Magazine of Civil Engineering. 2021. 107(7). Article No. 10712

Magazine of Civil Engineering

ISSN 2712-8172

journal homepage: http://engstroy.spbstu.ru/

DOI: 10.34910/MCE.107.12

Long-term strength of polyethylene pipes with increased temperature resistance without reinforcement

A.S. Semenov, A.I. Grishchenko, V.G. Artiukh*, B.E. Melnikov

Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia

**E-mail: artiukh@mail.ru*

Keywords: polyethylene pipe, long-term hydrostatic strength, durability, elasticity, temperature, pressure, equivalent stress

Abstract. Results of long-term hydrostatic strength study of piping systems made from polyethylene with increased temperature resistance PE-RT type II of Hostalen 4731B without reinforcement are presented and discussed in this paper. The different approximations of durability curves and various equivalent stress measures are considered and compared. An analytical expression for the maximum allowable internal pressure as function of service life of pipes, temperature, geometrical parameters of pipe cross-section and material properties is given. Pipes without reinforcement with nominal outer diameters from 32 mm to 225 mm were analyzed to assess long-term hydrostatic strength using equivalent stress, provided that there is no change in mechanism of damage accumulation. This allowed us to use linear extrapolation into area of long service life. The results indicate possible use of pipes SDR7.4 in heating networks for 50 years with heat transfer fluid parameters of 95 °C and internal pressure of 1 MPa.

1. Introduction

Until recently, European public utility pipe market has traditionally been dominated by copper and galvanized steel pipes. Over past 30 years this segment has seen accelerated growth in share of pipes made from plastic. Advantage of plastics is that they are non-corrosive and resistant to many chemicals. They are flexible and easy to assemble (like “endless” pipe), hermetically sealed by fusion welding and light in weight, which facilitates their transportation and handling on site [1–6].

Typically, plastics used for production of municipal pipes are PE (polyethylene), PP-R (random copolymer of polypropylene), PB (polybutene) and to a lesser extent C-PVC (chlorinated PVC). While PP-R, PB and C-PVC have their own good high temperature properties, PE was not considered suitable for this market segment due to operating temperature limitations [7–11].

However, crosslinking of polyethylene (PE-X) allowed achieving desired long-term hydrostatic strength at high temperatures. Better flexibility and elasticity, high thermal conductivity, good economic properties and inertness provided by polyethylene have led to rapid increase in popularity of crosslinked polyethylene. At present crosslinked polyethylene is a widespread plastic material in segment of pipes for heating and water supply systems [12–17].

Recently, a promising new class of polyethylene materials (PE-RT) with significantly improved long-term high temperature strength without the need for crosslinking draws more and more attention [18–21].

Purpose of this work is to study the long-term hydrostatic strength of pipes made from polyethylene with increased temperature resistance PE-RT type II without reinforcement. The durability analysis is carried out for the following range of pipe parameters:

Semenov, A.S., Grishchenko, A.I., Artiukh, V.G., Melnikov, B.E. Long-term strength of polyethylene pipes with increased temperature resistance without reinforcement. Magazine of Civil Engineering. 2021. 107(7). Article No. 10712. DOI: 10.34910/MCE.107.12

- working pressure in pipe (0÷2 MPa);
- temperature (50, 60, 70, 80, 90, 95, 100, 110, 115 °C);
- outer diameter of pipes (32÷225 mm);
- pipe wall thickness for SDR 7.4 (4.4÷30.8 mm); SDR 9 (3.6÷25.2 mm); SDR 11 (2.9÷20.5 mm), where SDR is the Standard Dimensions Ratio defined as the ratio of the pipe nominal outside diameter to the nominal (minimum) wall thickness.

2. Methods

2.1. Formulation of problem

Single-layer circular pipe (see Fig. 1) with inner radius R_0, outer radius R_1, outer diameter $d_n = 2R_1$ and wall thickness $e_n = R_1 - R_0$ is considered. Pressure p acts on the inner surface of the pipe and pressure q is applied on the outer boundary. The cylindrical coordinate system with z-axis along symmetry axis of the pipe is used.

The calculation of the equivalent stress measure, depending on geometric and loading parameters, is the aim of the boundary value problem solution. The problem has a well-known analytical solution for the stress-strain state (firstly proposed by Gabriel Lamé [22]) in the linear isothermal infinitesimal elastic formulation under assumption of isotropy of material properties.

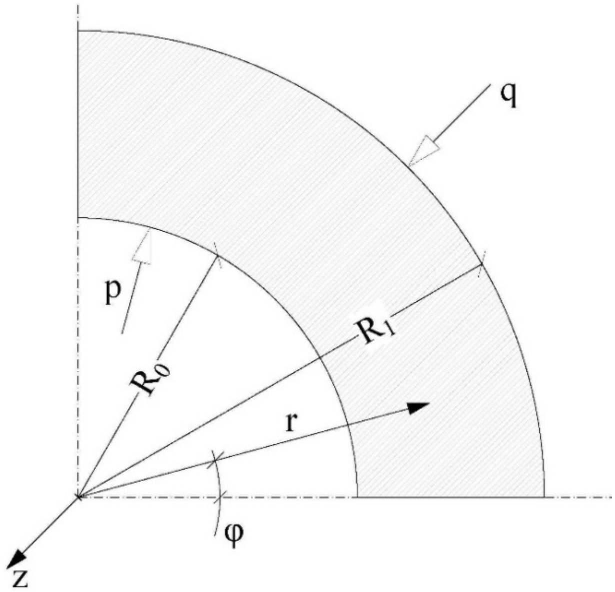

Figure 1. Schematic representation of pipe section fragment with indication of the main geometric parameters and acting loads.

2.2. Analytical solution for stress tensor components

Solution of Lamé boundary value problem [22] in linear elastic isothermal formulation in framework of hypothesis of a plane strain state when pressures acting on inner and outer surfaces of pipe are set as boundary conditions

$$\sigma_r\Big|_{r=R_0} = -p; \quad \sigma_r\Big|_{r=R_1} = -q, \tag{1}$$

has a form of following dependences of radial and circumferential stresses on applied loads, geometric parameters and distance r from axis [23]:

$$\begin{cases} \sigma_r = q\dfrac{1}{1-\left(\dfrac{R_0}{R_1}\right)^2}\left(\left(\dfrac{R_0}{r}\right)^2-1\right)+p\dfrac{1}{1-\left(\dfrac{R_0}{R_1}\right)^2}\left(\left(\dfrac{R_0}{R_1}\right)^2-\left(\dfrac{R_0}{r}\right)^2\right); \\ \sigma_\varphi = q\dfrac{-1}{1-\left(\dfrac{R_0}{R_1}\right)^2}\left(1+\left(\dfrac{R_0}{r}\right)^2\right)+p\dfrac{1}{1-\left(\dfrac{R_0}{R_1}\right)^2}\left(\left(\dfrac{R_0}{R_1}\right)^2+\left(\dfrac{R_0}{r}\right)^2\right). \end{cases} \quad (2)$$

The axial stress σ_z for the plane strain state case can be evaluated by the relation $\sigma_z = \nu\left(\sigma_r + \sigma_\varphi\right)$, where ν is the Poisson ratio.

In many practical applications, outer pressure is much less then internal. In this case, the influence of external pressure can be neglected and action of only internal pressure p is taken into account that leads to the simplification of relations (2) in the form:

$$\begin{cases} \sigma_r = p\dfrac{1}{1-\left(\dfrac{R_0}{R_1}\right)^2}\left(\left(\dfrac{R_0}{R_1}\right)^2-\left(\dfrac{R_0}{r}\right)^2\right); \\ \sigma_\varphi = p\dfrac{1}{1-\left(\dfrac{R_0}{R_1}\right)^2}\left(\left(\dfrac{R_0}{R_1}\right)^2+\left(\dfrac{R_0}{r}\right)^2\right). \end{cases} \quad (3)$$

The typical diagrams of stress tensor components distribution along the radius within the wall thickness are shown in Fig. 2 for the PE-RT type II pipe with outer diameter 50 and wall thickness 6.9 mm.

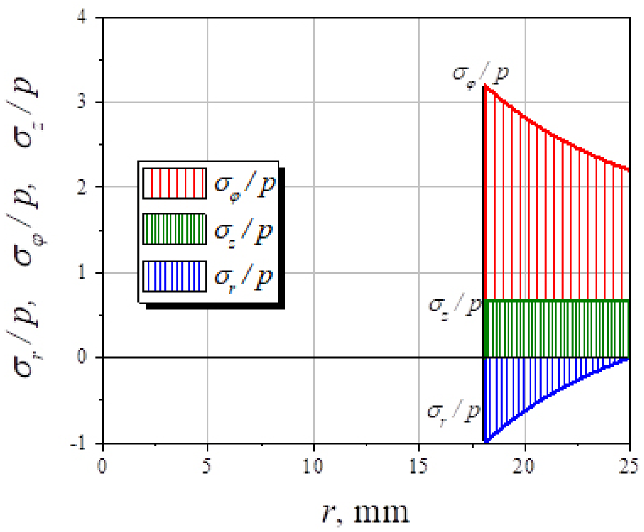

Figure 2. Example of stress tensor components distributions along the radius for the pipe with outer diameter 50 mm and wall thickness 6.9 mm.

Analysis of relations (3) allows asserting that the maximum values of circumferential stress (maximal principle stress) are realized on the inner radius

$$max\,\sigma_\varphi = \sigma_\varphi\left(R_0\right) = p\frac{\left(R_1\right)^2 + \left(R_0\right)^2}{\left(R_1\right)^2 - \left(R_0\right)^2}. \tag{4}$$

It should be noted that it is possible to obtain analytical solution of the problem in viscoelastic, elastoplastic or viscoplastic formulation [24, 25]. However, numerous experiments do not demonstrate the remarkable residual strains and use of such nonlinear material models for life-time prediction will require significant increase in amount of necessary experimental data. Note also, the linear elastic solution provides conservative evaluation of stress state.

2.3. Equivalent stress measures

It is necessary to introduce equivalent stress for which formulation of strength criterion is compared with the maximum permissible value of long-term strength for analysis of strength in case of non-uniaxial stress state. Circumferential component of stress (which is always tensile and exceeds value of compressive radial component) can be considered as the maximum principal value:

$$\sigma_{eq} = \sigma_1 = \sigma_\varphi. \tag{5}$$

Also doubled maximum shear stress (Tresca equivalent stress) can be considered as equivalent stress

$$\sigma_{eq} = \sigma_1 - \sigma_3. \tag{6}$$

Mises stress intensity

$$\sigma_{eq} = \sqrt{\frac{1}{2}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]}. \tag{7}$$

Thickness-average circumferential stress is determined by 'boiler equation'

$$\sigma_{eq} = \bar{\sigma}_\varphi = \frac{pR_0}{R_1 - R_0}. \tag{8}$$

Equation used in GOST 32415-2013 is approximation to the maximum principal stress, which can be obtained as a consequence of asymptotic equation (4) under assumption that the wall thickness is small:

$$\sigma_{eq} = \frac{p\left(R_1 + R_0\right)}{2\left(R_1 - R_0\right)} = \frac{p\left(d_n - e_n\right)}{2e_n} = \frac{p\left(SDR - 1\right)}{2}. \tag{9}$$

Comparison of the maximum values of equivalent stress (5)-(7) and predictions by (8) and (9) is shown in Fig. 3 for the pipe with outer diameter 50 mm and wall thickness 6.9 mm. There is 23 % difference between the minimum and maximum results.

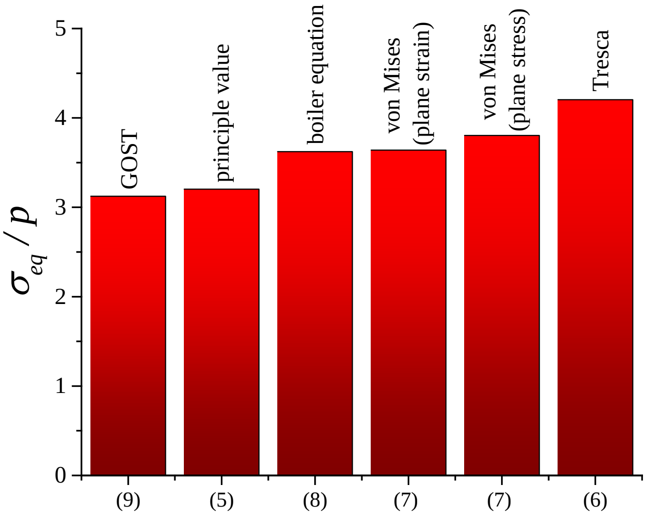

Figure 3. Comparison of equivalent stresses (5)-(9) for the pipe with outer diameter 50 mm and wall thickness 6.9 mm.

In [26, 27] results of tests of high-density polyethylene under biaxial tension are given and it is noted that when analyzing for long-term static strength at low stress levels and long durability the best prediction corresponds to the criterion of maximum principal stresses (5). At the same time, at high stress levels and short-term durability the best prognosis is provided by Mises criterion (7). Therefore, in analysis of long-term strength for long service lives the equivalent stress (5) and its simplified approximation (9) are used below.

2.4. Long-term strength curves approximation

In practice, there are various approximations of long-term strength curves [28]. In present research, the following four-term dependence of durability (time to failure) from equivalent stress and temperature originally introduced in DIN EN ISO 15875-2:2004 [29] was used for approximation of long-term strength curves of polyethylene PE-RT type II:

$$\lg(t) = A + \frac{B\lg(\sigma)}{T} + \frac{C}{T} + D\lg(\sigma), \tag{10}$$

where A, B, C and D are material constants. By transformation of (10) the more convenient for further analysis formulation with combination in one term the stress dependent expressions can be obtained:

$$\lg(t) = \left(D + \frac{B}{T}\right)\lg(\sigma) + \left(A + \frac{C}{T}\right). \tag{11}$$

Determination of coefficients of the equation (11) was carried out on the basis of minimizing following functional (according to the method of least squares):

$$L = \sum_{i=1}^{n}\sum_{j=1}^{k}\left[\left(D + \frac{B}{T_i}\right)\lg\left(\sigma_j\right) + \left(A + \frac{C}{T_i}\right) - \lg t\left(\sigma_i, T_j\right)\right]^2 \to \min. \tag{12}$$

Objective function (12) is the standard deviation. This objective function has a complex, non-linear form and a large number of local extremums. The sliding tolerance method (Nelder–Mead method [30, 31]) is used for finding a global extremum to minimize the objective function (12). Advantages of this method are ability to solve problems with both linear and nonlinear objective functions and constraints. This method does not use derivatives.

3. Results and Discussion

As a result of experimental data analysis [32] for curves of long-term strength of polyethylene of increased thermal resistance PE-RT type II of Hostalen 4731B brand approximation coefficients A, B, C

and D of equation (10) were obtained on the basis of least squares method (12). Coefficients are presented in Table 1.

Table 1. Coefficients of approximation (10) of long-term strength curve of polyethylene PE-RT type II of Hostalen 4731B.

A	–252.0882	lg(h)
B	–68217.06	K lg(h) / lg(MPa)
C	105350.4	K lg(h)
D	136.0416	lg(h) / lg(MPa)

Comparison of obtained approximations of long-term strength curves with experimental data is shown in Fig. 4, where points correspond to the experimental data, straight lines related to the calculated approximations.

Thus, equation (10) takes below given form after determining the coefficients:

$$\lg(t) = -252.0882 - \frac{68217.06}{T}\lg(\sigma) + \frac{105350.4}{T} + 136.0416\,\lg(\sigma), \tag{13}$$

in which the stresses are measured in MPa, time in h, temperature in K.

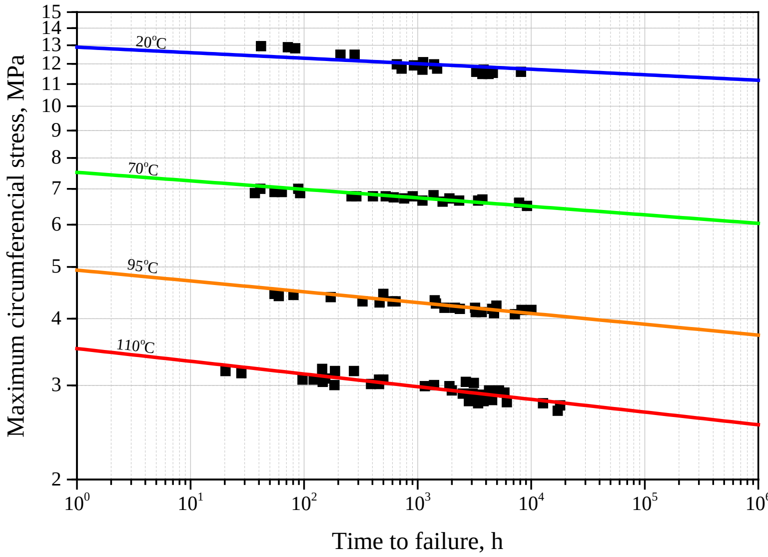

Figure 4. Curves of long-term strength based on equation (13).
Experimental results are shown by points and their approximations are shown by lines.

The standard deviation for all curves in Fig. 4 is less than 1 % that confirms adequacy of choice of model and high accuracy of determining the constants.

It is important to note that introduced approximation (13) allows linear extrapolation to region of long service lives only if there is no change in damage accumulation mechanism (for example, a transition from ductile to brittle fracture mechanism or microstructural changes in material). Verification of absence of change in the mechanism of damage accumulation can be carried out experimentally.

Comparison with experimental data of alternative approaches of long-term strength approximations such as Larson-Miller equation [33]

$$\lg(t) = A + \frac{B}{T} + \frac{C}{T}\lg(\sigma) + D\lg^2(\sigma) \tag{14}$$

and Manson-Hafed equation [34]

$$\lg(t) = A + B\lg(\sigma) + C\lg^2(\sigma) + DT \tag{15}$$

demonstrated advantage (see Fig. 5) of criterion (10) in comparison with (14) and (15) which are widespread for metallic materials.

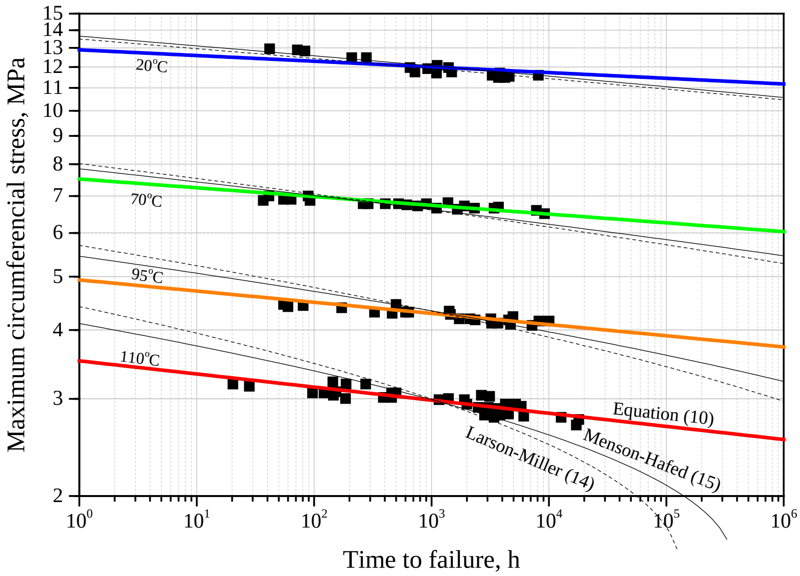

Figure 5. Comparison of experimental results with Larson-Miller approximation (14), Manson-Hafed (15) and approximation by equation (10).

Following coefficients in approximations were used (stresses are measured in MPa, time is in h, temperature is in K) for Larson-Miller criterion

$$\lg(t) = -69.0589 + \frac{28132.90}{T} + \\ + \frac{3123.772}{T}\lg(\sigma) - 8895.212\lg^2(\sigma) \tag{16}$$

and for the criterion of Manson-Hafed

$$\lg(t) = 96.82029 + 11.10418\lg(\sigma) - \\ - 30.12566\lg^2(\sigma) - 0.24095T. \tag{17}$$

It should be noted that use of unified analytical approximations over entire temperature range introduces some error in analysis of specific temperatures. Example of that difference is shown in Fig. 6, which compares approximation (10) uniform for all temperatures with coefficients A, B, C and D defined by the results of experiments at T = 20, 70, 95, 110 °C and isothermal approximation

$$\lg(t) = F + E \cdot \lg(\sigma), \tag{18}$$

obtained on the basis of least squares method (F = 0.677 lg(h), E = –0.01576 lg(h)/lg(MPa)) for set of experimental points at temperature of T = 95 °C. Obtained result indicates that use of approximation (10) at temperature of T = 95 °C for a time of more than three months provides conservative estimate with certain margin.

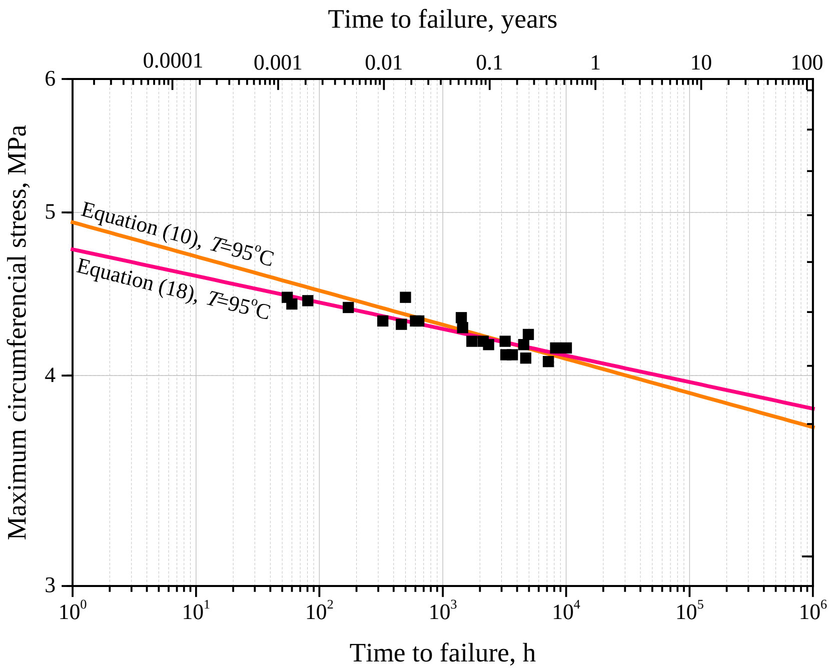

Figure 6. Comparison of approximation (10) uniform for all temperatures with approximation (18) introduced only for temperature of *T* = 95 °C.

2.5. Long-term strength nomograms

Actual for practice nomograms «pressure-temperature-durability» were obtained for three different SDR values (see Fig. 7-9) based on the analytical solution (4) for pipe under internal pressure, equivalent stress (9) and results of approximation of long-term strength curves (13).

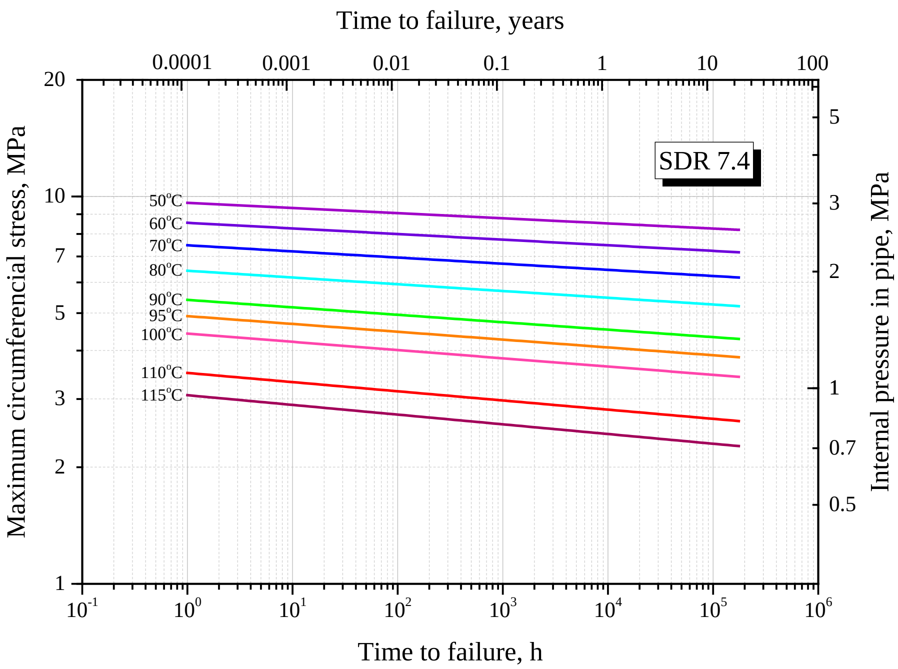

Figure 7. Long-term strength for pipes with SDR 7.4 made of polyethylene PE-RT type II of Hostalen 4731b brand.

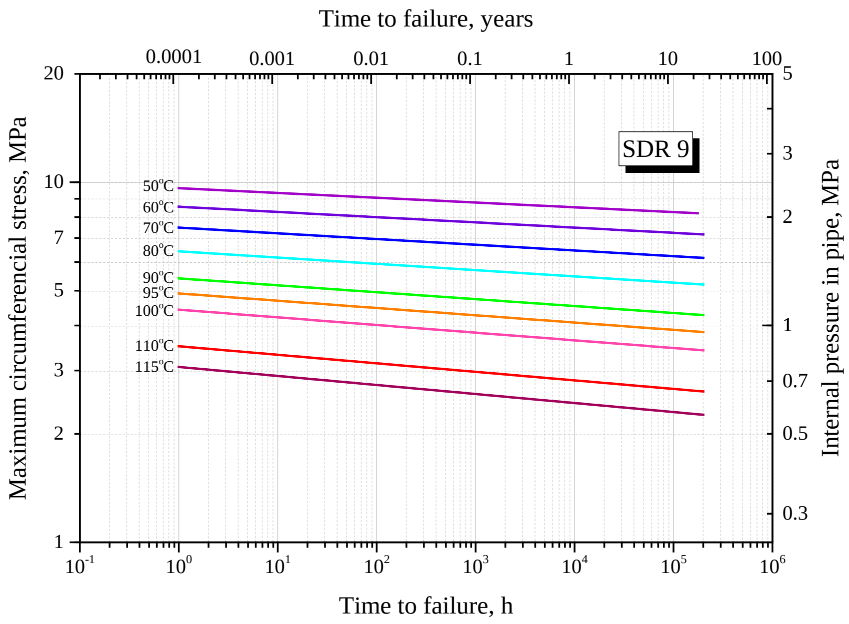

Figure 8. Long-term strength for pipes with SDR 9 made of polyethylene PE-RT type II of Hostalen 4731B brand.

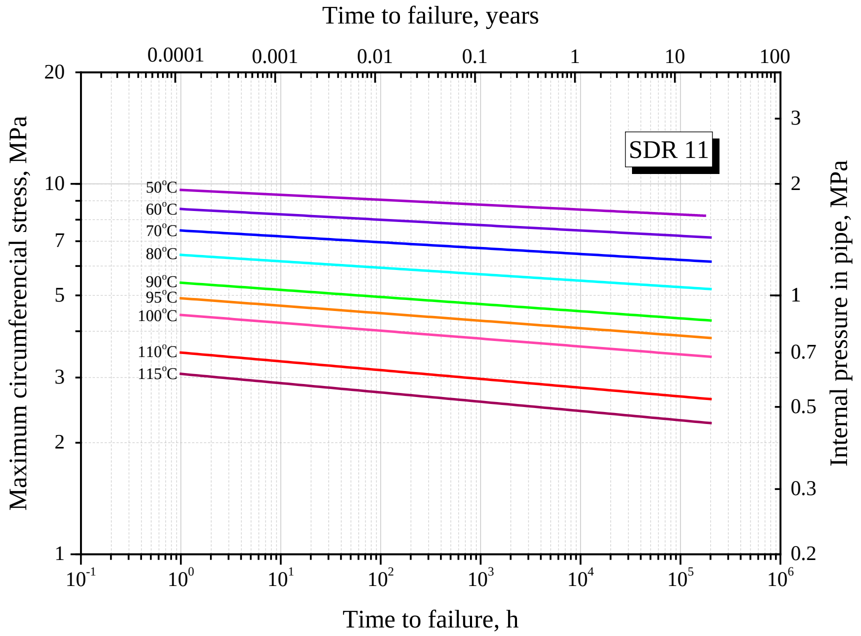

Figure 9. Long-term strength for pipes with SDR 11 made of polyethylene PE-RT type II of Hostalen 4731B brand.

With increasing SDR (decreasing relative wall thickness) the maximum allowable pressure level decreases (compare Fig. 7-9). The maximum allowable internal pressure was determined on the basis of the equation

$$p = \frac{2e_n}{d_n - e_n}\sigma_{eq} = \frac{2}{SDR-1}\sigma_{eq} = \frac{2}{SDR-1}10^{\frac{\lg(t)-\left(A+\frac{C}{T}\right)}{D+\frac{B}{T}}}, \quad (19)$$

which has been obtained from the equations (9) and (10).

Long-term strength curves may slightly differ for different standard sizes of pipes with the same SDR value due to specifics of choosing nominal wall thickness from a tabulated discrete range of thicknesses in accordance with regulatory documents. As a rule, nominal wall thickness slightly differs in direction of increase from value of ratio of outer diameter to SDR that leads to conservative estimate of strength. The durability is sensitive to variation of the wall thickness, therefore it is necessary to individually check fulfillment of strength condition for each standard size in especially critical cases.

Calculation results of the maximum allowable pressures using criterion (9) for pipes of various standard sizes SDR 7.4 made of polyethylene of increased temperature resistance PE-RT type II Hostalen 4731B brand at temperature of T = 95 °C for various service lives (from 50 years to 100 hours) are presented in Table 2.

Table 2. Maximum allowable pressure for pipes of various standard sizes (SDR 7.4) made of polyethylene PE-RT type II of Hostalen 4731B brand at temperature of T = 95 °C for various service lives.

No.	d_n, mm	e_n, mm	p, MPa			
			50 years	*2 years*	*1 year*	*100 h*
1	32	4.4	1.209	1.290	1.308	1.433
2	40	5.5	1.209	1.290	1.308	1.433
3	50	6.9	1.214	1.296	1.313	1.439
4	63	8.6	1.199	1.279	1.297	1.421
5	75	10.3	1.207	1.288	1.307	1.431
6	90	12.3	1.200	1.281	1.299	1.422
7	110	15.1	1.206	1.288	1.306	1.430
8	125	17.1	1.201	1.283	1.301	1.424
9	140	19.2	1.205	1.286	1.304	1.428
10	160	21.9	1.202	1.283	1.301	1.425
11	180	24.6	1.200	1.281	1.299	1.422
12	200	27.4	1.204	1.285	1.303	1.427
13	225	30.8	1.203	1.283	1.302	1.425

It can be seen from Table 2 that for all considered standard sizes at pressure of p = 1 MPa condition of long-term strength is provided at heat transfer fluid temperature of T = 95 °C for service life of 50 years. The safety factor is 1.2 when using criterion (9) for all cases of standard sizes. The safety factor exceeds 1.17 when using criterion of maximum principal stresses (5).

Calculations made for verification purposes using Mises criterion (7) for plane strain state showed that in this case condition of long-term strength is also provided at pressure of p = 1 MPa and heat transfer fluid temperature of T = 95 °C for service life of 50 years. At the same time, the safety factor for the considered standard sizes of pipes exceeds 1.03.

The maximum allowable pressure obtained for equivalent stress (9) for pipes of various standard sizes SDR 9 made of polyethylene of increased temperature resistance PE-RT type II of Hostalen 4731B brand at temperature of T = 95 °C for various service life (from 50 years to 100 hours) are presented in Table 3.

Table 3. Maximum allowable pressure for pipes of various standard sizes (SDR 9) made of polyethylene PE-RT type 2 of Hostalen 4731B brand at temperature of T = 95 °C for various service life.

No.	d_n, mm	e_n, mm	p, MPa			
			50 years	*2 years*	*1 year*	*100 h*
1	32	3.6	0.961	1.026	1.040	1.139
2	40	4.5	0.961	1.026	1.040	1.139
3	50	5.6	0.956	1.026	1.035	1.133
4	63	7.1	0.963	1.026	1.042	1.141
5	75	8.4	0.956	1.026	1.035	1.133
6	90	10.1	0.958	1.023	1.037	1.136
7	110	12.3	0.954	1.019	1.033	1.131
8	125	14	0.956	1.021	1.035	1.133
9	140	15.7	0.958	1.022	1.037	1.135
10	160	17.9	0.955	1.019	1.034	1.132
11	180	20	0.948	1.012	1.026	1.123
12	200	22.4	0.956	1.021	1.035	1.133
13	225	25.2	0.956	1.021	1.035	1.133

It can be seen from Table 3 that for all considered standard sizes at pressure of p = 1 MPa condition of long-term strength is provided at heat transfer fluid temperature of T = 95 °C for service life of 2 years. The safety factor is 1.02 when using criterion (9) for all cases of standard sizes.

All considered sizes of pipes SDR 9 withstand the pressure of 0.7 MPa for 50 years with safety factor 1.35 and the pressure of 0.6 MPa with safety factor 1.5.

Calculation results of the maximum allowable pressure using criterion (9) for pipes of various standard sizes SDR 11 made of polyethylene of increased temperature resistance PE-RT type II of Hostalen 4731B brand at temperature of T = 95 °C for various service life (from 50 years to 100 hours) are presented in Table 4.

Table 4. Maximum allowable pressure for pipes of various standard sizes (SDR 11) made of polyethylene PE-RT type II of Hostalen 4731B brand at temperature of T = 95 °C for various service life.

No.	d_n, mm	e_n, mm	p, MPa			
			50 years	*2 years*	*1 year*	*100 h*
1	32	2.9	0.773	0.825	0.837	0.916
2	40	3.7	0.768	0.820	0.832	0.910
3	50	4.6	0.769	0.821	0.832	0.911
4	63	5.8	0.756	0.807	0.818	0.896
5	75	6.8	0.760	0.811	0.823	0.901
6	90	8.2	0.758	0.809	0.821	0.899
7	110	10.0	0.761	0.812	0.824	0.902
8	125	11.4	0.756	0.807	0.819	0.896
9	140	12.7	0.761	0.813	0.824	0.902
10	160	14.6	0.760	0.811	0.823	0.901
11	180	16.4	0.759	0.810	0.822	0.900
12	200	18.2	0.760	0.811	0.823	0.901
13	225	20.5	0.773	0.825	0.837	0.916

It can be seen from Table 4 that for all considered standard sizes at pressure of p = 0.6 MPa condition of long-term strength is provided at heat transfer fluid temperature of T = 95 °C for service life of 50 years. The safety factor is 1.26 when using criterion (9) for all cases of standard sizes for pressure 0.6 MPa.

The safety factor 1.5 does not allow to increase pressure above 0.5 MPa for 50 years, above 0.55 MPa for 1 year and above 0.6 MPa for 100 hours for pipes of SDR 11.

The above estimates are valid for constant pressures and temperatures throughout the entire service life. In the case of realistic loading conditions with variable (piecewise constant) values, it is recommended to use the Miner’s linear damage summation rule [35, 36].

4. Conclusions

1. The four-term approximation (13) of long-term hydrostatic strength curves is proposed and analyzed for polyethylene of increased temperature resistance PE-RT type II of Hostalen 4731B brand.

2. The maximum allowable internal pressure (19) is determined as a function of service life of pipes, temperature, geometrical parameters of pipe cross-section and material properties.

3. Data of proposed nomograms (Fig. 7–9) should be used to determine durability of pipes, critical pressures and safety factors for the various temperature conditions.

4. We studied pipes without reinforcement with nominal outer diameter from 32 mm to 225 mm made of polyethylene of increased temperature resistance PE-RT type II of Hostalen 4731B brand. We assessed the long-term strength using provided equivalent stress under assumption that there is no change in damage accumulation mechanism. The results obtained indicate possible use of these pipes in heating networks for 50 years with heat transfer fluid of 95 °C and working pressure of 1.0 MPa for SDR 7.4, pressure 0.8 MPa for SDR 9, pressure 0.6 MPa for SDR 11 with safety factor 1.2 in all cases.

5. Miner's relation with account of summation of damages within each interval of constancy of temperature and pressure should be used for calculating durability of pipes with changing over time levels of temperatures and pressure.

6. For validation and verification of obtained analytical results further experimental and finite element verification are required.

5. Acknowledgments

The research was funded by the Ministry of Science and Higher Education of the Russian Federation as part of the World-class Research Center program: Advanced Digital Technologies (contract No. 075-15-2020-934 dated 17.11.2020). The authors declare that there is no conflict of interest regarding the publication of this paper.

References

1. Seguela, R. On the Natural Draw Ratio of Semi-crystalline Polymers: Review of the Mechanical, Physical and Molecular Aspects. Macromolecular Materials and Engineering. 2007. 292(3). Pp. 235–244.
2. Artiukh, V., Mazur, V., Kukhar, V., Vershinin, V., Shulzhenko, N. Study of polymer adhesion to steel, E3S Web of Conferences. 2019. 110, 01048. https://doi.org/10.1051/e3sconf/201911001048.
3. Drozdov, A.D., Klitkou, R., Christiansen, J.D. Cyclic Viscoplasticity of Semicrystalline Polymers with Finite Deformations. Mechanics of Materials. 2013. 56. Pp. 53–64. DOI: 10.1016/j.mechmat.2012.09.005
4. Ishchenko, A., Artiukh, V., Mazur, V., Poberezhskii, S., Aleksandrovskiy, M. Experimental study of repair mixtures as glues for connecting elastomers with metals, MATEC Web of Conferences, 2019. 265, 01016. DOI: 10.1051/matecconf/201926501016
5. Pawlak, A., Galeski, A., Rozanski, A. Cavitation During Deformation of Semicrystalline Polymers. Progress in Polymer Science. 2014. 39(5). Pp. 921–958. DOI: 10.1016/j.progpolymsci.2013.10.007
6. Artiukh, V.G., Galikhanova, E.A., Mazur, V.M., Kargin, S.B. Energy intensity of parts made from polyurethane elastomers. Magazine of Civil Engineering. 2018. 81(5). Pp. 102–115. DOI: 10.18720/MCE.81.11
7. Biron, M. Thermoplastics and Thermoplastic Composites. Oxford, UK: Elsevier Ltd. 2014.
8. Boros, S. Long-term hydrostatic strength and design of thermoplastic piping compounds. Journal of ASTM International. 2011. 8(9). Pp. 57–72.
9. Pawlak, A., Krajenta, J., Galeski, A. Cavitation Phenomenon and Mechanical Properties of Partially Disentangled Polypropylene. Polymer. 2018. 151. Pp. 1–26. DOI: 10.1016/j.polymer.2018.07.033
10. Ultrapolymers zeigt Polyolefine mit besonderen Eigenschaften. Österr. Kunstst. Z. 2005. – 36(9-10). P. 221.
11. Fallatah, G., Dobbs, N., Gibson, A. Long Term Creep and Stress Rupture of Aramid Fibre. Plastics, Rubber and Composites. 2007. 36(9). Pp. 403–412.
12. Xiong, B., Men, Y., Lame, O., Chenal, J.-M., Seguela, R., Vigier, G. Critical Stress And Thermal Activation Of Crystal Plasticity In Polyethylene: Influence Of Crystal Microstructure And Chain Topology Polymer. 2017. 118. Pp. 192–200. DOI: 10.1016/j.polymer.2017.05.011
13. Humbert, S., Lame, O., Séguéla, R., Vigier, G. A Re-Examination Of The Elastic Modulus Dependence On Crystallinity In Semi-Crystalline Polymers. Polymer. 2011. 52(21). Pp. 4899–4909.
14. Artiukh, V.G., Karlushin, S.Yu., Sorochan, E.N. Peculiarities of Mechanical Characteristics of Contemporary Polyurethane Elastomers Procedia Engineering. 2015, No. 117, Pp. 938–944. DOI: 10.1016/j.proeng.2015.08.180
15. Xiong, B., Lame, O., Chenal, J.M., Seguela, R., Vigier, G., Rochas, C. In-Situ Saxs Study and Modeling Of The Cavitation/Crystal-Shear Competition In Semi-Crystalline Polymers: Influence Of Temperature And Microstructure In Polyethylene. Polymer. 2013. V. 54. N. 20. Pp. 5408–5418.
16. Zhang, Y., Ben Jar, P.-Y., Nguyen, K.-C.T., Le, L.H. Characterization of Ductile Damage in Polyethylene Plate Using Ultrasonic Testing. Polymer Testing. 2017. 62. Pp. 51–60. DOI: 10.1016/j.polymertesting.2017.06.010
17. Xiong, B., Lame, O., Chenal, J.-M., Seguela, R., Vigier, G., Rochas, C. Temperature-Microstructure Mapping of The Initiation Of The Plastic Deformation Processes In Polyethylene Via In Situ Waxs And Saxs. Macromolecules. 2015. 48(15). Pp. 5267–5275.
18. Schramm, D. PE-RT: A New Class of Polyethylene for Industrial Pipes. 25th Int. Conference on Offshore Mechanics and Arctic Engineering. Vol. 3: Safety and Reliability; Materials Technology; Douglas Faulkner Symposium on Reliability and Ultimate Strength of Marine Structures. Hamburg, Germany, June 4-9, 2006. Paper No. OMAE2006-92266, pp. 513–521.
19. Montes, J. Castillo, Cadoux, D., Creus, J. Ageing of polyethylene at raised temperature in contact with chlorinated sanitary hot water. Part I – Chemical aspects. Polymer Degradation and Stability. 2012. 97(2). Pp. 149–157.
20. Detrez, F., Seguela, R., Cantournet, S. Plasticity/Damage Coupling In Semi-Crystalline Polymers Prior To Yielding: Micromechanisms and Damage Law Identification. Polymer. 2011. 52(9). Pp. 1998–2008.
21. Zhang, Y., Xue, S., Ben Jar, P.Y., Li, L. Quantification of Strain-Induced Damage in Semi-Crystalline Polymers: a Review. Journal of Materials Science. 2019. 54(1). Pp. 62–82. DOI: 10.1007/s10853-018-2859-2
22. Lamé, G. Leçons sur la théorie mathématique de l'élasticité des corps solides, Paris, 1852.
23. Timoschenko, S.P., Goodier, J.N. Theory of elasticity. McGraw-Hill. 1969. 567 p.
24. Dudnik, A.E., Chepurnenko, A.S., Nikora, N.I. Plane axisymmetric problem of thermo-viscoelasticity for a polymer cylinder. Engineering Bulletin of Don. 2015. No. 1, part 2.
25. Semenov, A., Melnikov, B. Interactive rheological modeling in elasto-visco-plastic finite element analysis. Procedia Engineering. 2016. 165. Pp. 1748–1756.
26. Greenman, A.M., Goldman, A.Ya. Long-term strength of polyethylene under conditions of biaxial tension. Mechanics of polymers. 1976. No. 3. Pp. 401–408.
27. Potapova, L.B., Yartsev, V.P. Mechanics of materials under complex stress conditions. M.: «Mechanical engineering», 2005. 209 p.
28. Kucher, N.K., Prikhod'ko, R.P. Prediction of high-temperature long-term strength of materials. Strength of Materials. 2013. 45. Pp. 517–522. https: //doi.org/10.1007/s11223-013-9488-4

29. DIN EN ISO 15875-2:2004. Plastics piping systems for hot and cold water installations – Crosslinked polyethylene (PE-X) – Part 2: Pipes.
30. Himmelblau, D. Applied Nonlinear Programming. McGraw-Hill, 1972. 536 p.
31. Grishchenko, A.I., Semenov, A.S. Effective methods of parameter identification for creep models with account of III stage. MATEC Web of Conferences. 2016. Vol. 53. Pp. 01043.
32. Hostalen 4731 B. Introducing a new PE-RT Type II material. Lyondell Basell // www.lyondellbasell.com.
33. Larson, F.R., Miller, J. Time–temperature relationship for rupture and creep stress // Trans. ASME. 1952. 74(5). Pp. 765–775.
34. Manson, S.S., Haferd, A.M. A linear time–temperature relation for extrapolation of creep and stress rupture data. NASA TN 2890. 1953.
35. DIN EN ISO 13760:1998. Plastics pipes for conveyance of fluids under pressure – Miner's rule – Calculation method for cumulative damage.
36. Petrakov, G.P. The service life of plastic pipe in the polyurethane foam insulation, used for heating system. Magazine of Civil Engineering. 2012. No. 3. Pp. 54–62.

Contacts:

Artem Semenov, Semenov.Artem@googlemail.com
Alexey Grishchenko, gai-gr@yandex.ru
Viktor Artiukh, artiukh@mail.ru
Boris Melnikov, kafedra@ksm.spbstu.ru