The influence of rheological properties of diesel fuel in the pumping process for collapsible pipelines in low temperature conditions

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Abstract. The results of studies of the influence of rheological properties of diesel fuels on the pumping process for collapsible pipelines in low temperature conditions. It is established that diesel fuel when they are cooled below the solidification point represent a viscoplastic medium with curves of current, which describes a universal equation of Buckley-Herschel. A refined method for hydraulic calculation of collapsible tubing to determine the head losses to reflect changes in the rheological properties of diesel fuels at low temperatures. The simulation of the processes of transfer of winter diesel fuel for collapsible pipelines in low temperature conditions and offers recommendations for their application in low-temperature conditions.

Introduction

Policy of realization of strategy of development of the Arctic zone of the Russian Federation and ensuring national security in the Arctic involves the development of transport infrastructure, which entails the organization of the system of fuel supply that can operate at low temperatures down to - 60 °C. The Solution of the problem of fuel supply can be realized with the use of collapsible pipelines.

Experience in the application of collapsible pipelines shows that the transportation of diesel fuels at temperatures below their temperature of filterability possible. While there is a significant deviation of the actual parameters of the pipeline design due to the high viscosity of the pumped product.

The existing method of calculation of parameters of the work collapsible pipelines does not influence the rheological characteristics of the fuels on the process of their transportation in conditions of low temperatures, which leads to inaccurate results of the hydraulic characteristics. The current method of determination of hydraulic losses, based on the use of kinematic viscosity of fuels passport data, has sufficient accuracy, which also leads to inaccurate assessment of the hydraulic characteristics of the pumping process at low temperatures. The influence of the viscosity of the fuel in the collapsible pipelines mode of operation in low temperatures causes the actuality of researches of rheological properties of diesel fuels, determining the rheological model of viscous fluid needed for the hydraulic calculation of collapsible pipelines and reliable operation of the pipeline equipment, and development of refined
methods for the assessment of the hydraulic characteristics of the process of transportation of diesel fuels on collapsible pipelines in the conditions of low temperatures.

As objects of research were selected 13 samples of diesel fuel (DF) of different plants. In tables 1-3 lists the actual values of the main physico-chemical and operational parameters of the test specimens of diesel fuel.

**Table 1.** Actual values of the main physico-chemical and operational performance of diesel fuel EURO Class 3 and Class C in accordance with the requirements of GOST R 52368-2005

| Name of the indicator | Brand diesel fuel |
|-----------------------|------------------|
|                       | Class 3, type III | Grade C, type III | Sample No. 5 | Grade C, type III | Sample No. 6 | Grade C, type III | Class 3, type III |
| Density at 15 °C, kg/m³ | 806 | 827 | 839 | 835 | 806 |
| Kinematic viscosity while 40 (20) °C, mm²/s (cSt) | 1.6 (2.3) | 2.99 (4.76) | 2.96 (4.65) | 2.79 (4.31) | 1.69 (2.41) |
| Fractional composition: |  |  |  |  |  |
| to a temperature of 180°C, % (by volume) | 6.3 | - | - | - | 7.0 |
| at a temperature of 250°C, % (by volume) | - | 23 | 28 | 31 | - |
| at 350°C, % (by volume) | 98.9 | 98 | 97 | 98 | 98.0 |
| 95 % (by volume) distills at a temperature of °C, % | 277 | 332 | 343 | 330 | 290 |
| Cloud point, °C | no higher – 38 | not less than 9 | not exceeding 6 | not exceeding 6 | not less than 40 |
| Cold filter plugging point, °C | not less than 40 | not less than 14 | not less than 15 | no higher – 13 | no higher – 51 |
| Pour point, °C | no higher – 44 | not less than 21 | not less than 22 | no less than 22 | no higher – 53 |

**Table 2.** Actual values of the main physico-chemical and operational performance of diesel fuel EURO Class 2 and of Class C in accordance with the requirements of GOST R 52368-2005

| Name of the indicator | Brand diesel fuel |
|-----------------------|------------------|
|                       | Grade C, type III | Grade C, type III | Grade C, type III | Grade C, type III |
| Density at 15 °C, kg/m³ | 830 | 824 | 828 | 838 |
| Kinematic viscosity while 40 (20) °C, mm²/s (cSt) | 3.16 (5.10) | 1.784 | 2.86 (4.61) | 2.44 |
| Fractional composition: |  |  |  |  |
| to a temperature of 180°C, % (by volume) | - | 7.7 | - | - |
| at a temperature of 250°C, % (by volume) | 23 | - | 32 | 42 |
| at 350°C, % (by volume) | 97 | 99.0 | 96 | 94 |
| 95 % (by volume) distills at a temperature of °C, % | 340 | 293 | 344 | 356 |
| Cloud point, °C | - | Not exceeding 33 | not less than 9 | not exceeding 6 |
| Cold filter plugging point, °C | not above – 11 | no higher – 34 | not above – 11 | not above – 8 |
| Pour point, °C | - | no higher – 37 | not less than 23 | not less than 16 |
### Table 3. Actual values of the main physico-chemical and operational characteristics of summer diesel fuel EURO Class C environmental class 5 in accordance with the requirements of GOST 32511-2013

| Name of the indicator | Sample No. 2 | Sample No. 4 | Sample No. 7 | Sample No. 9 |
|----------------------|--------------|--------------|--------------|--------------|
| Density at 15 °C, kg/m³ | 829          | 843          | 839          | 837          |
| Kinematic viscosity while 40 (20) °C, mm²/s (cSt) | 2.88         | 2.84 (4.5)   | 3.17         | 3.16 (5.06)  |
| Fractional composition: |              |              |              |              |
| to a temperature of 180°C, % (by volume) | -            | -            | -            | -            |
| at a temperature of 250°C, % (by volume) | 33           | 33           | 26           | 26           |
| at 350°C, % (by volume) | 94           | 98           | 95           | 94           |
| 95% (by volume) distills at a temperature of °C, % | 352          | 334          | 345          | 353          |
| Cloud point, °C | not less than 5 | not less than 14 | -          | not less than 5 |
| Cold filter plugging point, °C | no higher – 13 | not less than 15 | not above – 12 | not less than 5 |
| Pour point, °C | not above – 18 | not less than 24 | -          | not less than 17 |

Studies have been conducted and analysis of the viscosity-temperature characteristics the following samples, EURO diesel, type III (sulfur content less than 10 mg/kg) according to GOST R 52368-2005 (EN 590:2009) Rev. 1:

- sample No. 1. Class 3 – manufacturer: JSC "NNK - Khabarovsk refinery"; component composition: diesel hydro-treating fraction 286-304 °C – 99.9% by mass, anti-wear additive "of Coltec DS 7739" – 0.035% by mass., Cetane Improver additive "of Coltec DS 1406" – 0.01% by mass;
- sample No. 3. Grade C – manufacturer: JSC "NNK - Khabarovsk refinery"; component composition: Hydro-treated diesel fraction 340-371 °C – 99.947% by mass anti-wear additive "of Coltec DS 7739" – 0.05% by mass, Cetane Improver additive "of Coltec DS 1406" – 0.05% by mass;
- sample No. 5. Grade C – manufacturer: JSC "Gazpromneft - ONPZ"; component composition: hydro-treated diesel fraction 375 °C – 100% by mass., anti-wear additive DC-32 Total – 0.12% by mass;
- sample No. 6. Grade C – manufacturer: JSC "ANHK"; component composition: Hydro-treated diesel fraction 301-317 °C – Of 99.02 by mass%, anti-wear additive "Baikal" – 0.02% by mass, Cetane Improver additive "Ecosetol" – 0.06% by mass;
- sample No. 8. Class 3 – manufacturer: JSC "NNK - Khabarovsk refinery"; component composition: Hydro-treated diesel fraction 378-399 °C – 99.945% by mass, anti-wear additive "of Coltec DS 7739" – 0.05% by mass, Cetane Improver additive "of Coltec DS 1406" – 0.005% by mass;
- sample No. 10. Grade C – manufacturer: JSC "NNK - Khabarovsk refinery"; component composition: hydro-treated diesel fraction 286-304 °C – 99.955% by mass, anti-wear additive "of Coltec DS 7739" – 0.035% by mass., Cetane Improver additive "of Coltec DS 1406" – 0.01% by mass;
- sample No. 11. Class 2 – manufacturer: JSC "ANHK"; component composition: hydro-treated diesel fraction 349-362 °C – 99.889% by mass, anti-wear additive "Baikal" – 0.03% by mass, Cetane Improver additive "Ecosetol" – 0.08% by mass; anti-oxidation additive "Agidol-1" – 0.001% by mass;
- sample No. 12. Grade C manufacturer: JSC "Slavneft - YANOS"; component composition: hydro-treated diesel fraction L-24-6 325-330 °C – 23.81% by mass, diesel fraction (hydrocracking) 395-391 °C – of 29.84% by mass, hydro-treating diesel fraction L-24-7 325-330 °C – 21.73% by mass, hydro-treating diesel fraction 325-330 °C DT – 24.60% by mass, anti-wear additive "Dodilube"-4940 "Clariant" – 0.0225% by weight., anti-static additive Stadis firm "Innospect" – 0.002% by mass;
— sample No. 13. Grade C — manufacturer: OOO "Gazprom Neftekhim Salavat"; component composition: hydro-treated diesel fraction 348-366 °C – A 99.97% by mass, anti-wear additive "ADDY TOP CM"/AddiTOP-1 – 0.03% by mass

Studies have been conducted and analysis of the viscosity-temperature characteristics of samples the following summer EURO diesel, environmental class K5 for GOST 32511-2013:

— sample No. 2. Grade C – manufacturer: JSC "TANECO"; component composition: hydro-treated diesel fraction from counter 355 to 358 °C – 89.77% by mass, hydro-treated kerosene fraction 295-296 °C – 2.18% by mass, diesel fraction (hydrocracking) 346-424 °C – 6.43% by mass, diesel fraction of oil production 362-363 °C and 1.57% by mass, anti-wear additive "GT-16" – 0.03% by mass, Cetane Improver additive "Kerobrisol EHN" – 0.02% by mass;

— sample No. 4. Grade C – manufacturer: JSC "ANPZ VNK"; component composition: hydro-treated diesel fraction 331-338 °C – Of 99.96% by mass, anti-wear additive "Baikal" – 0.022% by mass, Cetane Improver additive "Ecosetol" – 0.016% by mass;

— sample No. 7. Grade C – manufacturer: OOO "RN - Komsomolsk refinery"; component composition: hydro-treated diesel fraction 334-365 °C – Efficiency of 99.78% by mass, anti-wear additive "Baikal" – 0.029% by mass, Cetane Improver additive "Ecosetol" – 0.016% by mass;

— sample No. 9. Grade C – manufacturer: JSC "Republic popular"; component composition: hydro-treated diesel fraction 361-366 °C – Of 99.96% by mass, anti-wear additive "Baikal" – 0.022% by mass, Cetane Improver additive "Ecosetol" – 0.016% by mass.

**Results**

Laboratory investigations of the physico-chemical properties of the samples DF, three winter and ten summer showed that at temperatures above the cloud point temperature of the investigated the samples do not form the structure and behave as a Newtonian fluid (figure 1, 2), which allows to Express the viscosity-temperature characteristics of diesel fuel coefficient of kinematic viscosity on temperature analytical dependencies.

![Figure 1. Viscosity-temperature dependence winter diesel fuels at low temperatures](image-url)
Figure 2. Viscosity-temperature dependence of summer diesel fuel (diesel fuel EURO, grade C) to low temperatures

Figure 1 shows that at temperatures below -40 degrees, winter diesel fuel starts to show anomalies of viscosity, then the expression of their viscosity-temperature properties in this manner is incorrect. By reducing the fuel temperature below its limiting temperature of filterability can be formed microcrystals of n-paraffin hydrocarbons, there is a sharp, abrupt increase in the values of the parameter viscosity [1]. For winter fuels, these changes are less pronounced. Therefore, to conduct hydraulic calculations necessary to investigate the rheological properties of diesel fuels in the temperature range from -20 to -60 degrees.

The nature of fluid responsiveness to external stimuli are divided into Newtonian and non-Newtonian. Newtonian fluids are called viscous fluids, reporting in its flow of viscous friction law of Newton, i.e. shear stress and velocity gradient in a liquid is linearly dependent. Rheological model of the fluid flow Newton [2] according to equation:
\[ \tau = \mu D , \]  

where: \( \mu \) – dynamic viscosity, Pa\cdot s; \( D \) – shear rate, s\(^{-1}\).

The nature of the reaction fluid on the external influences are divided into Newtonian and non-Newtonian. To describe the behavior of non-Newtonian fluids there are more than 30 rheological models that pass within a certain range of shear stresses individual features of real currents. The greatest practical distribution to describe the viscoplastic behavior of structured disperse systems received a rheological model of the flow of non-Newtonian fluids Shvedov-Bingham [3] according to equation:

\[ \tau = \tau_0 + \mu_p D , \]  

where: \( \tau \) – shear stress, Pa; \( \tau_0 \) – ultimate dynamic shear stress (yield stress), the excess of which leads to viscous flow, Pa; \( \mu_p \) – the ratio of plastic (structural) viscosity, Pa\cdot s; \( D \) – shear rate, s\(^{-1}\).

During the rheological studies of samples of DT on the rotary viscometer Rheotest RN 4.1 using the cylindrical measuring system according to GOST 1929 the obtained flow curves at low temperatures, which determine the rheological model of the fluid flow.

Values of dynamic viscosity were recorded with the gradual cooling of DF from -20 to -60 degrees. Additionally, a study was conducted of the rheological behavior of the winter DF in terms of: pour point, cloud point and cold filter plugging point. The build results based on changing the magnitude of shear stress from the gradient of shear rate, the curves of the currents for several samples of DF are presented in figures 3-5.

It is established that DF when they are cooled below the solidification point represent a viscoplastic medium with curves of current, which describes a universal equation of Buckley-Herschel for nonlinear viscoplastic liquid [4] according to equation:

\[ \tau = \tau_{st} + kD^n , \]  

where: \( \tau_{st} \) – critical shear stress, Pa; \( k \) – the coefficient of consistency; \( n \) – the rate of flow (index flow).

The transition from Newtonian to non-Newtonian fluids (viscoplastic and nonlinear viscoplastic) is carried out smoothly as the temperature is decreasing. Comparison of results of calculations of currents of DF curves of the sample No. 1 obtained by experimental means with rheological models of fluid flow Newton equation (1), Shvedov-Bingham equation (2) and Buckley-Herschel equation (3) in terms of low temperatures presented in figure 6.

To quantify the accuracy of determining rheological model for yield curves of the sample No. 1 of DF were used, the relative deviation, the smaller the error the higher the accuracy.

It is seen that the results of the calculations of the curves of the currents to the rheological models of Newton coincide with experimental data at temperatures above the temperature of cloud point of diesel fuel (figure 6a, b). At lower temperatures there is a deviation of the curve of the flow of diesel fuel to the rheological models of Newton (figure 6b, d). The appearance of the ultimate dynamic shear stress occurs at a temperature close to the melting point (figure 6b). Such a non-Newtonian fluid obeys the equation of a Shvedov-Bingham. This is confirmed by the calculation results of flow curve, which good agreement with experimental data.

At temperatures below -50°C in the range low velocity of the flow curve is non-linear with decreasing shear rate. Such a move is contrary to a valid curve model Shvedov-Bingham (figure 6d). This contradiction is eliminated in the mathematical model Buckley-Herschel for nonlinear viscoplastic environment.

The analysis of the curves of the currents revealed that when the critical shear rate the dynamic viscosity of the fuel becomes constant for each particular temperature.
Figure 3. Flow Curves of winter diesel fuel samples No. 1, 8 and 11 (1 – at -60 °C; 2 – at -50 °C; 3 – at -40 °C; 4 – at -30 °C; 5 – at -20 °C; 6 – at -44 °C; 7 – at -38 °C; 8 – at -51 °C; 9 – at -53 °C; 10 – at -37 °C; 11 – at -34 °C; 12 – at -33 °C)
Figure 4. Flow Curves of diesel fuel samples No 2, 3, 4, 5, 6, 7 (1 – at -60 °C; 2 – at -50 °C; 3 – at -40 °C; 4 – at -30 °C; 5 – at -20 °C)
Figure 5. Flow Curves of diesel fuel samples No. 9, 10, 12, 13 (1 – at -60 °C; 2 – at -50 °C; 3 – at -40 °C; 4 – at -30 °C; 5 – at -20 °C)

A refined method of hydraulic calculation of collapsible pipelines, allows to determine the pressure loss, taking into account changes of the rheological properties of diesel fuels at low temperatures. One of the main objectives when performing hydraulic calculations of pipelines is the determination of the magnitude of the head losses due to friction $h_c$ calculated according to Darcy-Weisbach equation:

$$h_c = \frac{\lambda l}{d} \left(\frac{w}{g}\right)^2,$$

where: $h_c$ – friction head loss, m; $\lambda$ – Darcy friction factor; $l$ – estimated pipeline length, m; $d$ – pipeline inner diameter, m; $w$ – average fluid velocity, m/s; $g$ – acceleration of gravity, m/s$^2$.

The Darcy friction factor $\lambda$ is determined depending on the flow regime. To determine if there are many different empirical formulas. The boundaries of the flow regimes and areas of hydraulic friction set depending on the Reynolds number $Re$ and the coefficient of relative roughness of the internal surface of the pipe $e$.

There are three modes of fluid flow: laminar $Re < 2320$, transition zone $2320 < Re < 10000$ and turbulent $Re > 10000$. Turbulent regime for Newtonian liquids conventionally divided into the three areas of the hydraulic friction: smooth $10000 < Re < 10/e$ mixed $10/e < Re < 500/e$ quite rough (quadratic) $Re > 500/e$. 
Figure 6. Comparison of rheological models of flow and experimental the curves of the flows of diesel fuel sample No. 1 at different temperatures: (1 – model of the Newton; 2 – model of Shvedov-Bingham; 3 – model of the Buckley-Herschel)
The coefficient of relative roughness of the pipe is determined from equation:

\[ \varepsilon = \frac{k_e}{d}, \quad (5) \]

where: \( \varepsilon \) – coefficient of relative roughness of the inner surface of the pipe; \( k_e \) – the coefficient of equivalent roughness of the inner surface of the pipe, m.

The Reynolds number for Newtonian and non-Newtonian fluids is defined as follows.

The Reynolds number for a Newtonian fluid is determined from equation:

\[ Re = \frac{wd}{\mu} = \frac{w d \rho}{\mu}, \quad (6) \]

where: \( v \) – coefficient of kinematic viscosity, mm²/s (cSt); \( \rho \) – fluid density, kg/m³.

The Reynolds number for non-Newtonian viscoelastic (rheological model Shvedov-Bingham) fluids is determined from equation [5]:

\[ Re_0 = \frac{Re}{\left(1 + \frac{II}{6}\right)}, \quad (7) \]

where: \( Re_0 \) – the Reynolds number for non-Newtonian viscoplastic (rheological model Shvedov-Bingham) fluids; \( Re \) – the Reynolds number for a Newtonian fluid; \( II \) – the number of Ilyushin for non-Newtonian viscoplastic (rheological model Shvedov-Bingham) fluids.

The number of Ilyushin is the ratio of initial shear stress to the stress of viscous friction and is determined from equation [6]:

\[ II = \frac{\tau_0 d}{\mu w}, \quad (8) \]

The Reynolds number for non-Newtonian nonlinear viscoelastic (rheological model Buckley-Herschel) liquid is determined from equation:

\[ Re_1 = \frac{d^n w^{\lambda - n} \rho}{k \left( \frac{6n+2}{n} \right)^n I_1^h + 8 \frac{8}{3n+1} \left[ n + \frac{2(2n+1)^2 + Il_n(3n+1)}{4} \right]^{\frac{3}{2}} \left( \frac{3n+1}{2(2n+1)(5n+3)} \right)^{\frac{3}{2}}}, \quad (9) \]

where: \( Re_1 \) – the Reynolds number for non-Newtonian nonlinear viscoplastic (rheological model Buckley-Herschel) fluids; \( I_1 \) – the number of Ilyushin for non-Newtonian nonlinear viscoplastic (rheological model Buckley-Herschel) fluids.

Option Ilyushin is determined from equation:

\[ Il_1 = \frac{\tau_0 d^n}{k \left( \frac{6n+2}{n} \right)^n w^n}, \quad (10) \]

With respect to the hydraulic calculations of pipeline transport of oil products to determine the Darcy friction factor is recommended to use the formulas presented in table 4 [5].

Based on the results of research of rheological properties and characteristics of the current diesel fuel at low temperature conditions by using the mathematical model of hydrodynamic processes of pumping diesel fuel at low temperatures, it is possible to expeditiously determine the losses in the hydraulic calculation.

The study was conducted modeling of the pumping of diesel fuel in the collapsible pipelines different diameters 100 and 150 mm in low temperatures.

The graphs (figures 7-9) the resulting show a loss of pressure from performance of the pump at the collapsible pipelines of different diameters in conditions of low temperatures.
**Table 4.** The formula for determining the Darcy friction factor

| Flow regime                                    | Determination formula for Darcy friction factor |
|------------------------------------------------|--------------------------------------------------|
| 1. Laminar                                     |                                                  |
| 1.1 Newtonian fluid, \( Re < 2320 \) (Stokes formula) | \( \lambda = \frac{64}{Re} \)                  |
| 1.2 Non-Newtonian viscoplastic fluid with an ultimate dynamic shear stress \( \tau_0 \), \( Re_0 \leq 2320 \cdot (1+11/6) \) | \( \lambda = \frac{64}{Re_0} \)               |
| 2. Transition                                  |                                                  |
| 2.1 Newtonian fluid, \( 2320 < Re < 10000 \) (Wullis-Ginzburg formula) | \( \lambda = \frac{64}{Re} \cdot (1-\gamma) + \frac{0.3164}{Re^{1/4}} \cdot \gamma \), \( \gamma = 1 - \exp[-0.002 \cdot (Re - 2320)] \) |
| 2.2 non-Newtonian viscoplastic fluid with an ultimate dynamic shear stress \( \tau_0 \), \( Re_0 \) | \( \lambda = \frac{64}{Re_0} \cdot (1-\gamma_0) + \frac{0.3164}{Re_0^{1/4}} \cdot \gamma_0 \), \( \gamma_0 = 1 - \exp[-0.002 \cdot (Re_0 - 2320)] \) |
| 3. Turbulent                                   |                                                  |
| 3.1 Newtonian fluid                            |                                                  |
| - smooth friction area, \( 10000 < Re < 10/\varepsilon \) (Blasius formula) | \( \lambda = \frac{0.3164}{Re^{1/4}} \) |
| - mixed friction area, \( 10/\varepsilon < Re < 500/\varepsilon \) (Altshul formula) | \( \lambda = 0.11 \left( \frac{68}{Re} + \varepsilon \right)^{1/4} \) |
| - completely rough (quadratic) friction area, \( Re > 500/\varepsilon \) (Shiffron formula) | \( \lambda = 0.11(\varepsilon)^{1/4} \) |
| 3.2 non-Newtonian viscoplastic fluid with critical shear stress \( \tau_0 \), \( 10000 < Re_0 < 100000 \) | \( \lambda = \frac{0.3164}{Re_0^{1/4}} \) |

**Figure 7.** The Dependence of the head loss and noise transfer of different diameters collapsible pipelines winter diesel fuel at temperatures of 20°C (a) and 30°C (b)
Determined that the choice of a wrong rheological model of the flow can lead to errors in hydraulic calculations and reduce the expected productivity of transfer in the collapsible pipelines by up to 17%. The study also determined that depending on the flow, head losses for collapsible pipelines with a nominal diameter of 100 mm can be up to 700 m/km, 7 times higher than with a diameter of 150 mm. The foregoing allows to conclude that the use of collapsible pipelines with a diameter of 100 mm is impractical under these conditions, as before the mobile pumping unit PNU-75 will not be able to provide pumping for no more than 1 km. Use collapsible pipelines with a diameter of 150 mm allows to move the one PNU-75 for a distance of 9 km.

In the technical documentation of the hydraulic characteristics of the pump means of pumping are presented at nominal frequency of rotation of the shaft of the pump, taken on water or on light oil products.
at positive temperature and small values of the kinematic viscosity. For conversion of the hydraulic characteristics of centrifugal pumps with regard to the influence of the viscosity of the fluid became widespread based on the theory of similarity and dimensions the method proposed by Sukhanov and Eisenstein [7].

This resampling method accounts for the effects of kinematic viscosity on the hydraulic characteristics of the pumps are obtained by test on water, by introducing correction factors to the performance \( K_Q \), \( K_H \) and efficiency \( K_\eta \). Consequently, for liquids with a viscosity greater than water, the design characteristics of get the appearance, according to equation:

\[
Q_v = K_Q Q_w; \quad H_v = K_H H_w; \quad \eta_v = K_\eta \eta_w,
\]

where: \( Q \) – flow rate; \( H \) – pump head; \( \eta \) – pump efficiency; in equation (11) the indices \((v, w)\) refer to the work of the pumps, respectively, at the viscous liquid and water.

The values of the coefficients \( K_Q \), \( K_H \) and \( K_\eta \) depend on the Reynolds number \((Re_p)\), according to equation:

\[
Re_p = \frac{Q}{D_{eq} \nu},
\]

where: \( D_{eq} \) – equivalent diameter of the impeller of the pump.

The equivalent diameter of the impeller of the pump \( D_{eq} \) is determined from the equation [7]:

\[
\frac{\pi D^2}{4} = \pi D b k_r,
\]

where: \( D \) – outer diameter of the impeller of the pump; \( b \) – the width of the impeller blades of the pump on the outside diameter; \( k_r \) – coefficient of restriction of the impeller blades at the outlet, the calculations shall be equal to 0.92-0.95.

From the expression (13) follows equation:

\[
D_{eq} = 4 D b k_r,
\]

where: \( D \) – outer diameter of the impeller of the pump; \( b \) – the width of the impeller blades of the pump on the outside diameter.

In engineering practice, the coefficients \( K_Q \), \( K_H \) and \( K_\eta \) it is recommended to determine if the rated capacity of the pump and make permanent for the working area of the pump. The value of the nominal flow rate of pump utilized performance value flow rate of pump at maximum efficiency. The boundaries of the working area are taken in the capacity range from 0.8 to 1.2 of nominal pump flow rate [8].

In the application of funds transfer in the collapsible pipelines is likely to work in a wider range of performance values, it is therefore advisable factors \( K_Q \), \( K_H \) and \( K_\eta \) determined from the calculated, not the nominal performance values.

The coefficients \( K_Q \) and \( K_H \) defined on graphs [7] or by approximating the dependencies [9], according to equations:

\[
K_Q = -0.774 + 0.580 \log Re_p ; \quad 100 < Re_p \leq 600 , \quad (15)
K_Q = 0.412 + 0.153 \log Re_p ; \quad 600 < Re_p < 7000 , \quad (16)
K_Q = 1; \quad Re_p < 7000 , \quad (17)
K_\eta = -0.852 + 0.483 \log Re_p ; \quad 100 < Re_p \leq 2300 , \quad (18)
K_\eta = 0.201 + 0.170 \log Re_p ; \quad 2300 < Re_p < 50000 , \quad (19)
K_\eta = 1; \quad Re_p \leq 50000 . \quad (20)
\]

Ratio \( K_H \) is determined from the graphs or from equation:

\[
K_Q = K_H^{\frac{1}{2}},
\]

(21)
At values of Reynolds number \( R_{ep} > 7000 \), the coefficients \( K_Q \) and \( K_H \) differ little from 1, while the ratio \( K_n \) in these limits \( R_{ep} \) changing to a much greater extent.

Methodological apparatus (11-21) allows the recalculation of characteristics for centrifugal pump with the values of the coefficient of specific speed \( n_S \) in the range from 50 to 130. In terms of the hydraulic characteristics of this method in a specified range of values of the coefficient of speed \( n_S \) the value of the relative deviation of the obtained values is less than 5%. For pumps with greater or lower rate of speed \( n_S \) the method is extended conditionally and with a certain approximation.

The coefficient of rapidity \( n_S \) – universal characteristics used to establish the fact of their similarity, calculation of geometrical parameters and characteristics and for classification of pumps. Calculation of specific speed is carried out according to the equation \([7]\):

\[
n_S = 3.65\frac{Q^{\frac{1}{2}}}{H^{\frac{3}{4}}},
\]

where: \( n_S \) – pump specific speed; pump speed.

To assess the possibility of applying this methodology at different pump operation modes the value of the pump speed must be qualified taking into account changes in the characteristics of the head pump and the pump efficiency.

To justify the use of mobile pumping units in the conditions of low temperatures, for example PNU-75, you have converted the basic characteristics of pump operation 80-60 when pumping diesel fuel. Data for conversion of the hydraulic characteristics of pump mobile pumping unit PNU-75 (CN 80-60): outer diameter of the impeller of the pump \( (D_{o}) \) 197 mm; width of the impeller blades of the pump on the outside diameter \( (b_{o}) \) 9.5 mm; flow and head corresponding to maximum efficiency on the water 80 m\(^3\)/h and 580 m, respectively. Taking the coefficient of restriction of the impeller blades at the outlet \( (k_r) \) is equal to 0.94, according to the above formulas is defined by the equivalent diameter of the impeller of the pump \( D_{eq} \) and the Reynolds number \( R_{ep} \) for values of the volumetric pump flow rate. The equivalent diameter of the impeller of the pump \( D_{eq} \) equal 83.9 mm. On the basis of the obtained values was determined as the magnitude of the correction factors \( K_Q \), \( K_{H} \) and \( K_n \), and the calculated values of the hydraulic characteristics of the pump head, pump flow rate and pump efficiency.

Data to build the hydraulic characteristics of mobile pumping unit PNU-75 (CN 80-60) converted based on the calculation results for winter diesel fuel in low temperatures presented in tables 5.

Table 5: Results of the recalculation of characteristics of the pumping unit PNU-75 (CN 80-60) when working at the winter diesel fuel

| The pumping temperature, °C | -20 | -30 | -40 | -44 | -50 | -60 |
|-----------------------------|-----|-----|-----|-----|-----|-----|
| The product viscosity, \( v \), cSt | 30.11 | 35.93 | 43.32 | 82.97 | 242.95 | 579.07 |
| The Reynolds Number, \( R_{ep} \) | 8798 | 7373 | 6115 | 3193 | 1090 | 457 |
| Correction factors: | | | | | | |
| to pump flow rate, \( K_Q \) | 1 | 1 | 0.991 | 0.948 | 0.877 | 0.769 |
| to pump efficiency, \( K_n \) | 0.87 | 0.86 | 0.84 | 0.8 | 0.62 | 0.43 |
| to pump head, \( K_H \) | 1 | 1 | 0.994 | 0.965 | 0.916 | 0.839 |

The graphs (figures 10-12) presents a recalculation of the hydraulic characteristics of mobile pumping unit PNU-75 (CN 80-60), with the maximum values being taken from the engines of the means of transfer of power, from water to diesel fuel at different low temperatures.
According to the results of the simulation of centrifugal pumps, mobile pump units established that increase the viscosity of the fluid hydraulic characteristics of the pump means pumping deteriorate, there is a decrease in pressure, flow and efficiency, increased power consumption, so you need to clarify on the technique [7] and considered in the hydraulic calculation.

Studies to assess the impact of rheological properties on the process of transportation of diesel fuels on collapsible pipelines in the low temperatures of the obtained flow curves with which it is possible to determine how the rheological models must be given environment at various temperatures. It is established that DF upon cooling below the freezing temperature represent a viscoplastic medium with
curves of current, which describes a universal equation of Buckley-Herschel. It is revealed that when the critical shear rate dynamic viscosity becomes constant at a specific temperature.

![Figure 12. The estimated performance of PNU-75 (CN 80-60) for winter diesel fuel at temperatures of 50°C (a) and 60°C (b)](image)

This has helped to clarify the methodology of hydraulic calculations, allowing to determine the pressure loss, taking into account changes of the rheological properties of diesel fuel in low temperatures.

**Conclusion**

The result of the simulation of the DF pumping at the collapsible pipelines established that:

- the wrong choice of the rheological model of the flow can lead to errors in hydraulic calculations and reduce the expected performance of pumping through the pipeline by up to 17%.
- use tubing with a diameter of 100 mm is impractical in low temperature conditions, for practical application it is recommended to use tubing with a diameter of 150 mm

As a result of simulation of operation of centrifugal pumps mobile pumping unit it is established that with increasing viscosity worsen the hydraulic characteristics of the pump that must be considered in hydraulic calculations

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