pl(astic)]

$$Q = \frac{\pi \Delta p R^4}{8\eta_{пл} l}\left[1 - \frac{4}{3}\frac{\Delta p_0}{\Delta p} + \frac{1}{3}\left(\frac{\Delta p_0}{\Delta p}\right)^4\right].$$

The Buckingham equation relates the flow to the pressure loss for a Bingham liquid in a horizontal pipeline. Flow is usually stipulated and it is necessary to determine the corresponding pressure loss, which can be done using the Buckingham formula only by means of several iterations. Since in many cases Δp_0 is considerably less than Δp, the third term in the brackets in these cases can be neglected, which somewhat simplifies the determination of pressure loss Δp.

As might be expected, when $\tau_0 = \Delta p_0 = 0$ the Buckingham equation is transformed into a computation formula for a laminar regime -- the Poiseuille equation

$$\Delta p = \frac{128}{\pi g} \cdot \frac{Q\nu}{D^4} l \rho g.$$

#8.9. Optimum Heating Temperature

In contrast to isothermic pipelines, where in the planning it is necessary to optimize only the diameter of the pipeline and the pressure at the output from the pumping station, in the planning of a "hot" pipeline it is necessary to optimize a great number of parameters: the diameter of the pipeline, the temperature at the heater input and output, the number of pumping-heating stations, heating stations and pumping stations, etc. It seems impossible to solve this problem in general form, analytically, obtaining dependences by means of which it would be possible to compute the values of parameters suitable for practical use. In each specific case this problem must be solved by a comparison with respect to the economic indices of the entire complex of variants which are feasible on a practical basis. Due to the great volume of computations, and also the considerable number of variants, it is desirable that electronic computers be used in selecting the optimum parameters.

Accordingly, the temperature of heating of the petroleum at the stations on "hot" pipelines is one of the planning parameters, related to the other construction parameters of the pipeline, and its optimum value must be determined in the stage of pipeline planning.

However, in the operation of an already constructed "hot" pipeline the problem arises of selecting the optimum temperature of petroleum heating. The fact is that in the planning process the optimization of pipeline parameters is accomplished for any stipulated conditions: definite air and ground temperature, fixed throughput capacity, properties of the petroleum to be transported, etc. In the operation of a pipeline many of these conditions change or can change. In particular, in the course of the year there is a change in the temperature of the medium surrounding the pipeline, there can be a change in the pumped volumes and the nature of the petroleum to be pumped. In these cases the planned temperature of heating of the petroleum at the stations ceases to be optimum and in each individual case it must be determined anew.

The optimum temperature of heating of petroleum at the stations is determined from the following considerations. With an increase in the heating temperature there is an increase in the expenditures on heating of the petroleum; at the same time there is a decrease in petroleum viscosity, and this means head losses in the pipeline and corresponding expenditures on petroleum pumping. The optimum temperature of petroleum heating corresponds to the minimum of the sum of expenditures on the heating and pumping of petroleum.

With the introduction of some simplifications the problem of optimization of heating temperature can be solved analytically, but the graph analysis solution of this problem is more precise and graphic.

The power N or the quantity of energy expended in a unit time on the pumping of petroleum is determined from the expression

$$N=\frac{QH\rho g}{\eta_{M}},$$

where Q is the discharge; H is the head developed by the pumping plants, equal to the total head loss in the segment of the pipeline between two pumping-heating stations (if there are pumping stations on the line between the pumping-heating stations, this head is equal to the sum of the heads developed by all the pumping plants in the segment of the line; η_M is the mechanical efficiency of the pumping plant.

The cost of the mechanical energy is

$$S_{M}=\frac{QH\rho g}{\eta_{M}}\sigma_{M}, \tag{8.23}$$

where σ_M is the cost of a unit of mechanical energy.

The cost of the thermal energy expended in a unit time on the heating of petroleum is determined from the expression

$$S_{t}=\frac{Q\rho c\,(t_{H}-t_{K})}{\eta_{t}}\sigma_{t}, \tag{8.24}$$

[H = in; K = end]

where η_t is the efficiency of the heating apparatus; σ_t is the cost of a unit of thermal energy.

If there are heating stations on the line between the pumping-heating stations, the value obtained using formula (8.24) must be multiplied by the number of heatings on the line between the pumping-heating stations (it is assumed, as is usually done, that at the pumping-heating stations and all heating stations the difference in petroleum temperatures at the emergence and entry into the station is identical). The loss of head H, determined using formula (8.11), is dependent on the temperature t_{in} at the emergence from the pumping-heating station. The temperature t_{end} at the end of the line between pumping-heating stations can also be determined using formula (8.5) as a function of t_{nuc}. Stipulating a series of t_{in} values, we determine the corresponding values S_M and S_t and in the coordinates S and t_{in} we construct (Fig. 8.12) the curves $S_M = f(t_{in})$ and $S_t = f(t_{in})$. The optimum temperature is that corresponding to the minimum of the function $S_M + S_t = f(t_{end})$.

Despite the fact that the structure of formula (8.24) indicates, it would seem, that there is a linear dependence $S_t = f(t_{in})$, in a general case this dependence is expressed by a curved line, since with an increase in heating temperature t_{in} there is a change in the ratio of the lengths of segments with turbulent and laminar flows; an increase in t_{in} leads to an increase in the length of the turbulent segment, an increase in the mean weighted heat transfer coefficient for the particular pipeline segment, and as a result, an increase in the temperature difference t_{in} and t_{end}.

The t_{in} values must be adopted taking technological limitations into account. The heating temperature of the petroleum t_{in} must not exceed the values at which there will occur a clogging-up of the pipes in the heat-exchange apparatus or the decomposition of petroleum begins. At the same time, the petroleum temperature at the end of the run t_{end} must exceed its congealing point by not less than 3-5°C in the case of highly congealing petroleums; accordingly, using formula (8.5) with a known minimum t_{end} value we determine the lower limit of the possible t_{end} values. For highly viscous petroleums there is no technological restriction with respect to the lower limit t_{end}.

#8.10. Placement of Stations on "Hot" Pipeline

The installation of three types of stations is possible on a "hot" pipeline: heating stations (HS), pumping stations (PS) and pumping-heating stations (PHS). For practical purposes there can be three combinations of stations on the pipeline: 1) only PHS; 2) PHS and HS and 3) PHS and PS.

We will examine how the stations are placed on the pipeline in all the mentioned variants.

1. Only pumping-heating stations are installed on the pipeline (Fig. 8.13).

On the vertical drawn on the profile from the beginning of the route we plot the backup h_{back} created by the backup pumps and the head H_{pump} created by the mainline pumps (if the stations are equipped with piston pumps, then only the head created by the mainline pumps is plotted).

Using the Shukhov formula, we determine the point where the temperature drops to the value t_{cr} corresponding to a transition of the flow regime from turbulent to laminar.

Breaking down the sector with turbulent flow into several segments (preferably with identical ground conditions in each of these segments, which will make it possible for each of them to take a particular value of the total heat transfer coefficient), we will determine the head losses in each of them ($m = 0.25$) and from the determined values we will construct a curve of the piezometric heads. If this curve intersects the route profile, this means that in the entire run to the next pipeline pumping-heating station a turbulent regime will be observed. However, if the curve does not intersect the route profile, then from the point where the turbulent regime undergoes transition into a laminar regime we will determine the head losses in short segments, using the same Chernikin formula (8.11a), but with $m = 1$, successively until the curve of piezometric heads intersects the profile of the pipeline route. Then, dropping back along the profile to the point where the head is equal to the necessary anticavitation backup h_{cav} for the pumps, from the curve of piezometric heads we plot the head H_{main} developed by the mainline pumps installed at the pumping-heating station at this point and we will continue the construction the same as for the run between the first and second pumping-heating stations. With the equipping of the stations with piston pumps the station is constructed at the point of intersection of the lines of the piezometric heads and the route profile.

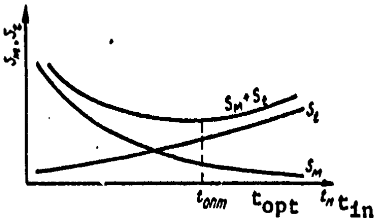


Fig. 8.12. Graph for determining optimum heating temperature.

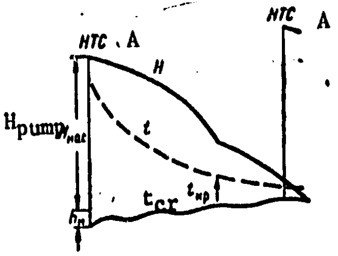


Fig. 8.13. Placement of pumping-heating stations along pipeline route.

2. It is necessary to install pumping-heating stations and heating stations on the pipeline (Fig. 8.14).

As in the preceding case, on the profile from the beginning of the pipeline route we plot the head at the main pumping-heating station. Taking into account the possible change in the heat transfer coefficient we determine the distance L_{fin} from the pumping-heating station to the point where the temperature drops to the computed value t_{fin} (the final temperature before the next station) and ℓ_{cr} from the pumping-heating station to the point where the temperature drops to t_{cr}. We will break down the distance L_{fin} into segments with the constant heat transfer coefficients k and if $L_{fin}<\ell_{cr}$, we use computations with the Chernikin formula with construction of the curve of piezometric heads only for a turbulent regime ($m = 0.25$), and if $L_{fin} > \ell_{cr}$ -- for two regimes -- to ℓ_{cr} for a turbulent regime and from ℓ_{cr} to L_{fin} for a laminar regime ($m = 1$). If the curve of piezometric heads intersects the route profile to L_{fin}, in the particular segment between pumping-heating stations it is not necessary to have a heating station and the placement of a second pumping-heating station is accomplished the same as in the preceding case. However, if the piezometric curve does not intersect the route profile, then in the place where the curve ends, that is, at the distance L_{fin} from the head pumping-heating station it is necessary to construct a heating station which again raises the temperature of the petroleum to t_{in}. Then we determine the distance L'_{fin} to the point where the temperature drops to t_{fin} and also the distance ℓ'_{cr} and as before, we will carry out computations and make our constructions. These computations are repeated until the piezometric line intersects the route profile. Retreating along the route to the point where the backup is equal to (or exceeds) the anticavitation value, we place there a pumping-heating station. Further computations and constructions for the placement of heating stations and pumping-heating stations are similar to those described.

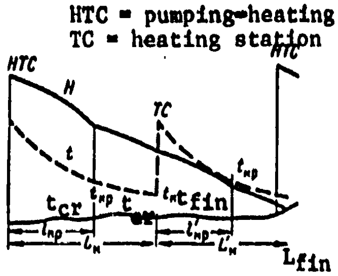


Fig. 8.14. Placement of pumping-heating stations and heating stations along pipeline route.

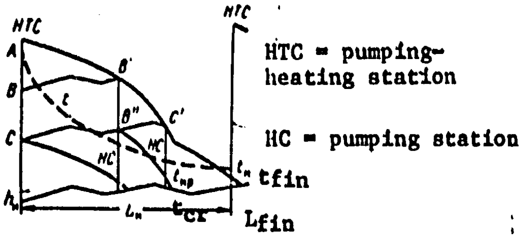


Fig. 8.15. Placement of pumping-heating stations and pumping stations along pipeline route.

3. It is necessary to install pumping-heating stations and pumping stations on the pipeline (Fig. 8.15).

Using the Shukhov formula (8.5) we determine the distance L_{fin} from the beginning of the pipeline at which the temperature drops from t_{in} to t_{fin}, obtained by computations when determining the optimum pipeline parameters. In the case of a substantial difference in the heat transfer coefficients in the different segments of the route the computations of the temperature decrease are made by segments. At the distance L_{fin} from the beginning of the pipeline a second pumping-heating station is constructed (the first is installed at the beginning of the pipeline).

Substituting the L_{fin} value into the Chernikin formula (8.11a) we find the head loss in this segment (in the case of two regimes in the segment -- turbulent and laminar -- we compute the losses in each segment and sum them).

On the route profile we draw a vertical from its origin; on this profile we plot the backup created by the supporting (backup) pumps and then we add the head H, equal to the computed head loss. The head H is divided by an equal number of parts in such a way that each part is equal to or is somewhat less than the admissible head at the station (points B and C).

We construct a conditional curve of piezometric heads from the point A in accordance with the Chernikin formula. This curve with a vertical drawn from the location of the second pumping-heating station on the profile intersects at a height from the profile line h_{cav} corresponding to the anticavitation head which is imparted to the second pumping-heating station.

From the points B and C we draw lines equidistant to the route profile to the intersection with the conditional curve of the piezometric heads (B', C'). The points on the intersections of the verticals drawn through B' and C' with the line of the route profile correspond to the points of location of the pumping stations. If we draw from C and B" lines which are equidistant from the lines AB' and B'C', we obtain the lines of piezometric heads on the segments (runs) between stations.

Other combinations of stations are also possible: pumping-heating stations with pumping stations and heating stations, pumping stations and heating stations; the construction principles for the placement of stations in these cases are similar to those described above.

#8.11. Increase in the Throughput Capacity of "Hot" Pipelines

As in the case of isothermic pipelines, increases in the throughput capacity of "hot" pipelines by a change in their design can be achieved by three methods: by the laying of a looping, by an increase in the number of stations and a combination of these two methods. But since stations of all three types can be constructed on a "hot" pipeline, accordingly there is an increase in the number of methods: 1) the laying of a looping; 2) an increase in the number of pumping-heating stations; 3) an increase in the number of heating stations; an increase in the number of pumping stations.

In addition, it is possible to increase the throughput capacity by a combination of the mentioned methods. We will examine each of them.

1. An increase in the throughput capacity by the laying of a looping (Fig. 8.16). With different diameters of the looping and the main pipeline the thermal regimes in these two lines in parallel sectors will not be the same, and this will exert an influence on the distribution of the flows. Therefore, the formulas for isothermic hydraulics for computations of the loopings on "hot" pipelines are inapplicable. In order to determine the length of the looping necessary for attaining a stipulated increase in throughput capacity we will write a system of equations:

1) head balance in the segment between stations (see Fig. 8.16)

$$H=\beta\frac{Q_c^{2-m}\nu_\text{н}^m}{D^{5-m}}l_1\frac{e^{mu(t_\text{н}-t_0)}}{al_1}\{Ei[-mu(t_\text{н}-t_0)]-Ei[-mu(t_{\text{н}1}-t_0)]\}+ \tag{8.25}$$
$$+\beta\frac{Q_1^{2-m}\nu_{\text{н}1}^m}{D_\text{л}^{5-m}}l_\text{л}\frac{e^{mu(t_{\text{н}1}-t_0)}}{a_1l_\text{л}}\{Ei[-mu(t_{\text{н}1}-t_0)]-Ei[-mu(t_{\text{к}1}-t_0)]\}+\Delta h;$$

[t_H = t_{in}; t_K = t_{fin}; Л = loop(ing); $t_{K,Л}$ = $t_{loop\ fin}$ (end of looping)]

2) the condition of equality of head losses in the looping and the segment of the main pipeline parallel to it

[c = tot(al)]

$$\frac{Q_1^{2-m}}{a_1D^{5-m}}\{Ei[-mu(t_{\text{н}1}-t_0)]-Ei[-mu(t_{\text{к}1}-t_0)]\}= \tag{8.26}$$
$$=\frac{Q_\text{л}^{2-m}}{a_\text{л}D_\text{л}^{5-m}}\{Ei[-mu(t_{\text{н}1}-t_0)]-Ei[-mu(t_{\text{к},\text{л}}-t_0)]\};$$

3) equations of temperature decrease along length of pipeline

$$t_{\text{н}1} = t_0 + (t_{\text{н}} - t_0)\,e^{-a l_1}; \quad (8.27)$$

$$t_{\text{к}1} = t_0 + (t_{\text{н}1} - t_0)\,e^{-a_1 l_{\text{л}}}; \quad (8.28)$$

$$t_{\text{к.л}} = t_0 + (t_{\text{н}1} - t_0)\,e^{-a_{\text{л}} l_{\text{л}}}; \quad (8.29)$$

4) balance equations for lengths and flows

$$L = l_1 + l_{\text{л}}, \quad (8.30)$$

$$Q_c = Q_1 + Q_{\text{л}}; \quad (8.31)$$

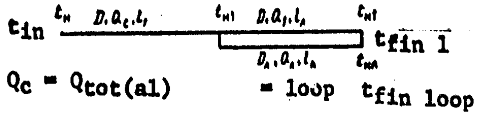


Fig. 8.16. Increase in throughput capacity of petroleum pipeline by the laying of a looping.

5) other dependences:

$$a = \frac{k\pi D}{Q_c \rho c}, \quad (8.32)$$

$$a_1 = \frac{k\pi D}{Q_1 \rho c}, \quad (8.33)$$

$$a_{\text{л}} = \frac{k\pi D_{\text{л}}}{Q_{\text{л}} \rho c}, \quad (8.34)$$

$$\nu_{\text{н}} = \nu_{t1} e^{-u(t_{\text{н}} - t_1)}, \quad (8.35)$$

$$\nu_{\text{н}1} = \nu_{t1} e^{-u(t_{\text{н}1} - t_1)}. \quad (8.36)$$

In these equations L, l_1 and l_{loop} are the lengths of the entire segment, the segment to the looping and the looping; Q_{loop}, Q_1 and Q_{tot} [c = tot(al)] are the flows in the looping, in the line parallel to the looping and the total flow; t_{in}, $t_{fin\ 1}$, $t_{fin\ loop}$, $t_{fin\ 1}$ are the temperatures at the beginning of the line segment, at the beginning of the looping, at the end of the looping and at the end of the pipeline segment parallel to the looping.

By the joint solution of the equations cited above we determine the length of the looping l_{loop} of the stipulated diameter D_{loop} ensuring an increase in the throughput capacity to the stipulated value Q_{tot}.

The following sequence of computations can be recommended:
1) we stipulate the length of the looping l_{loop} and from (8.30) we determine l_1;
2) from (8.27) we determine t_{in} 1, first determining a from (8.32);

3) from (8.35) and (8.36) we find ν_{in} and $\nu_{in\ 1}$;
4) we stipulate the value Q_1 and from (8.31) we determine Q_{loop};
5) substituting Q_1 and Q_{loop} into (8.33) and (8.34), we determine a_1 and a_{loop};
6) from (8.28) and (8.29) we determine $t_{fin\ 1}$ and $t_{fin\ loop}$;
7) we substitute all the determined values of the parameters into (8.26). If the identity is not satisfied, we change the adopted Q_1 value and repeat all the operations in 4)-7) until (8.26) is transformed into an identity;
8) we substitute all the determined values of the parameters into (8.25). If the identity is not satisfied, we change the adopted ℓ_{loop} value and we repeat all the operations in 1)-8) until (8.25) is transformed into an identity.

In all the formulas cited above it is assumed that the flow regime in the entire extent of the pipeline is identical. Somewhat complicating the formulas, it is also possible to obtain a solution for the case of different regimes in the pipeline segments.

As a result of the great number of uniform computations, it is desirable to use an electronic computer for determining the length of the looping.

In contrast to isothermic pipelines, the position of the looping on a "hot" pipeline exerts an influence on the total head loss. The loopings must be situated on the "cold" ends of the segments; the thermal losses will be less than when laying a looping at the "hot" end, and accordingly, the total head loss will be less with the same flow.

2. An increase in the number of pumping and heating stations (Fig. 8.17). We will examine the segment between two pumping and heating stations with a uniform rise or descent of the route and identical thermophysical characteristics of the ground along the route. Then the second pumping and heating station with the same head and heating temperature as the first pumping and heating station must be constructed in the middle of the segment (run) and the head H of each pumping and heating station will be expended on overcoming resistance in a half of the segment length, that is, $H = f(Q_{tot}, \ell/2)$. Therefore, in accordance with (8.11a) we obtain

$$H=\beta\frac{\nu_{н}^{m}}{D^{5-m}}Q_{c}^{2-m}\frac{c\rho}{k^{*}\pi D}\left\{Ei\left[-mu\left(t_{н}-t_{0}\right)\right]-Ei\left[-mu\left(t_{н}-t_{0}\right)e^{-\frac{k^{*}\pi D}{c\rho}\frac{l}{2Q_{c}}}\right]\right\}\Delta_{r*}+\frac{\Delta h}{2}, \quad (8.37)$$

[c = tot(al); H = in(itial)] where k^* and Δ_{R*} are the values of the coefficients k and Δ_r after an increase in the throughput capacity.

The Q_{tot} value is determined by the successive approximations method or by graphic interpolation from (8.37).

In the case of a dissected route profile, dissimilar thermophysical properties of the ground along the route or a change in flow regimes in the segment prior to the installation of an additional pumping-heating station,

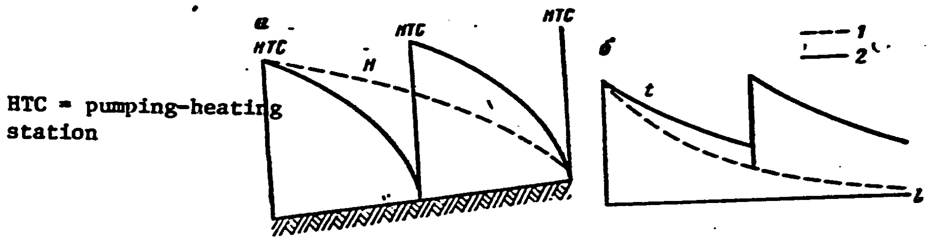


Fig. 8.17. Distribution of heads H(a) and temperatures t(b) along length of "hot" pipeline before doubling of pumping-heating stations (1) and after doubling of pumping-heating stations (2).

the latter need not be placed in the middle of the above-mentioned segment, the positioning of the additional pumping and heating stations is determined in this same case the same as when positioning it on a newly planned pipeline.

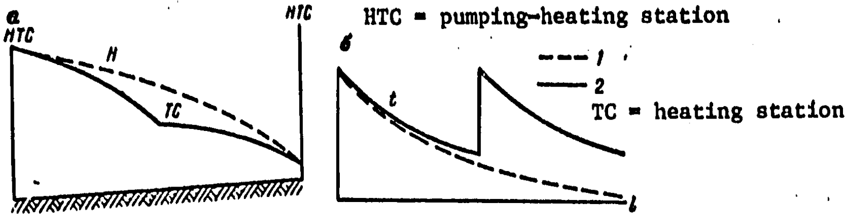


Fig. 8.18. Distribution of heads H (a) and temperatures t (b) along length of "hot" pipeline before doubling of pumping-heating stations (1) and after doubling of pumping-heating stations (2).

It should be noted that in the case of a dissected profile and different thermophysical properties of the ground along the route the number of additional pumping and heating stations in different segments for attaining a stipulated increase in throughput capacity can be dissimilar.

Figure 8.17 also shows the distribution of petroleum temperatures along the route before and after installation of additional pumping and heating stations. The higher temperature on the approach to the additional pumping and heating station than before its construction is attributable to an increase in flow due to the installation of the additional pumping and heating station.

3. An increase in the number of heating stations (Fig. 8.18). With identical thermophysical properties of the ground along the route and an identical flow regime in the entire segment it is necessary that an additional heating station be constructed in the middle of the segment. The head H of the pumps will be expended in overcoming the resistances of two segments of the length $l/2$ identical in thermal regime, where l is the length of the segment between the pumping-heating stations, that is,

$$H=2f\left(Q_c,\ \frac{l}{2}\right).$$

[c = tot(al)]

Substituting these notations into formula (8.11a), we obtain

$$H=2\beta\frac{\nu_н^m}{D^{5-m}}Q_c^{3-m}\frac{c\rho}{k^*\pi D}\left\{Ei\left[-mu(t_н-t_0)\right]-Ei\left[-mu(t_н-t_0)e^{-\frac{k^*\pi D}{c\rho}\cdot\frac{l}{2Q_c}}\right]\right\}\Delta_{ре}+\Delta h. \qquad (8.38)$$

[c = tot(al); H = in(itial); cp = mean]

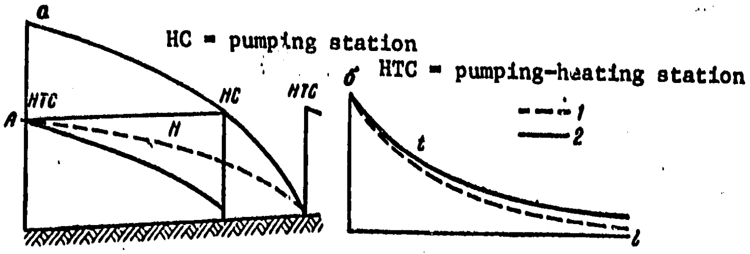


Fig. 8.19. Distribution of heads (a) and temperatures t (b) along length of "hot" pipeline before doubling (1) and after doubling (2) of pumping stations.

The Q_{tot} value, as in the preceding case, is determined by the iterations method.

4. An increase in the number of pumping stations (Fig. 8.19). With the construction of an additional pumping station the doubled head of the station will be expended on overcoming the resistances on the segment between the pumping and heating stations, that is

$$2H = f(Q_{tot}, \ell)$$

or

$$2H=\beta\frac{\nu_{H}^{m}}{D^{5-m}}Q_{c}^{3-m}\frac{cp}{k^{*}\pi D}\left\{Ei\left[-mu\left(t_{H}-t_{0}\right)\right]-Ei\left[-mu\left(t_{H}-t_{0}\right)e^{-\frac{k^{*}\pi D}{cp}\cdot\frac{l}{Q_{c}}}\right]\right\}\Delta_{re}+\Delta h. \quad (8.39)$$

[c = tot(al); cp = mean)]

The additional pumping station must be located closer to the end of the line so that the head losses overcome by each station will be identical. The positioning of the additional pumping station can be determined analytically, but it is more convenient to do this by the graph analysis method.

For this purpose on the profile of the route at the beginning of the run we plot off the backup and the doubled head of the mainline pumping stations. Substituting different ℓ values into formula (8.39), we determine the corresponding values of the head losses and we construct a conditional piezometric curve. From the point A, corresponding to the head at one station, we draw a line which is equidistant to the route profile; its intersection with the conditional piezometric line determines the position of the additional pumping station.

#8.12. Special Operating Regimes of "Hot" Pipelines

"Hot" pipelines a considerable part of the time operate in a nonstationary thermal and hydraulic regime. A thermal nonstationary state, associated with slow heating or cooling of the medium surrounding the pipeline, can lead to a stoppage of the pipeline due to an exceptional increase in the head in it -- to its "freezing up."

One of the most serious and responsible operations is the start-up of a newly constructed hot pipeline. Before being put into operation the petroleum pipeline is filled with cold water after welding. If this water is forced out by hot viscous petroleum or petroleum which has great tendencies for congealing, for whose pumping the pipeline was designed, the petroleum (especially that part of it in contact with the cold water) will cool rapidly, its viscosity is greatly increased or it solidifies and plugs up the pipeline, stopping the flow.

In the case of a short distance between the heating stations and a relatively low viscosity or solidification point of the petroleum it is sometimes possible to accomplish a start-up of pumping into a cold pipeline by heated viscous petroleum or petroleum with high solidifying properties. However, in most cases such conditions do not exist and the pipeline must be heated before pumping in any petroleum. It is necessary to create a corresponding heat field in the ground around the pipeline. Such a field before startup is created by pumping a heated low-viscosity petroleum, petroleum products or water through the petroleum pipeline.

For determining the duration of heating (pumping through of a heating fluid) P. I. Tugunov has proposed a simplified formula:

$$\tau = 0{,}111\,\frac{D_{\text{н}}^{2}}{a}\exp\left(\frac{t_{\text{тр}}-t_{0}}{q}4\pi\lambda\right), \tag{8.40}$$

where τ is the duration of heating by a low-viscosity petroleum product; D_{ex} [D_H] is the external diameter of the pipe; a and λ are the thermal diffusivity and thermal conductivity coefficients for the ground; t_{pipe} [t_{TP}] is the temperature of the outer wall of the pipeline, assumed equal to the temperature of the heating fluid at the end of the segment between heating stations; t_0 is the temperature of the ground in an unimpaired thermal state at the depth at which the pipeline is laid; q is the heat transfer from a unit length of the pipeline in a unit time,

$$q \approx Gc\,(t_{\text{н}}-t_{\text{к}})\,\frac{1}{L};$$

[H = in; K = fin(al)]

G is the mass flow of the heating fluid; c is the heat capacity of the fluid; t_{in} and t_{fin} are the initial and final temperatures of the heating fluid; L is the distance between the heating stations.

The wall temperature of the pipe is 2-10°C lower than the flow temperature and therefore, assuming in (8.40) that the temperature of the pipe wall t_{pipe} is equal the the flow temperature t_{fin}, the heating time is somewhat exaggerated, that is, there is assurance of some time reserve.

The volume of the heating fluid is then determined from the formula

$$V = \frac{G}{\rho} \tau.$$

The value $t_{pipe} = t_{fin}$ is assumed to be such that the total head loss in the segment between the pumping stations with pipeline filling by the transported petroleum does not exceed the maximum admissible head at the stations and at the same time the flow will be turbulent or situated in the third zone of the characteristic curve in the case of laminar flow. This will make it possible to put the pipeline into a stationary thermal regime while already pumping the oil to be transported. The heating can be speeded up by using for this purpose heated water instead of a low-viscosity petroleum product; the heated water has approximately a twofold greater heat capacity than petroleum products. The heating time of the water τ_{water} with a known time for heating by a petroleum product τ_{pet} is determined using the approximate formula:

$$\tau_{\text{в}} = \tau_{\text{н}} \exp\left(-\frac{4\pi\lambda L}{G_{\text{в}} c_{\text{в}}}\right),$$

[B = water; H = pet(roleum products)] where G_{water} and c_{water} are the mass flow and the heat capacity of water.

By technical-economic computations it can be determined to what thermal level (above the minimum, determined by the maximum admissible head losses in the segment between pumping stations with the pumping of the petroleum to be transported) it is desirable during the heating of water to heat the petroleum pipeline before the initial pumping of petroleum.

The formulas cited above must be used for preliminary computations of heating of the petroleum pipeline. Due to the inaccuracy in determining the thermal diffusivity, thermal conductivity coefficients and other parameters, and also the inaccuracy in the mathematical model the actual heating time can differ substantially from the computed value. Therefore, the pumping in of the petroleum to be transported must begin when the temperature of the heating fluid at the end of the segment between heating stations, measured with instruments, attains the stipulated value t_{fin}.

In the operation of a "hot" pipeline it is inevitable that it will experience stoppages for more or less prolonged periods. These can be caused by damage in one of the segments, the need for carrying out repair work, disruptions in the delivery of petroleum to the head station and the technology adopted for cyclic transfers. In order, insofar as possible, to prevent the "freezing up" of the petroleum pipeline, it is necessary to know the so-called safe time for stoppage of the pipeline, that is, the time during which the petroleum with a tendency to congeal will still not solidify in the stopped pipeline and a highly viscous petroleum will not attain that viscosity level at which the head loss will exceed the admissible head at the pumping station.

Approximately, the safe time τ of pipeline stoppage can be computed using the formula

$$\tau = 0{,}111 \frac{D_H^2}{a} \left(\frac{4H}{D_H}\right)^{2(1-\beta_0)},$$

$[D_H = D_{ex}]$ where H is the depth at which the pipeline is laid

$[t_H = t_{in(itial)}]$ $$\beta_0 = \frac{t - t_0}{t_H - t_0};$$

t_{in} is the initial temperature of the pipe wall (immediately after cessation of pumping); t is the temperature of the pipe wall at which it is still possible, without any complications, to renew the pumping.

In some cases a "hot" pipeline has a throughput capacity considerably exceeding the quantity of petroleum received for transport. So it is during the initial period of working of the deposit when the production volume is still inadequate for loading of the main pipeline designed for the complete development of the field or during a period of decreasing production in a deposit which is being exhausted.

In these cases there can be two variants of pipeline operation: with continuous pumping with reduced flows and with cyclic pumping in which some of the time the pipeline operates with a full load and the remainder of the time the pumping ceases.

In order to ascertain which of the operating variants is more advantageous it is first necessary to determine the optimum number of cycles (in this case a cycle is the period of time including the duration of one interval of continuous pumping and one interval of stoppage) with cyclic pumping.

The greater the number of pumping cycles, the lesser need be the capacity of the additional tanks for the storage of petroleum at the two ends of the pipeline and the expenditures associated with them, but on the other hand, the greater will be the expenditures on the heating and substitution of the main product to be transported by a low-viscosity product at the time of pipeline stoppages. On the other hand, a reduction in the number of cycles causes an increase in expenditures on additional capacity and a decrease in the expenditures on substituting the petroleum in the pipeline by a low-viscosity product. By stipulating the cycles with different numbers, it is possible to ascertain the sum of the reduced expenditures on the capacity and expulsion of petroleum for each variant. The optimum number of cycles will be that corresponding to the variant with the minimum reduced expenditures.

Now we will compare variants with continuous and cyclic pumping. With continuous pumping with a reduced flow the petroleum temperature between the heating stations will drop off more than in the case of a nominal flow, which can lead to an excessive increase in head loss or the congealing of the petroleum. Accordingly, with a decrease in flow in comparison with the normal planned flow it is necessary to construct a definite number of additional heating stations, which involves additional expenditures on their construction and operation. However, in the case of cyclic pumping additional expenditures arise for tanks and for expulsion of petroleum by low-viscosity products during stoppages of pumping. The variant with minimum reduced expenditures will be better.

With the stoppage of petroleum pumping in a "hot" pipeline for a prolonged period, in order to prevent its "freezing-up" the petroleum must be expelled by a low-viscosity petroleum or petroleum product. In some cases the petroleum has succeeded in congealing before onset of expulsion.

If the petroleum to be expelled is a Newtonian fluid, that is, for this fluid, in particular, there is no static shearing stress, its expulsion from the entire segment between the pumping stations is possible by the station pumps. However, if the petroleum is non-Newtonian, such expulsion is possible only in a case when the pressure p developed by the station is adequate for overcoming the static shearing stress τ_{st}, that is, if there is satisfaction of the condition (for horizontal pipelines)

$$p\frac{\pi D^2}{4} \leqslant \pi D l \tau_{\text{ст}},$$

hence

$$p \geqslant \frac{4 l \tau_{\text{ст}}}{D},$$

[CT = st] where D and ℓ are the diameter and length of the pipeline segment between stations.

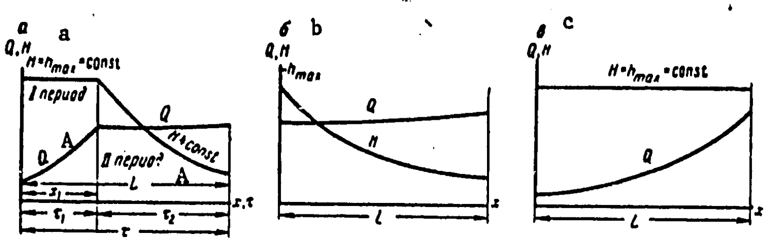


Fig. 8.20. Graph of expulsion of congealing petroleum from pipeline. A) period.

If this condition is not satisfied, the petroleum expulsion must be accomplished in lesser segments.

Now we will examine the piston process for the expulsion of petroleum which is employed with the placement of a separator in front of the expelling product or in the case of a structured flow of the petroleum to be expelled.

In order to accelerate the petroleum expulsion process it is desirable that it be accomplished with the maximum possible flow. In this case the restrictions are the maximum admissible head at the output from the pumping station, taking into account the strength of the pipeline and equipment, or the maximum delivery of the station pumps.

In a general case the petroleum expulsion process can be broken down into two periods (Fig. 8.20, a). During the course of the first period the head of these is limited to the maximum admissible value h_{max} and the flow Q with an increase in the length of the segment occupied by the low-viscosity product increases. Finally, the flow attains the maximum possible delivery of the pumps under the given conditions, that is, by this time the head restriction is completely removed. This is followed by a second period associated with a further increase in the length of the segment occupied by a low-viscosity product, a total loss of head, and together with it the head at the station is reduced and the flow in the pipeline slowly increases due to movement of the point of intersection of the head characteristics of the centrifugal pumping station and the petroleum pipeline in the direction of an increase in the flows (with the outfitting of the station with piston pumps the flow during the course of the second period will be constant).

Two special cases are possible. If in the case of total delivery by the pumps at the very beginning of expulsion the head developed by the pumps is equal to or less than the maximum admissible level (Fig. 8.20,b), the head at the station will constantly decrease and the flow will slowly increase. However, if the head losses in the pipeline corresponding to the maximum delivery by the station pumps when the expelling product reaches the end of the segment between the pumping stations exceed the maximum admissible head at the station h_{max}, the head at the station must constantly be maintained equal to h_{max} and the flow will constantly increase (Fig. 8.20, c).

For the first period (see Fig. 8.20,a) with expulsion of Newtonian petroleum the head losses in the pipeline at any moment are expressed as follows:

$$h_{max}\rho_1 = \frac{\beta_1 Q^{2-m_1} \nu_1^{m_1} x \rho_1}{D^{5-m_1}} + \frac{\beta_2 Q^{2-m_2} \nu_2^{m_2} (l-x)\rho_2}{D^{5-m_2}} + \Delta z \rho_{cp}, \qquad (8.41)$$

where the subscripts 1 and 2 relate to the expelling and expelled fluids respectively; Δz is the difference in the elevations of the end and beginning of the segment; ρ_{mean} is the mean density of the fluids in the pipeline.

Breaking down the pipeline into short segments, we will substitute the corresponding x values into (8.41) and determine the Q values for different flow regimes of the two fluids. Using the Q values for the segments we determine the time of passage through the discontinuity of each segment, and then summing them, we find the time τ_1 -- the duration of the first expulsion period.

In the case of a laminar flow regime of both fluids expression (8.41) is simplified:

$$\rho_1 h_{max} = \frac{128Q}{\pi g D^4}[\nu_1 x \rho_1 + \nu_2 (L - x)\rho_2] + \Delta z \rho_{cp}, \tag{8.42}$$

[cp = mean] hence

$$Q = \frac{\pi g D^4 (\rho_1 h_{max} - \Delta z \rho_{cp})}{128 [\nu_1 x \rho_1 + \nu_2 (L - x)\rho_2]}, \tag{8.43}$$

Substituting into the continuity equation

$$Q\,d\tau = \frac{\pi D^2}{4}\,dx \tag{8.44}$$

the Q value from (8.43), after integration we obtain the duration of the first expulsion period

$$\tau_1 = \frac{32}{g D^2 (\rho_1 h_{max} - \Delta z \rho_{cp})}\left(\nu_2 L x_1 \rho_2 - \frac{\rho_2 \nu_2 - \rho_1 \nu_1}{2} x_1^2\right) \tag{8.45}$$

The length of the segment x_1 corresponding to the first period of expulsion is determined from (8.42) by substitution of the Q value corresponding to the head h_{max} in accordance with the head characteristic curve for the pumping station.

For the second period it is possible to write the pressure balance equation

[H = in]
$$g\rho_1 (a_0 - h_{н} Q) = \frac{128Qg}{\pi g D^4}[\rho_1 \nu_1 x + \rho_2 \nu_2 (L - x)] + \Delta z \rho_{cp} g, \tag{8.46}$$

hence

$$Q = \frac{\pi g D^4 (a_0 \rho_1 - \Delta z \rho_{cp})}{128 [\rho_1 \nu_1 x + \rho_3 \nu'_2 (L - x)] + h_{н} \pi g D^4 \rho_1} \tag{8.47}$$

and after substitution into equation (8.44) and integration we obtain

$$\tau_2 = \frac{32}{g D^2 (\rho_1 a_0 - \Delta z \rho_{cp})}\left[\left(\nu_2 L \rho_2 + \frac{1}{128}\rho_1 h_{н} \pi g D^4\right)(L - x_1) - (\nu_2 \rho_2 - \nu_1 \rho_1)\frac{L^2 - x_1^2}{2}\right]$$

Here a_0 and h_{in} are coefficients of the interpolation formula in the form

$$H = a_0 - h_{in} Q,$$

describing the head characteristic curve of a centrifugal pumping station.

The total expulsion time is

$$\tau = \tau_1 + \tau_2.$$

If the petroleum to be expelled flows in a structured regime, the total pressure loss p_{tot} in the pipeline can be represented as follows:

$$p_{tot} = \frac{128 \nu_1 Q x \rho_1}{\pi D^4} + \frac{128 \nu_2 Q (L - x)\rho_2}{\pi D^4} + \frac{16}{3}\frac{\tau_0 (L - x)}{D}.$$

Here the first term represents the pressure loss in the segment x occupied by the "pushing" fluid, which moves in a laminar regime; the second and third terms represent the pressure loss in the segment L - x occupied by the fluid to be expelled, which moves in a structured regime, in accordance with the simplified Buckingham formula.

In this equation replacing p_{tot} by the maximum admissible pressure $h_{max}\rho_1 g$ for the first period and $(a_0 - h_{in}Q)\rho_1 g$ for the second period and solving this equation jointly with the continuity equation (8.34), similar to the preceding case we will determine the time for expulsion of the petroleum flowing in a structured regime.

If the petroleum to be expelled is a Newtonian fluid at the expulsion temperature, the product expelling it (with a laminar flow of both fluids) will be wedged into it (in the absence of a separator at the discontinuity of the fluids) and the vertex of the wedge attains the end of the line segment sooner than the remaining mass of the product. Accordingly, the entire process of petroleum expulsion can be divided into two phases: expulsion phase, ending when the wedge vertex of the expelling fluid reaches the end of the line segment, and the "washing" phase, during which there is a virtually complete expulsion of all the petroleum to be expelled from the line segment.

If it is assumed that during expulsion there is retention of the profile of velocities characteristic for a laminar regime, that is, the axial velocity is two times greater than the mean velocity, it is possible to determine approximately the duration of the first expulsion phase, which will be half as great as the duration determined using the formulas cited above.

The duration of the second phase -- the "washing out" -- is determined using the formulas for the similar operation of successive pumping in a laminar regime.

#8.13. Clearing of Paraffin Deposits from Petroleum Pipelines

Many petroleums, especially petroleums from eastern regions, contain paraffin. For example, the following contain paraffin: Volga region petroleums -- from 2 to 11%, petroleums of Turkmenia -- up to 16%, Ozeksuatskaya petroleum (Stavropol'skiy Kray) -- 24% and Mangyshlak petroleums (Kazakhstan) -- up to 29%.

Under stratum conditions the paraffin is dissolved in the petroleum. With rising to the surface and during pumping through pipelines the petroleum temperature is reduced, the solution becomes saturated and under definite conditions the paraffin precipitates from it, being deposited on the pipeline walls. The paraffin deposits decrease the pipe cross section and accordingly reduce the throughput capacity. For example, the deposition of paraffin in some pipelines in the Bashkirskaya ASSR has reduced their throughput capacity to 50%. As demonstrated by an investigation of the deposits, they consist of paraffins with a high melting point and ceresin wax (up to 50%), asphalt-tar substances (up to 20%), mechanical impurities and oils.

The deposits are distributed nonuniformly along the pipeline. In the initial segment of the pipeline, where the temperature is higher than the onset of precipitation temperature for paraffin, its deposits are insignificant. Then, where the temperature is lower, the paraffin is released intensively and its deposits are substantial. Thereafter the thickness of the paraffin deposits along the length of the pipeline decreases since the petroleum already moves at an almost constant temperature equal to the ground temperature and the main mass of the paraffin precipitating at this temperature has already been deposited in the preceding segment.

However, it should be noted that both the weather conditions exerting an influence on the temperature of the ground surrounding the pipeline and the properties of the petroleum can introduce significant corrections into the described pattern of distribution of paraffin deposits in the pipeline.

A study of paraffin deposition in petroleum pipelines made it possible to clarify the conditions necessary for the formation of such paraffin deposits on the inner surface of pipes:

presence in the petroleum of a considerable quantity of paraffin, which with a decrease in the temperature to a value when the paraffin content attains a saturation content begins to precipitate out;

a relatively low petroleum viscosity, making it possible for the paraffin crystals to move freely in the petroleum flow;

a temperature decrease in the petroleum pipeline to the level at which the paraffin precipitates out due to a decrease in solubility.

In order to maintain the pipeline throughput capacity at a level close to the planned level it is necessary to clear it from the paraffin deposits. The most effective method for clearing the inner surface of the pipeline at the present time is mechanical cleaning by means of scrapers. Both in the Soviet Union and abroad many designs of metal scrapers have been developed in which the cleaning elements are disks, knives and wire brushes. The scrapers of different designs are different in the effectiveness of removing deposits from the walls of the pipes, with respect to resistance to wear and passability. The latter quality is very important for pipelines having even insignificant obstacles in the inner cavity in the form of backing rings, burrs and constrictions in fittings. During regular cleaning of a pipeline metal scrapers can pass up to 100 km without excessive wear.

Good passability qualities are characteristic of spherical rubber separators which can also be used for clearing pipelines from paraffin deposits. The optimum periodicity of passage of scrapers (or spherical separators) along a pipeline is determined on the basis of the following considerations. The deposition of paraffin in a pipeline causes a decrease in throughput capacity and corresponding losses; the greater the time lapse between use of the scrapers, the greater will be these losses. On the other hand, the lesser the time lapse between use of the scrapers, that is, the greater the number of passes of the scrapers, the greater will be the expenditures on scraping (and also the losses due to stoppages of the stations when the scraping is being done if such stoppages are required by the established cleaning methods). The optimum periodicity of passage of the scrapers corresponds to the variant in which the losses from paraffin deposition in the pipeline and the reduced expenditures on passage through of the scrapers are minimum.

5303
CSO: 8344/0811 END