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Research

A NEW METHOD OF RAPID DEFINING POWER CONSUMPTION OF ELECTRIC HEATING OF ABOVEGROUND "HOT" TRUNK OIL PIPELINES

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ABSTRACT

The article describes the principle of nomographs building that make it possible to quickly determine the required power consumption of the electric heating systems for stationary thermal operating mode of a pipeline. For pipelines with standard outside diameters, dependency of the linear and power type of the required linear power consumption of heat tracing on the average oil temperature has been shown. Also, tabular and graphical forms that simplify the process of calculating the required thickness of pipeline thermal insulation have been shown. The obtained dependences, charts and nomographs make it possible to calculate the thermal mode of a "hot" trunk oil pipeline with the minimum amount of source data. The results shown in the paper have been obtained with the accuracy sufficient for calculation.

INTRODUCTION

Steady temperature condition of oil trunk pipelines

The steady temperature condition is characterized by continuous movement of a viscous product in the pipeline. The temperature at the inlet and the outlet of the pipeline is considered to be the same. With that, the required linear power consumption of heat tracing (W/m) is defined as (Fonaryov, 1973):

$$P = k_s k_o \frac{t_{o.av} - t}{\frac{1}{2\pi\lambda_{ins}} \ln \frac{d_{ins}}{d_o} + \frac{1}{\alpha_o \pi d_{ins}}} \quad (1)$$

where

$t_{o.av}$– the average temperature of the oil pumped through the entire length of the pipeline;

$t_{env.}$ – temperature of the environment, K (for underground pipes laying, t_0: the temperature of the soil in its natural thermal condition at the depth of the pipeline axis makes sense);

λ_{ins} - coefficient of thermal insulation thermal conductivity, W/(m·K);

d_{ins} - the outer diameter thermal insulation, m;

d_o - the outer diameter of the pipeline, m;

α_o - the coefficient of heat transfer from the outer surface of the insulation to the environment, W/(m²*K).

For the pipelines located in open areas, the coefficient k_n of heat loss through the supports and valves is taken equal to 1.25, and for pipelines in confined areas - equal to 1.2. The unknown losses coefficient k_o is taken equal to 1.1.

In the denominator of formula (1), the first summand is the thermal resistance of the heat insulating structure, and the second summand is the thermal resistance of heat transfer from the surface of the insulation structure to the environment. Here we will neglect the thermal resistance of the pipeline metal and thermal resistance of heat transfer from the oil to the inner wall of the pipe due to their small values.

The heat conduction coefficient of the main insulation layer of the structur λ_{ins}, W/(m·K) can be found using formula (Kopko, 2002):

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$\lambda_{ins} = \lambda k$ (2)

where λ in the heat conduction coefficient of dry material of the main layer, W/(m·K) (taken according to (SNiP 41-03-2003, 2003);

k is the correction coefficient of increasing thermal conductivity from moisturizing (depending on the type of the insulation material and type of soil, kis taken according to (SNiP 41-03-2003, 2003).

For calculating the minimum required thickness of the insulation layer, density of the heat flow between the pipeline and the environment is to be found (SNiP 41-03-2003, 2003):

$q = q_L K$ (3)

where q_L is the standard heat flux density, W/m, (adopted according to (SNiP 41-03-2003, 2003);

K is the coefficient of changes of normal density of the heat flow, depending on the area of construction (adopted according to (SNiP 41-03-2003, 2003).

Thickness of the insulating layer δ_{ins}, depending on the normal density of the heat flow, can be determined by simplified formula (Kopko, 2002):

$$\delta_{ins} = \frac{d_o(B-1)}{2} \quad (4)$$

where coefficient B is found as:

$$B = \exp\left[2\pi\lambda_{ins}\left(\frac{t_{o.av} - t_{env}}{q} - \frac{1}{\pi d_o \alpha_o}\right)\right] \quad (5)$$

For insulation structures made of compacting materials, sealing of the main layer to the expected values calculated with regard to the compaction factor (Kopko, 2002) is provided. To determine the ordered amount (volume) of compacting insulation products, the volume of the insulating layer of these products in the structure is multiplied by the compaction factor K_c (SNiP 41-03-2003, 2003).

To build nomographs for quick selection of the required power consumption of the pipeline trace heating system, let us adopt the following values of unknown parameters:

- Thermal conductivity of the insulating material λ=0.05W/(m·K) (based on the average values of the most common insulating materials according to (Vasiliev, 1971; Goova, 2002; Kammerer, 1965; Design and construction specifications 41-103-2000, 2001);

- The norm of the heat flow density*q* will be defined by interpolating the tabular values of the norms of heat flow density for pipelines with positive temperatures located in the open air and the work number over 5,000 (SNiP 41-03-2003, 2003) (coefficient K is taken equal to 0.96);

- Coefficient k_s is taken equal to 1.25;

- The heat conduction coefficient from the surface of insulation α_o=26 W/(m^2*K) (recommended value in the absence of specific information about wind speed) (Design and construction specifications 41-103-2000, 2001).

METHODS

Nomographs for selecting power consumption of trace heating

Based on the above dependencies, let us build a nomograph for fast approximates selection of the trace heating system power consumption for a pipeline with nominal diameter 219 mm, with the maximum possible temperature difference between the pumped oil and the environment (Fig. 1).

The dashed line describes the variation of the required linear power consumption of trace heating at the maximum temperature difference between the oil product and the environment. Solid straight lines determine operation mode of the pipeline trace heating system for which the maximum difference between the temperature of oil and the environment is known, and help to define the linear power consumption of trace heating in case of increasing the temperature of the environment. Each of the modes described by the olid straight lines corresponds to a certain minimum thickness of the pipeline thermal insulation (indicated in the top part of the graph).

The ambient temperature is taken equal to the temperature of the coldest fivedays, based on the climate reference books (SNiP 23-01-99, 2008), with the probability of 0.92.

To determine the required linear power consumption of trace heating, it is enough to know the maximum difference of temperatures between the pumped fluid and the environment, and the outer diameter of the pipeline. For example, the maximum temperature difference between oil and the environment is 50°C for a pipeline with the outer diameter equal to 219 mm. In the nomograph (Fig. 1), let us draw a vertical line from 50°C to the intersection with the dashed line, and determine the required linear power consumption of trace heating (49 W/m) and insulation thickness (58 mm).

It is necessary to underline the fact that this method is suitable for calculating power consumption of trace heating in the stationary thermal mode of pipeline operation.

The nomographs data have been built with the

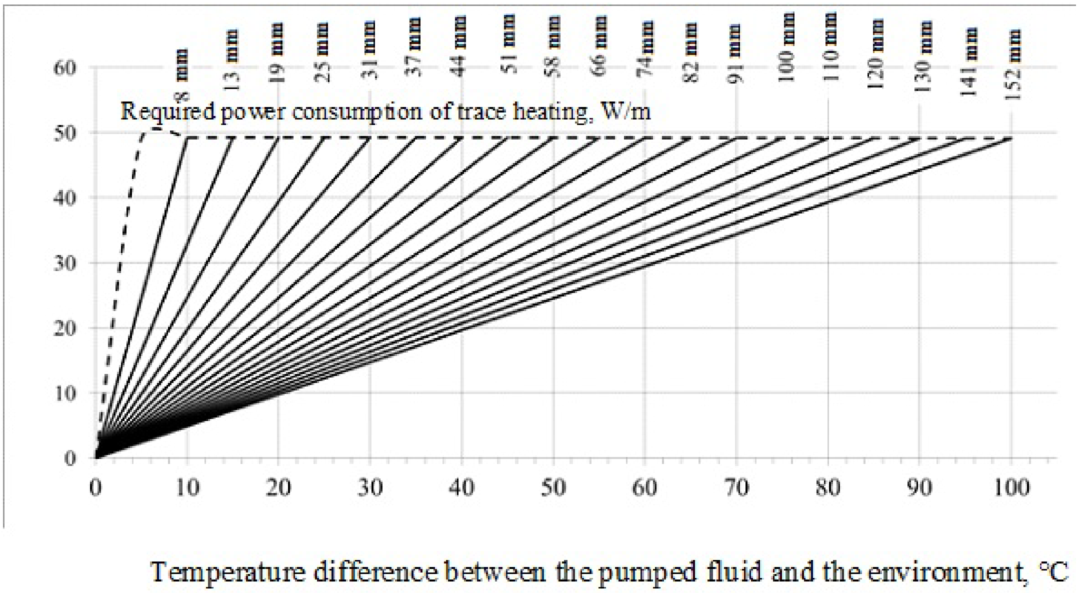

Fig. 1 Nomograph of selecting heart tracing power consumption of a pipeline with the outer diameter of 219 mm.

assumption that the temperature of the pumped product is equal to the maximum temperature allowable for pumping oil, 70°C.

Nomographs may be built for all sizes of pipelines, including the pipelines of most common outer diameters: 32 mm, 57 mm, 83 mm, 108 mm, 133 mm, 159 mm, 219 mm, 245 mm, 273 mm, 325 mm, 426 mm, 530 mm, 630 mm, 720 mm, 820 mm, and 1,020 mm (GOST 30732-2006; Zhuravlev, 1954).

The simplified method of determining thickness of a trunk pipeline insulating layer

The product temperature defines the value of the normal flux density, and, therefore, the values of the minimum allowable thickness of the insulation and the required trace heating power consumption.

Thus, in the next stage, the problem of obtaining simplified linear dependencies of the required power consumption of trace heating and thickness of heat insulation on the temperature of pumped product arises. Analysis of the initial data allowed us to obtain dependencies of the required power consumption of trace heating P_d on the temperature of the product $t_{o.av}$ like:

$$P_d = A \cdot t_{\text{o.av}}^a \quad (6)$$

$$P_d = A \cdot t_{\text{o.av}} + B \quad (7)$$

where A, B are coefficients.

The accuracy of describing the initial tabular data with the obtained equations was ensured by using the absolute σ and the relative σ values of the mean square approximation error:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(P_{i,theor} - P_{i,calc})^2}{N-n}} \quad (8)$$

where N – the number of sample points from the dataset;

$n$is the number of constants in the equation;

$P_{i.theor}$ – $P_{i.calc}$ is the discrepancy between the initial values of trace heating power consumption and those obtained with the use of the approximation equation, W/m;

$$\sigma_{\%} = \sqrt{\frac{\sum_{i=1}^{N}((P_{i,theor} - P_{i,calc})/P_{i,theor})^2}{N-n}} \cdot 100\% \quad (9)$$

Table 1 shows the obtained dependences of heat trace heating power consumption on the average temperature of oil. The approximation error for these equations is fairly small Table 1 - it does not exceed 2 per cent – which bespeaks of the possibility of their practical use.

Approximating equations for thermal insulation thickness could not be obtained with the accuracy sufficient for technical calculations, so the calculated values of insulation thickness were presented in a table. Table 2 shows the values of heat insulation thickness, depending on the average temperature of the pumped product and the difference of temperatures between the environment and the pumped product. If the tabular data are presented as a chart, a family of curves will be obtained (Fig. 2).

These tabular and graphical forms of determining

Table 1. Errors in calculation by obtained equations

Pipe diameter, mm	Linear power consumption, W/m	Root mean square approximation error, W/m	Relative mean square approximation error, %
32	$P_{32} = 0.286 \cdot t_{\text{o.av.}} + 1.133$	0.23	1.37
57	$P_{57} = 0.514 \cdot t_{\text{o.av.}}^{0,922}$	0.17	0.90
83	$P_{83} = 0.392 \cdot t_{\text{o.av.}} + 3.193$	0.20	1.10
108	$P_{108} = 0.982 \cdot t_{\text{o.av.}}^{0.834}$	0.18	0.73
133	$P_{133} = 0.472 \cdot t_{\text{o.av.}} + 4.311$	0.23	1.12
159	$P_{159} = 0.521 \cdot t_{\text{o.av.}} + 4.5$	0.18	0.77
219	$P_{219} = 0.602 \cdot t_{\text{o.av.}} + 6.992$	0.23	0.80
245	$P_{245} = 1.817 \cdot t_{\text{o.av.}}^{0.795}$	0.36	0.84
273	$P_{273} = 1.966 \cdot t_{\text{o.av.}}^{0.793}$	0.23	0.57
325	$P_{325} = 2.083 \cdot t_{\text{o.av.}}^{0.817}$	0.46	0.85
426	$P_{426} = 3.375 \cdot t_{\text{o.av.}}^{0.757}$	0.66	0.97
530	$P_{530} = 1.122 \cdot t_{\text{o.av.}} + 19.148$	1.09	1.85
630	$P_{630} = 4.819 \cdot t_{\text{o.av.}}^{0.743}$	0.56	0.66
720	$P_{720} = 5.508 \cdot t_{\text{o.av.}}^{0.737}$	0.60	0.65
820	$P_{820} = 6.468 \cdot t_{\text{o.av.}}^{0.723}$	0.74	0.74
1,020	$P_{1020} = 8.091 \cdot t_{\text{o.av.}}^{0.712}$	0.82	0.68

thermal insulation thickness can be built for the entire range of frequently used types and sizes of pipelines.

Substantiation of applicability of the obtained dependencies

The Let us perform a comparative analysis of these charts and the chartsobtained by Z. I. Fonariov (Fonaryov, 1982; Fonaryov, 1984). (Fig. 3) shows, for a ND 25 mm pipe, the charts of selecting power consumption built according to the data of Z. I. Fonariov and the above method in other equal conditions (insulation thickness, heat conduction coefficient of the insulation, etc.).

Thus, these dependencies are described by the same law with some deviation in the values.

Table 3 shows the maximum possible relative deviation of the obtained values with the use of the two methods of calculating power consumption of trace heating for DN 25-300 mm pipes in the range of temperature differences of $t_{o.av} - t_i$=20...100°C.

Large maximum relative deviations of power consumption occur with small absolute values of power consumption, when the deviation of the charts by the y-axis is comparable to the absolute values of power consumption at this point in (Fig. 3), for example, at 20°C).

Table 2. Thickness of thermal insulation for a pipeline with outer diameter of 219 mm

$t_{o.av.} - t_i$, ° C	The temperature of pumped product, ° C								
	20	30	40	50	60	70	80	90	100
10	26	19	14	11	10	8			
15	43	30	23	19	16	13	12		
20	62	43	33	26	22	19	17	15	
25	83	57	43	35	29	25	22	19	17
30	107	73	54	43	36	31	27	24	21
35	134	89	66	52	44	37	33	29	26
40	164	107	79	62	52	44	38	34	30
45	198	127	93	73	60	51	44	39	35
50	237	149	107	83	69	58	51	45	40
55	279	173	123	95	78	66	57	50	45
60	328	198	140	107	88	74	64	56	50
65	382	227	158	120	98	82	71	62	55
70	443	257	178	134	109	91	78	68	61
75	511	291	198	149	120	100	86	75	66
80		328	221	164	132	110	94	81	72
85		368	245	181	144	120	102	88	78
90			270	198	157	130	110	96	84
95			298	217	171	141	119	103	91
100				237	186	152	128	111	97

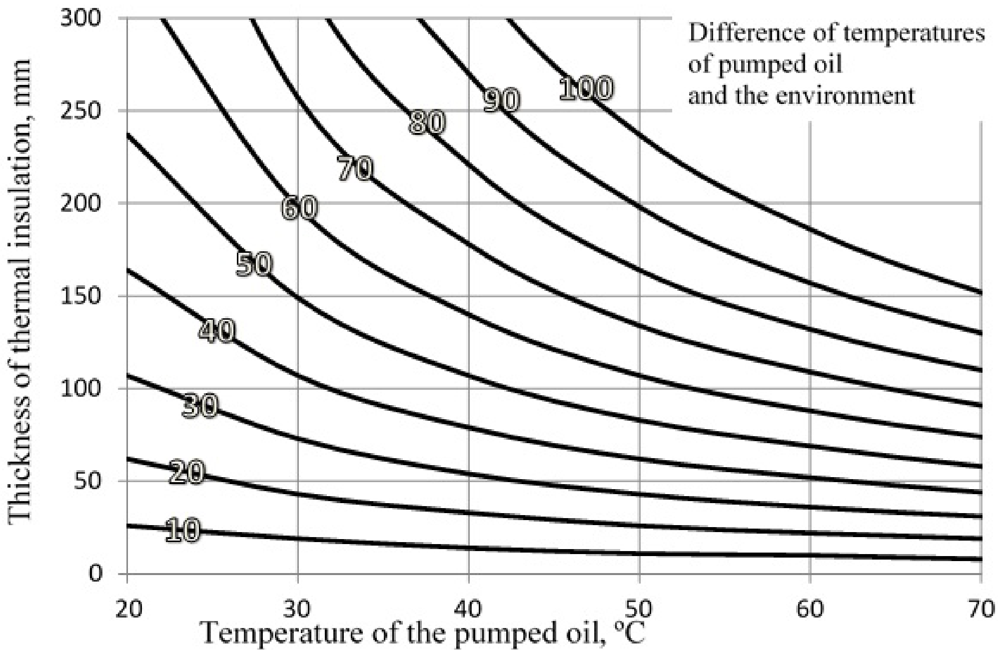

Fig. 2 Dependencies of heat insulation thickness on the temperature of the pumped oil for a pipeline with the outer diameter of 219 mm.

To check the compliance of the theoretical dependencies proposed by Z. I. Fonariov, let us use the analysis of the Fisher's F criterion: let us compare total variance $\overline{S}_P^2$ to residual variance $\overline{S}_{P\_rem}^2$.

The total and residual variances are calculated as:

$$\overline{S}_P^2 = \frac{\sum_{i=1}^{n}(P_{1i})^2 - (1/n)(\sum_{i=1}^{n}P_{1i})^2}{n-1} \quad (10)$$

where P_1 is the value of power consumption obtained by the method of Z. I. Fonariov, W/m; n is the number of analyzed points;

$$\overline{S}_{P\_rem}^2 = \frac{\sum_{i=1}^{n}(P_{1i} - P_{2i})^2}{n-2} \quad (11)$$

where P_2 is the value of power consumption obtained by the proposed method, W/m.

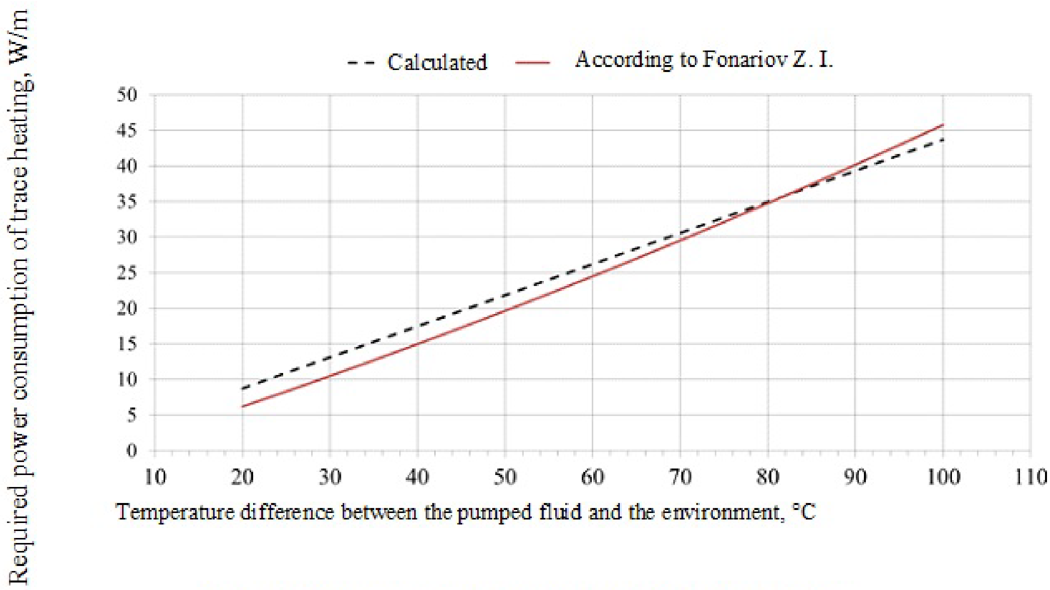

Fig. 3 Power consumption of trace heating for a DN 25 mm pipe.

Table 3. Comparing the data with the use of two methods

Pipe DN, mm	The maximum absolute deviation of power consumption, W/m	The maximum relative deviation of power consumption, %	Standard deviation σ, W/m
25	2.62	41.23	1.90
50	2.24	5.22	1.76
75	2.27	8.80	1.23
100	3.83	15.24	1.90
150	12.87	18.04	8.76
200	16.63	10.15	10.48
250	30.86	17.59	21.53
300	37.15	19.34	26.81

The stages of calculation for a DN 25 mm pipe are shown in Table 4.

Fisher's F criterion is calculated as relation (Lvovsky, 1982):

$$F = \overline{S}_P^2 / \overline{S}_{P\_rem}^2 \quad (12)$$

The obtained theoretical dependence for power consumption with the 5% significance level adequately describes the values of power consumption obtained according to the method of Z. I. Fonariov, due to the fact that the calculated Fisher's criterion was greater than the tabular one (Lvovsky, 1982):

$$F = 38,30 > F_{(16;15;5\%)} = 2,39$$

Table 5 shows the values of the Fisher's F criterion obtained with other conventional tube diameters.

As the table shows, the obtained theoretical dependencies for all pipe diameters with the 5% significance level adequately describe the values of power consumption obtained according to an alternative method of Z. I. Fonariov.

RESULTS

Air Thus, nomographs were built and developed that make it possible to determine the required power consumption of trace heating for a pipeline with certain outer diameter, and the thickness of the insulation layer provided that certain temperature of the pumped fluid is maintained. It should be noted that the proposed nomographs do not have the shortcomings present in the work of (Z. I. Fonariov, 1984). In addition, with the accuracy sufficient for technical calculations, the approximating formulas were obtained for determining the required power consumption of trace heating, depending on the average temperature of oil flow. The obtained formulas make it possible to quickly and accurately enough obtain values of the required power consumption of the pipelines trace heating.

DISCUSSION

The results of the research make it possible:

1. Knowing the current readings of oil flow temperature measuring instruments and the actual

Table 4. Calculation of variances

No.	$t_{\hat{o}.av} - t$	P_1	P_1^2	P_2	$P_1 - P_2$	$(P_1 - P_2)^2$	$\bar{S}_P^2$	$\bar{S}_{P\_rem}^2$
1	20	6.19	38.305	8.74	-2.55	6.511		
2	25	8.32	69.168	10.93	-2.61	6.809		
3	30	10.49	110.051	13.11	-2.62	6.869		
4	35	12.71	161.555	15.30	-2.59	6.688		
5	40	14.98	224.295	17.48	-2.51	6.276		
6	45	17.29	298.898	19.67	-2.38	5.656		
7	50	19.65	386.005	21.85	-2.21	4.863		
8	55	22.05	486.267	24.04	-1.99	3.944		
9	60	24.50	600.352	26.22	-1.72	2.960	156.295	4.081
10	65	27.00	728.937	28.41	-1.41	1.985		
11	70	29.54	872.713	30.59	-1.05	1.105		
12	75	32.13	1,032.385	32.78	-0.65	0.419		
13	80	34.77	1,208.669	34.96	-0.20	0.039		
14	85	37.45	1,402.295	37.15	0.30	0.089		
15	90	40.17	1,614.005	39.33	0.84	0.707		
16	95	42.95	1,844.554	41.52	1.43	2.042		
17	100	45.77	2,094.710	43.70	2.06	4.259		
∑		425.95	13,173.165			61.222		

Table 5. Fisher's F criteria

DN, mm	25	50	75	100	150	200	250	300
F	38.30	70.87	247.5	155.16	11.26	15.58	4.95	4.39
$F_{(16;15;5\%)}$	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39

thickness of the insulating layer, to define either the electrical power consumption for maintaining a stable temperature of the pipeline (for automated trace heating system), or the required frequency of enabling/disabling the trace heating systems (timer operation mode) in the conditions of temperature changes in the environment (daily/seasonal temperature fluctuations).

2. Knowing the current readings of oil flow temperature measuring instruments and the ranges of the ambient temperature, to assess the cost of the trace heating system at the stage of project feasibility study: the required amount of the heating cable, heat insulation, cost of electrical energy for operation of the trace heating system, etc.

The results show that the method of determining power consumption of the heat tracing system and the thickness of heat insulation for maintaining stable temperature of a non-isothermal pipeline should be described as a special method. From the point of view of practical significance, the method will be convenient after specialized software (a computer application) is used as its basis.

The obtained results are useful for a wide range of persons engaged in applied research and performing engineering tasks in the area of studying and choosing thermal conditions of pipelines.

With regard to the fundamental differences between the processes of oil flow transfer and heat exchange in the near-wall layer of the pipeline and in its central part (the so-called "flow core"), the obtained results may be used for further studies, making it possible to obtain similar dependencies for shorter pipelines (technological pipelines).

CONCLUSION

During the research, an integrated approach was used, which combined theoretical and experimental methods of research: planning experiments, testing in specialized laboratory installations, and numerical experiments on computer mathematical models of the pipeline built with the use of modern computer programs.

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REFERENCES

Design and construction specifications 41-103-2000. 2001. Proektirovanie teplovoy izolyatsii oborudovaniya i truboprovodov [Designing thermal insulation of equipment and pipelines]. Gosstroy of Russia. Moscow: SUE DPC, pp. 33.

Fonaryov, Z. I. 1982. Elektropodogrev truboprovodov na neftebazah [Pipelines heat tracing at tank farms]. Moscow: All-Russian Research Institute for the Organization. *Management and Economics of the Oil and Gas Industry*. 42.

Fonaryov, Z. I. 1973. Transportirovanie vyazkih zhidkostei s primeneniem elektropodogreva [Transportation of viscous liquids with the use of trace heating]. *The Leningrad House of Science and Technology Promotion*. 36.

Fonaryov, Z. I. 1984. Elektropodogrev truboprovodov, rezervuarov i tehnologicheskogo oborudovaniya v neftyanoi promyshlennosti [Heat tracing of pipelines, tanks and process equipment in oil industry]. Leningrad: "Nedra". 148.

Goova, A. Y. 2002. Kratkii teplofizicheskii spravochnik [A brief thermophysical guide]. Novosibirsk: Sibvuzizdat. 300.

GOST 30732-2006. Trubi i fasonnie izdeliya stal'nie s teplovoi izolyatsiei iz penopoliuretana s zaschitnoi obolochkoi. [Steel pipes and fittings with thermal insulation made of polyurethane foam with protective shell.]. Moscow: Standartinform, pp. 49.

Kammerer, I. S. 1965. Teploizolyatsiya v promyshlennosti i stroitelstve [Thermal insulation in industry and construction]. Moscow: Stroyizdat, pp. 378.

Kopko, V. M. 2002. Teploizolyatsiya truboprovodov teplosetei [Thermal insulation of pipelines of heating pipe networks]: Work book. Minsk: Tekhnoprint, pp. 160

Lvovsky, E. N. 1982. Statistical methods of building empirical formulas: work book. Moscow: Vyshaya shkola.

SNiP 23-01-99. 2000. Stroitelnaya klimatologiya [Construction climatology]. Gosstroy of Russia Moscow: SUE DPC, pp. 57.

SNiP 41-03-2003. 2003. Teplovaya izolyatsiya oborudovaniya i truboprovodov [Thermal insulation of equipment and pipelines]. Gosstroy of Russia. Moscow, pp. 66.

Vasiliev, L. L. 1971. Teplofizicheskie svoistva poristih materialov [Thermophysical properties of porous materials]. *Minsk: Nauka I Tekhnika*. pp. 268.

Zhuravlev, B. A. 1954. Konstruktivnie elementi sistem teplosnabzheniya i ventilyatsii [Structural elements of heating and ventilation systems]. Mocow: Stroyizdat, pp. 384.