

Influence of the temperature factor on the hydraulic resistance of pressure pipes

Vladimir Orlov and Sergey Zotkin*

Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, 129337, Russia

Abstract. The assessment of the temperature factor influence on the pressure pipeline hydraulic operation mode is very relevant, since it is considered primarily as an opportunity to reduce the cost of mechanical water transportation. Smaller pressure pipe hydraulic resistances save the electrical energy consumption, and the temperature factor has an additional positive effect on the energy saving process. The purpose of the research is to identify the nature of changes in the hydraulic friction value in relation to the temperature conditions of the transferred water temperature and environmental conditions in the designed ranges, with the subsequent possible control of the transportation process with minimum electrical energy consumption. The method of achieving these goals is an experimental and analytical approach aimed at determining the dynamics of changes in the hydraulic parameters of pipelines made of various materials. The tasks of experimental bench studies include the development of a method for calculating the values of hydraulic friction coefficients for pressure pipelines. The results of hydraulic experiments and comprehensive analysis of the experimental and calculated data for determining the hydraulic friction coefficients for polyethylene pipe are presented. The calculated values of the hydraulic friction coefficient were compared with the experimental ones, which enabled identification of their sufficiently high convergence. The conclusions show a positive effect of reducing hydraulic resistances depending on the increase in the temperature of the transported water.

1 Introduction

The strength and hydraulic parameters [1] should be considered as the basic ones when selecting the piping material for designing of construction and repair works on pressure engineering pipelines. In turn, the hydraulic parameters should be understood as the degree of the pipe inner surface roughness [2]. A special role of the hydraulic component is assigned to the choice of the repair materials for pipes and protective coatings during trenchless renovation of pressure pipelines [3]. The determination of roughness is necessary for the calculation of pressure losses in water transport pipelines and other fluid media, where such an indicator as the coefficient of hydraulic friction is the mechanism for its

* Corresponding author: zotkinsp@mgsu.ru

metering [4]. In the pipeline system hydraulics, a significant number of methods for determining the hydraulic friction coefficient are used [5-7]. However, when the question concerning the influence of the temperature of the liquid transported through the pipeline on the value of the hydraulic friction coefficient is raised, the methodological approaches to solving the problem of determining the coefficient decrease and require additional studies [8]. The basic condition for determining the hydraulic friction coefficient for any pipeline material is to conduct bench experimental studies [9]. In the future, it is possible to simulate various fluid flow modes, including thermal modes, with the search for new dependencies for determining the values of the hydraulic friction coefficient, provided that the limiting ranges for a number of parameters are observed [10]. Thus, the researchers welcome the symbiosis of experimental and analytical approaches to determining the dynamics and the ranges of changes in the flow individual hydraulic characteristics, in particular, the value of the hydraulic friction coefficient under different pipeline operating conditions [11-13]. Hence, the purpose of the simulation may be to compare the experimental and design values of the hydraulic friction coefficients, i.e. the values of their possible discrepancies with the correlation of the results within the previously established optimal ranges of the Reynolds number values and the dynamic viscosities [14]. Thereby, the main task of the present research has been adaptation of the methodology for calculating the hydraulic friction coefficients to the determination of the pipeline hydraulic parameters in wide ranges of water and environmental temperature changes.

2 Materials and methods

The studied materials have been represented by polyethylene pipes, subject to necessary identification of the dynamics of the coefficient of hydraulic friction change in a wide range of temperatures both of the transported liquid and the pipeline environment (for example, indoors, during ground or underground pipe laying, etc.). The results of the hydraulic experiments were processed using automated software programs [15-16].

Consequently, the methods considered in the article are: experimental studies and modelling of situations with changing temperature modes using the theory of semi-empirical turbulence [17]. The physical characteristics, such as the dynamic viscosity, which depends on the type of the liquid type and the temperature, and the kinematic viscosity, which is the ratio of the dynamic viscosity to the liquid density, have been provided as the values under investigation. The calculation of the hydraulic friction coefficients and other indicators of the system is carried out in automated and manual modes.

The main message of performing complex studies was that a liquid (in this case, water) is a viscous medium that, when moving through pipes, provides resistance to shear forces. In addition, it was taken into account that at different points of the transverse profile of the water flow in the pipeline, the temperature is not the same. The liquid particles from places with a higher temperature (near the flow axis) give off heat to the peripheral zone near the walls, where a laminar flow mode is observed. In practice, this phenomenon is called turbulent thermal conductivity.

Guided by the fact that the thickness of the laminar mode area in the turbulent flow, which is typical of water supply system pipelines, is not a constant value, it can be stated that it depends on the shape of the walls, their roughness and mainly on the liquid flow Reynolds number. Numerous experiments have shown that the thickness of the laminar area decreases with increasing Reynolds numbers [18]. Moreover, for large Reynolds numbers, it reaches very small absolute values. The researchers note that the circumstances which decrease the laminar mode area size do not exclude it from consideration as having no practical significance [19].

According to the boundary layer theory, the laminar area plays an essential role in the mechanism of flow inhibition by the pipe wall. This thesis was adopted in the present studies, where the dynamics of changes in the hydraulic friction coefficient were influenced by the ratio of dynamic viscosities, respectively related to the average pipe wall and flow temperatures along the length of the section.

When performing automated calculations, the following formulas were used, which consistently implement the algorithm for determining the corresponding parameters:

- the water flow rate V , m/s (1):

$$V=4Q/\pi d^2, \quad (1)$$

where - Q is the water flow rate in the pipeline, m³/s; d is the diameter of the pipeline, m

- the dynamic viscosity coefficient related to the liquid flow η_a , Pa·s (2):

$$\eta_a = 1/(562 + 17 \cdot t_a + 0,21 \cdot t_a^2 - 0,00093 \cdot t_a^3 + 0,000016 \cdot t_a^4), \quad (2)$$

where t_a is the water flow temperature;

- the coefficient of dynamic viscosity related to the temperature of the pipe wall η_r , Pa·s (3):

$$\eta_r = 1/(562 + 17 \cdot t_r + 0,21 \cdot t_r^2 - 0,00093 \cdot t_r^3 + 0,000016 \cdot t_r^4), \quad (3)$$

where t_r is the pipeline wall temperature;

- dynamic viscosity ratios (4):

$$Z^* = \eta_a/\eta_r \quad (4)$$

(*if the Z value was in the range from 2,5 to 0,83, the calculation was continued; otherwise, a printout was issued with the comment "optimization of temperature parameters is required").

- the coefficient of kinematic viscosity of the liquid ν , m²/s (5):

$$\nu = 1/(550000 + 21000 \cdot t_a + 110 \cdot t_a^2 - 0,35 \cdot t_a^3) \quad (5)$$

- Reynolds numbers Re^* (6):

$$Re^* = 4Q/(\pi d \nu) \quad (6)$$

(*if the value of the Re coefficient was in the range from $2,8 \cdot 10^4$ to $4,5 \cdot 10^5$, the calculation was continued; otherwise, a printout was issued with the comment "flow optimization required").

- design coefficient of hydraulic friction L_p (7):

$$L_p = 1/[1,82 \cdot \lg(Re \cdot Z) - 1,64]^2 \quad (7)$$

- the ratio of the design L_p and the experimental L_o values of the hydraulic friction coefficients X , % (8):

$$X = |100[(L_p/L_o) - 1]| \quad (8)$$

3 The study results and discussion

As noted above, a polyethylene pipe (PE 100, SDR 17) with an outer diameter of 100 mm has been taken as the object of the study investigation. The bench hydraulic studies, aimed at determining the hydraulic friction coefficient and other parameters, have been carried out in the Laboratory of the "Water Supply and Sanitation" Department according to the standard methodology of the Scientific and Research Institution VNII VODGEO [20]. The general view of the bench is shown in Figure 1.



Fig. 1. The hydraulic bench with pipelines: fiberglass (first from the top), steel with an internal polymer protective coating (second from the top), polyethylene PE 100 SDR 17 (third from the top).

As mentioned above, the results have been processed using automated software programs. The experimental studies were carried out at a temperature of water and the environment of 16° C. The L_o values for the tested pipe with an internal diameter of 0,09535 m have been the results of the experiments.

The following initial information was entered into the automated program: the material of the pipe and its inner diameter, the water flow consumption, the temperature of the liquid flow and the outer wall of the pipe, the coefficient of hydraulic friction obtained from the results of experiments. The following design values were considered as the parameters to be analyzed: the water flow rate, the values of the dynamic viscosity coefficients related respectively to the temperatures of the liquid flow and the pipe wall, the kinematic viscosity coefficient of the liquid, the Reynolds number, the hydraulic friction coefficient L_p (calculated).

At the first stage of the research, the results of the automated calculation were used to track and analyze the intermediate values of such indicators as the Reynolds number, the ratio of dynamic viscosities, as well as the ratio of the design and experimental values of the hydraulic friction coefficients. Table 1 shows the input and output information based on the results of an automated calculation for an arbitrarily selected water flow consumption and the same water and pipe wall temperatures.

The analysis of the data in the Table 1 shows the following: at the same temperatures of the liquid and the outer wall of the pipe, as well as within the optimal ranges of the Reynolds numbers Re and the established ratio of dynamic viscosities Z , the design hydraulic friction coefficients L_p differ from the experimental value L_o by $X=4,77\%$, which is an acceptable value for engineering calculations and allows using the formula (7) for calculating the hydraulic friction coefficient, without resorting to experimental studies on a hydraulic bench in differing conditions.

Table 1. Initial values and results of automated calculation of parameters at the same pipeline liquid and wall temperatures.

Pipe material	Polyethylene PE 100 SDR 17
Initial information	

The pipe inner diameter d , m	0,09535
Water consumption rate Q , m^3/s	0,00939
Water flow temperature t_a , $^{\circ}C$	16,0
Pipe wall temperature t_r , $^{\circ}C$	16,0
Hydraulic friction coefficient for the taken consumption (from experiments) L_o	0,01834
Calculation results	
Water flow rate V , m/s	1,315
Dynamic viscosity coefficient related to the fluid flow η_a , $Pa \cdot s$	$1,131 \cdot 10^{-3}$
Dynamic viscosity coefficient related to the pipe wall temperature η_r , $Pa \cdot s$	$1,131 \cdot 10^{-3}$
The ratio of the dynamic viscosities Z (η_a/η_r)	1,0
Coefficient of kinematic viscosity of the liquid ν , m^2/s	$1,096 \cdot 10^{-6}$
The Reynolds Number Re	$1,144 \cdot 10^5$
Design coefficient of hydraulic friction for the accepted flow rate L_p	0,017466
The ratio of the design and experimental values of the hydraulic friction coefficients X , %	4,77

The second stage of the research was an analysis of the dynamics of changes in the design coefficients of hydraulic friction, obtained on the basis of the mathematical dependencies presented above, taking into account the recommended ranges for the values of Re and Z .

The calculations were carried out at three water consumption rates Q : 0,00939 (1), 0,01217 (2) and 0,01683 (3) m^3/s . For each of the modes, the water temperature in the pipeline was assumed to be constant ($16^{\circ}C$). At the same time, the hydraulic parameters remained unchanged: flow consumption, flow rate, Reynolds coefficient. Only the pipe wall temperature was subject to step-by-step change from 9,5 to $61,5^{\circ}C$, which corresponded to the strict limits of the recommended parameters for Z , i.e. in the range of 0,839-2,498. Based on the automated calculation results, the dynamics of changes in the L_p value have been tracked, which is illustrated by the graphical dependencies in the Figure 2.

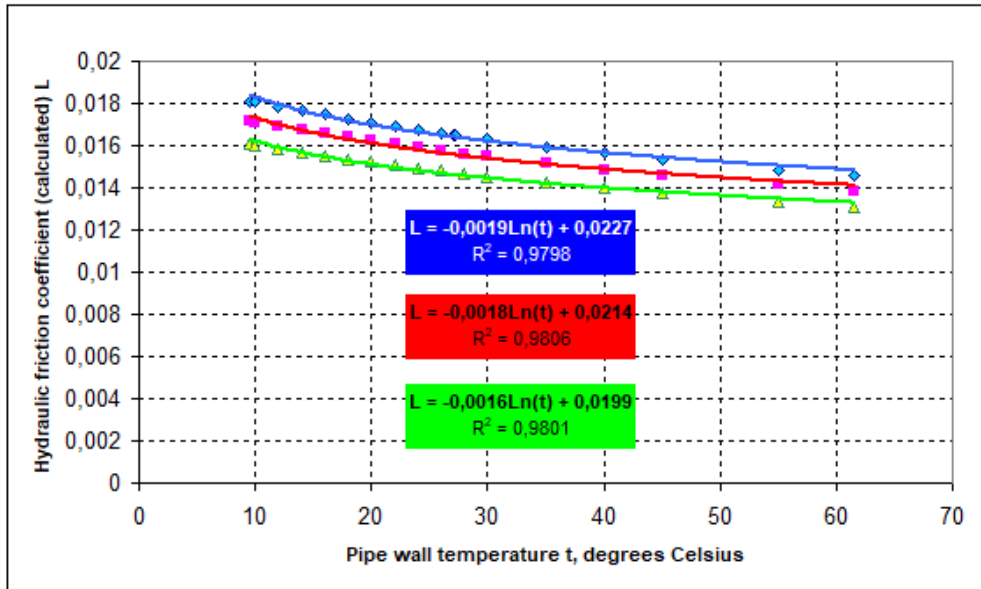


Fig. 2. Dependence of the hydraulic friction coefficient on the dynamic viscosity related to the pipe wall temperature: upper, middle and lower curves, respectively, for flow consumption rates (1), (2) and (3)

As shown in the Figure 2, there is an identification of the nature of the three curves described by the logarithmic dependence. The higher the pipe wall temperature becomes, the lower the hydraulic friction coefficient is by about 23,5 % for all water flow consumption rates. This can be described as a positive effect: higher pipeline temperatures lead to lower hydraulic resistances to the movement of the liquid, thus contributing the electrical power savings when transporting water through pressure water supply pipelines with a relatively high temperature of the outer walls. Otherwise, when placing a pipeline in low temperature zones (for example, underground, in winter conditions), its cold outer surface will provoke an increase in hydraulic resistances, directly affecting the dynamic viscosity of the boundary layer. Such a task becomes relevant for permafrost conditions during the underground or surface pipes laying, when it is necessary to reduce electrical power consumption during the water transfer.

Using the results of the hydraulic experiments together with an automated calculation program, it is possible to obtain similar mathematical dependencies with determination of the optimal area of an effective operation of engineering networks for any material and diameter. To do this, by setting the temperature of the water to be transferred and using mathematical dependencies, it is possible to calculate the values of the hydraulic friction coefficient for necessary temperature conditions of the pipeline operation, for example, in the rooms or when the pipes are laid under or above the ground.

4 Conclusions

1. An analytical investigation has been carried out to study the approaches aimed at developing a system for evaluating the hydraulic parameters of the pipes using the semi-empirical theory of turbulence and taking into account changes in the dynamic viscosity coefficients.
2. Provision has been made of a method for modelling the fluid flow temperature modes in the pipelines and an automated program for its operational implementation, which allows

the calculation of the hydraulic friction coefficients of pressure pipelines for water transfer within the established limits.

3. A positive effect of smaller hydraulic resistances depending on the temperature conditions of the pipeline operation is noted, which is expressed in the potential reduction of electrical power consumption for water transfer, including in complicated geological conditions at low temperatures.

References

1. S.V. Khramenkov, O.G. Primin, V.A. Orlov, Reconstruction of pipeline systems / M. ASV. 215 p. (2008)
2. R.I. Nigmatulin, A.A. Solovyev, Fundamentals of fluid mechanics / M.: Letter 400 p. (2012)
3. V.A. Orlov, I. A. Averkeev, E.V. Koblova, Hydraulic component of alternative materials of pipes and protective coatings during trenchless renovation of pressure pipelines. VST, **6**, pp. 22-26 (2013)
4. V.I. Aleksandrov, O.B. Gvozdev, A.E. Karelin, A.A. Morozov, Evaluation of the influence of the roughness of the inner surface of hydrotransport pipelines on the value of specific pressure losses. VST, **3**, 130, pp. 34-40 (2017)
5. S. Grossmann., D. Lohse, Curvature effects on the velocity profile in turbulent pipe flow. Eur. Phys. J. E., **40**, pp. 16-19 (2017)
6. D. Zh, Ilyasov, R.V. Aginey, Experimental assessment of the influence of fluid flow vortices on the hydraulic resistance of the pipeline. Science and Technology in the Gas Industry, **1**,81, pp. 40-47 (2020)
7. A.D. Altshul Hydraulic resistances. - M.: Nedra. 1982. 224 p.
8. O.D. Samarin, Building a universal dependence for pressure losses in pipelines. Journal of Plumbing, heating and air conditioning, **1**,169, pp. 24-25 (2016)
9. M.G. Sukharev, A.M. Karasevich , R.V. Samoilov, I.V. Tverskoy, Investigation of hydraulic resistance of polyethylene pipelines. Engineering and Physical Journal. **78**,2, pp. 136-144 (2005)
10. Yu. G. Chesnokov, New formulas for calculating the flow characteristics of a liquid or gas in a circular cross-section pipe. Engineering and Physical Journal, **90**, 4, pp. 1005-1011 (2017)
11. B.J. McKeon, M. V.Zagarola, A. J. Smits, A new friction factor relationship for fully developed pipe flow. J. Fluid Mech, **538**, pp. 429-443 (2005)
12. A. Avci, I. Karagoz, A novel explicit equation for friction factor in smooth and rough pipes. ASME J. Fluid Eng., **131**, 6, Article number 061203 (2009)
13. A. Ghanbari, F.F. Farshad, Newly developed friction factor correlation for pipe flow and flow assurance. J. Chem. Eng. Mat. Sci., **2**, pp. 83-86 (2011)
14. X. Fang, Y. Xu, Z. Zhou, New correlations of single-phase friction factor for turbulent pipe flow and evaluation of existing single-phase friction factor correlations. Nucl. Eng. Des., **241**, pp. 897-902 (2011)
15. V. Orlov, S. Zotkin, I. Dezhina, I. Zotkina, Calculation of the hydraulic characteristics of the protective coating used in trenchless technologies for the construction and renovation of pipelines to extend their service life. 6th R-S-P Seminar 2017 Theoretical Foundation of Civil Engineering, RSP 2017; Warsaw; Poland, **117**. UNSP (article number) 001852 (2017)

16. V. A.Orlov, S. P.Zotkin, M. A.Inshakova, D. A. Peterburgsky, Program for calculating hydraulic parameters of pressure pipes when changing the temperature regime. Certificate of state registration of the computer program No. **2020661754**. Registered in the Register of Computer Programs 30.09.2020 (2020)
17. A.D.Altshul, V. I.Kalitsun, F. G. Mairanovsky, P. P. Palgunov, Examples of calculations in hydraulics. M.: Publishing House Alliance, 255 p. (2013)
18. Yehia A. El Drainy, Khalid M. Saqr, Hossam S. Aly, Mohammad Nazri Mohd. Jaafar. CFD analysis of incompressible turbulent swirling flow through zanker plate. Journal Engineering Applications of Computational Fluid Mechanics, **3,4**, pp. 562-572 (2009)
19. S.S. Sayriddinov, Hydraulics of water supply and drainage systems. Moscow: DIA, 352 p. (2012)
20. A. Ya. Dobromyslov, Hydraulic calculation of non-pressure pipelines, Journal Pipelines and Ecology, **2**, pp. 21-24 (2000)