Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Numerical Modeling of the Transient Temperature Field in Polyethylene Pipe Welding at Low Temperatures with Active Cooling

Olga Ammosova
Institute of Oil and Gas Problems of the Siberian Branch of the Russian Academy of Sciences
Sandaara Tatarinova
sandaara7272@gmail.com

Institute of Oil and Gas Problems of the Siberian Branch of the Russian Academy of Sciences
Roman Tikhonov
Institute of Oil and Gas Problems of the Siberian Branch of the Russian Academy of Sciences

Research Article

Keywords: polyethylene pipes, welding, low temperatures, thermal process, phase transformation, mathematical modeling, finite element method

Posted Date: November 19th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11629519/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Numerical Modeling of the Transient Temperature Field in Polyethylene Pipe Welding at Low Temperatures with Active Cooling

Olga Ammosova, Sandaara Tatarinova† and Roman Tikhonov†

Laboratory of Climatic Tests, Institute of Oil and Gas Problems of the Siberian Branch of the Russian Academy of Sciences, 2 Petrovskogo Street, Yakutsk, 677000, Russia.

*Corresponding author(s). E-mail(s): ammosova_o@mail.ru;
Contributing authors: sandaara7272@gmail.com; roman_tikhon@mail.ru;
†These authors contributed equally to this work.

Abstract

Based on mathematical modeling that accounts for the latent heat of phase transformation within the temperature range and the evolution of the material's degree of crystallinity, this study investigates thermal processes during polyethylene (PE) pipe welding under various low-temperature conditions. Calculations demonstrate that preliminary heating and thermal homogenization of the welded assembly allow subsequent heating to follow the standard welding protocol. Furthermore, the results establish that maintaining a reference temperature on the outer surface of the electrofusion coupling reduces the cooling rate, ensuring the crystallization front propagates as it would under permissible ambient temperatures.

Keywords: polyethylene pipes, welding, low temperatures, thermal process, phase transformation, mathematical modeling, finite element method.

1 Introduction

Electrofusion welding of polyethylene (PE) pipes is typically performed at ambient air temperatures ranging from –10 to 40 °C [1]. While some specialized welding units can operate at temperatures down to –20 °C, welding below standard recommended

limits requires the use of heated shelters to maintain permissible conditions. This approach, in turn, demands extensive preparatory work to bring the components up to the required pre-welding temperatures.

To form a high-quality weld, the material must reach a viscous-flow state to a specific depth in the joint area during the heating stage. However, simply extending the heating time of cold components to achieve the required melt volume does not ensure quality, as peripheral areas remain underheated. Consequently, even within heated shelters at permissible ambient temperatures, rapid cooling occurs due to conductive heat transfer.

Reaching permissible temperatures in the pipe walls and the electrofusion coupling by holding them in shelters takes too long, which is unacceptable for emergency gas pipeline repairs in cold climates during winter. Alternative technologies for electrofusion welding use standard welding machines combined with thermal insulation layers to reduce the cooling rate [2, 3]. The main drawback of this approach is the loss of automation inherent in standard welding. At low ambient temperatures, the preheating voltage applied to the coupling terminals must be entered manually, and the operator must manually control the duration of preheating and thermal homogenization. Furthermore, varying insulation thicknesses are required to manage cooling rates at different low temperatures.

This study proposes an additional heating device to preheat the pipe and coupling assembly before the main welding cycle and to reduce the cooling rate of the joint at low ambient temperatures. Before welding, a silicone heating pad is tightly fitted around the outer surface of the coupling. Power is supplied via a controller with specialized software. During the preheating stage, the device heats the outer wall of the coupling. During the cooling stage, it maintains a reference temperature on the coupling's outer surface to slow down cooling. This paper determines the optimal preheating and thermal homogenization parameters for the assembly prior to low-temperature welding, as well as the cooling parameters. It also demonstrates the feasibility of achieving the required cooling rate using this additional heating device.

The heating device parameters are determined through mathematical modeling of the temperature fields during PE pipe welding.Mathematical modeling of the thermal process during welding has been successfully applied in studies [4–6] using the finite element method (FEM). For modeling thermal processes in polymers with phase transformations, the Avrami-Kolmogorov crystallization kinetics equation is widely used, with parameters derived from differential scanning calorimetry (DSC) thermograms [7, 8]. This approach is useful when nucleation and crystal growth must be explicitly modeled, linking the macroscopic thermomechanical behavior to microscopic crystallization kinetics [9–11]. However, if nucleation and growth are not the primary focus, or if the goal is to control the temperature field dynamics during cooling, directly using the heat flow functions recorded by DSC is more effective. Using a relative crystallinity function often assumes the polymer is fully crystalline, which can distort the temperature field dynamics. Therefore, this study models the thermal process of PE pipe welding, accounting for the latent heat of phase transformation, by using a temperature-dependent degree of crystallinity function.

2 Mathematical Model

The thermal process of PE pipe welding is analyzed using a 63 mm diameter pipe and its corresponding electrofusion coupling at various ambient temperatures. Due to symmetry across the plane orthogonal to the pipe axis through the center of the coupling, only half of the joint (coupling and pipe section) is modeled. The computational domain is shown in Fig. 1. Let Ω_1 denote the polyethylene region of the coupling and pipe wall, and Ω_2 denote the region of the embedded heating element. The transient temperature field in the joint during all operational stages was determined by solving the two-dimensional heat conduction equation in cylindrical coordinates:

$$C(T)\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda(T)\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(\lambda(T)\frac{\partial T}{\partial z}\right) + \frac{Q_s(t)}{V_s}\gamma, \quad (r,z) \in \Omega; \quad 0 < t \le t_m; \quad \gamma = 1,\ (r,z) \in \Omega_2; \quad \gamma = 0,\ (r,z) \notin \Omega_2. \tag{1}$$

where T is the temperature; t is the time; t_m is the simulation time; r and z are the cylindrical coordinates; Q_S is the power of the embedded heating element; C and λ are the volumetric heat capacity and thermal conductivity of the materials, corresponding to the pipe and coupling for $(r,z) \in \Omega_1$, and to the embedded heating element for $(r,z) \in \Omega_2$; and V_S is the volume of the heating coil.

Equation (1) is supplemented by the initial and boundary conditions:

$$T(r,z,0) = T_n(r,z), \quad (r,z) \in \Omega \tag{2}$$

$$-\lambda(T)\frac{\partial T}{\partial n} = \alpha_1(T - T_0), \quad (r,z) \in \Gamma_1, \Gamma_2 \tag{3}$$

$$T(r,z,t) = T_0, \quad (r,z) \in \Gamma_3 \tag{4}$$

$$-\lambda(T)\frac{\partial T}{\partial n} = 0, \quad (r,z) \in \Gamma_5 \tag{5}$$

$$-\lambda(T)\frac{\partial T}{\partial n} = \alpha_2(T - T_0), \quad (r,z) \in \Gamma_4 \tag{6}$$

where T_0 is the ambient air temperature; α_1 and α_2 are the heat transfer coefficients from the surface to the ambient air; and n is the normal.

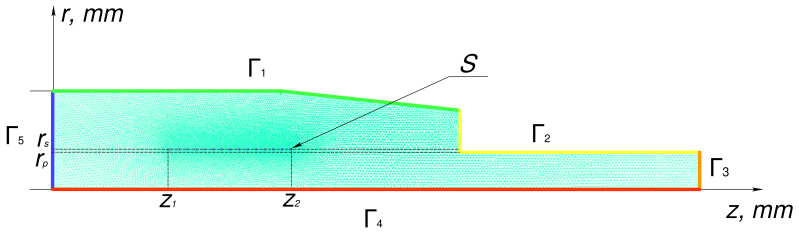


Fig. 1 Schematic of the pipe and coupling: S — embedded heating element

The latent heat of phase transformation is accounted for in the mathematical model by introducing an effective heat capacity into Equation (1) [12]:

$$\tilde{C}(T) = C(T) + \rho L^{100\%} \frac{\mathrm{d}X_c(T)}{\mathrm{d}T}, \quad C(T) = C^+ + X_c(T)\left(C^- - C^+\right). \tag{7}$$

The effective thermal conductivity is defined as:

$$\tilde{\lambda}(T) = \lambda^+ + X_c(T)\left(\lambda^- - \lambda^+\right). \tag{8}$$

Here, $X_c(T)$ is the temperature-dependent degree of crystallinity; $L^{100\%}$ is the specific latent heat of phase transformation of the fully crystalline polymer; $C^+, \lambda^+, C^-, \lambda^-$ are the volumetric heat capacity and thermal conductivity for the liquid and solid phases of the pipe polyethylene, respectively.

The temperature-dependent degree of crystallinity is expressed as:

$$X_c(T) = \begin{cases} X_c^\infty, & T \le T_S, \\ X_c^\infty - \frac{\int_{T_L}^{T} q(u)\mathrm{d}u}{L^{100\%} v_T}, & T_S < T < T_L, \\ 0, & T \ge T_L, \end{cases} \tag{9}$$

where X_c^∞ is the degree of crystallinity of the base pipe polyethylene; v_T is the temperature change rate; $q(T)$ is the heat flow dependence on temperature obtained by differential scanning calorimetry (DSC); T_S and T_L are the solidus and liquidus temperatures, respectively.

The power of the embedded heating element was calculated using the formula:

$$Q(t) = \frac{U^2}{R \cdot (1 + \beta(T(r, z, t) - 20))} \tag{10}$$

where U is the applied voltage; R is the electrical resistance; β is the temperature coefficient of electrical resistance of the heating element material.

Calculation parameters. The problem (1)–(6) was solved using the finite element method [13–15]. The open-source library FEniCS was used for the numerical solution [16, 17]. Triangulation of the computational domain Ω was performed using the Gmsh mesh generator [18]. The obtained results were visualized using the ParaView package [19].

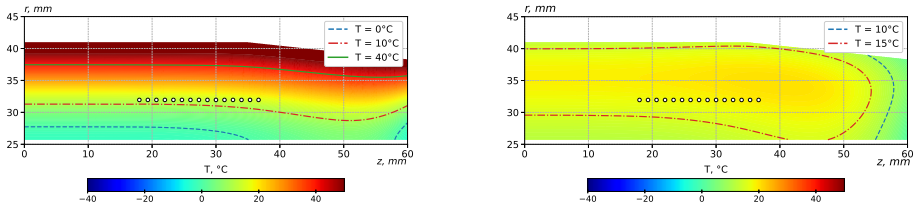
Modeling of the temperature fields during all welding operations was performed for a PE100 SDR 11 63×5.8 pipe at ambient temperatures of 20, –10, and –40 °C. Calculations were performed with the following data: $r_1 = 0.0257$ m is the inner radius of the pipe; $r_p = 0.0315$ m and $r_c = 0.041$ m are the outer radii of the pipe and the coupling, respectively; the heating element is located at radius $r_s = 0.03195$ m; the first turn of the heating coil is at $z_1 = 0.018$ m; the last turn is at $z_2 = 0.0366$ m; the coupling length is $l_m = 0.063$ m; the pipe length is $l_p = 0.1$ m; the electrical resistance of the heating element is $R = 1.87\ \Omega$; the temperature coefficient of electrical resistance of the heating element is $\beta = 0.0043\ ^\circ\mathrm{C}^{-1}$.

Within the confidence intervals, the following values of the thermal conductivity coefficient were found for the solid (superscript $^-$) and liquid (superscript $^+$) phases of the pipe polyethylene: $\lambda^- = 0.46$ W/(m·°C) and $\lambda^+ = 0.24$ W/(m·°C); and for the volumetric heat capacity: $c^- = 1.85 \times 10^6$ J/(m^3·°C) and $c^+ = 1.95 \times 10^6$ J/(m^3·°C).

With the found coefficient values, the model (1)–(6) adequately describes the real thermal process of welding at various ambient temperatures, including low climatic temperatures. The obtained effective thermophysical characteristics were further used for the computational determination of welding parameters under low-temperature conditions.

3 Preheating and Thermal Homogenization

During preheating of the pipe and coupling, it is crucial to ensure uniform heating of the heat-affected zones and the weld joint. For clarity, welding performed at an ambient temperature of 20 °C is referred to as standard welding. The heat-affected zone (HAZ) is bounded by the 120 °C isotherm, within which structural changes occur. Calculations show that for a 63 mm diameter pipe, the HAZ width during standard welding is 19 mm. We assume that achieving permissible pre-welding temperatures in these zones through preheating and thermal homogenization will allow the subsequent heating to follow the standard welding protocol and yield the required melt volume for a strong joint.



a b

Fig. 2 Temperature fields in the vertical cross-section of the pipe and coupling walls at the end of the preheating stage (a) and thermal homogenization (b) at an ambient temperature of −40 °C

When determining the preheating parameters, the following properties of polyethylene are taken into account. It is generally accepted that structural changes in polyethylene begin when heated above 80 °C, which is its softening temperature [20]. Therefore, during preheating, the additional heating device is maintained at 60 °C, which is below the softening temperature of polyethylene. In the mathematical model, during the preheating stage, the boundary condition on the outer surface Γ_1 is changed to a first-kind boundary condition (Dirichlet condition). Calculations show that at an ambient temperature of −40 °C, preheating the outer surface of the coupling for 4 minutes raises the temperature to the permissible welding range (Fig. 2a). To achieve a uniform temperature distribution within the HAZ, it is recommended to allow the pipe and coupling assembly to undergo free cooling for 2 minutes. During this stage, the boundary condition on Γ_1 is changed to a third-kind boundary condition (Robin

condition). The calculation results show that after free cooling, the temperature field in the embedded heating element zone becomes more uniform (Fig. 2b). For clarity, Figs. 2a and 2b also show the 120 °C isotherm reached at the end of the heating stage during standard welding.

4 Heating and Cooling

After thermal homogenization, the heating operation is performed as it would be at permissible ambient temperatures. Power is supplied to the embedded heating element according to the standard welding protocol. During the cooling stage of standard welding, the temperature change at a point near the outer surface of the coupling with coordinates $(0.025, 0.04)$ is recorded throughout the entire cooling stage as a function of time:

$$F(r, z, t) = T_1^{20}(r, z, t), \quad (r, z) \in \Omega, \quad t_w \leq t \leq t_m, \tag{11}$$

where t_w is the duration of the main heating stage.

At ambient temperatures below -10 °C, the additional heating device maintains the temperature on the outer surface of the coupling within the permissible range during the cooling stage. In the mathematical model, during cooling at low temperatures, the boundary condition on the outer boundary Γ_1 is changed to a first-kind boundary condition (Dirichlet condition) that depends on the time-dependent temperature function $F(t)$.

Maintaining a permissible temperature on the outer surface of the coupling is intended to reduce the cooling rate in the structural change region. Figure 3 shows the calculated boundaries of the structural change regions and the heat-affected zones (HAZ) in the weld joints obtained at different permissible ambient temperatures. Inside the structural change regions, the 100 °C isotherms are shown, along which crystallization completes at various times counted from the beginning of cooling, with a step of 1 minute. The total cooling time for this pipe and coupling size is 10 minutes. Calculations showed that the permissible range for the completion of crystallization is from 4 to 10 minutes. Under reference welding conditions, crystallization completes at 2 minutes and 37 seconds of cooling (Fig. 3a). At the minimum permissible ambient temperature, it completes at 1 minute and 16 seconds, with the HAZ width reaching 17 mm (Fig. 3b).

Calculations show that welding at -40 °C without following the standard protocol results in a reduced melt volume at the end of the heating stage. In this case, the HAZ width is 16.5 mm, and crystallization completes at 119 seconds of cooling (Fig. 3c). Using the additional heating device to maintain a reference temperature on the outer surface of the coupling reduces the crystallization rate (Fig. 3d). The calculations demonstrate that the melt volume is identical to that achieved during standard welding, and crystallization completes at 9 minutes and 23 seconds.

5 Conclusions

Preheating the pipe and coupling assembly with an additional heating device enables subsequent heating to follow the standard welding protocol under low-temperature

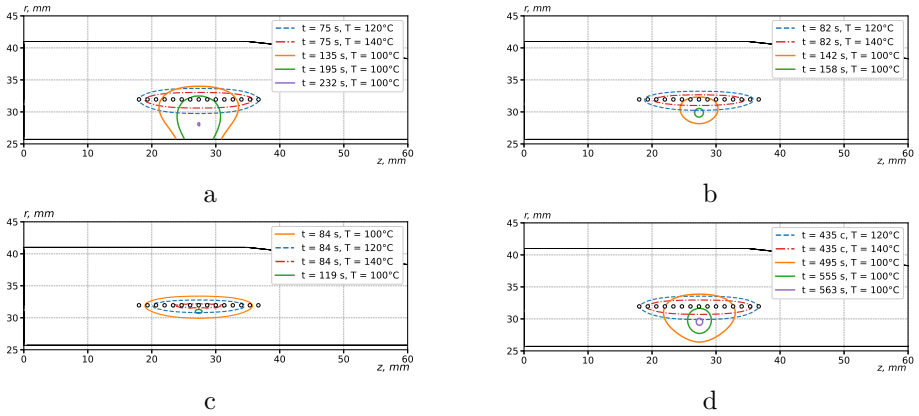


Fig. 3 100 °C isotherms in the vertical cross-section of the structural change regions of the coupling and pipe at various ambient temperatures from the 1st to the 3rd minute of cooling: (a) +20 °C; (b) −10 °C; (c) −40 °C; (d) −40 °C (using the proposed technology). The blue line indicates the 120 °C isotherm, and the red line indicates the 140 °C isotherm at the end of the heating stage.

conditions. Calculations of the transient temperature field during cooling show that using the additional heating device to maintain a reference temperature profile (equivalent to welding at a permissible ambient temperature) on the outer coupling surface ensures that the crystallization front propagates at −40 to −10 °C in the same manner as it does under permissible ambient temperatures. The proposed mathematical model of the thermal process can be used to calculate preheating, thermal homogenization, and cooling parameters for various sizes of polyethylene pipes.

6 Declarations

Funding This work was supported by the Russian Science Foundation (grant No. 26-29-20196, https://rscf.ru/en/project/26-29-20196/).

Competing interests The authors declare no competing interests.

References

[1] International Organization for Standardization: Plastics pipes and fittings — equipment for fusion jointing polyethylene systems — part 2: Electrofusion. Technical Report 12176-2:2008, ISO (2008)

[2] Starostin, N.P., Ammosova, O.A.: Rapid welding technology for polyethylene gas pipes at temperatures below standard. IOP Conference Series: Materials Science and Engineering **681**(1), 012041 (2019) https://doi.org/10.1088/1757-899X/681/1/012041

[3] Starostin, N.P., Ammosova, O.A.: Calculation of the technological parameters of electrofusion welding of polyethylene pipes at low temperatures. In: Proceedings of the 11th International Conference on Mechanics, Resource and Diagnostics

of Materials and Structures (MRDMS-2017). AIP Conference Proceedings, vol. 1915, p. 040057 (2017). https://doi.org/10.1063/1.5017405

[4] Zhang, W., Yang, Q., Wang, B., Yu, W., Tong, J.: Research on controlling method of welding temperature of pe electrofusion pipe fittings based on simulation of temperature field. In: Li, K., Coombs, T., He, J., Tian, Y., Niu, Q., Yang, Z. (eds.) Recent Advances in Sustainable Energy and Intelligent Systems. LSMS ICSEE 2021. Communications in Computer and Information Science, vol. 1468, p. 38. Springer, Singapore (2021). https://doi.org/10.1007/978-981-16-7210-1_38

[5] Yu, W., Yang, Q., Zhang, W., Chen, Y., Sun, J.: Simulation of electrofusion parameters of pe saddle pipe based on finite element analysis of temperature field. In: Li, K., Coombs, T., He, J., Tian, Y., Niu, Q., Yang, Z. (eds.) Recent Advances in Sustainable Energy and Intelligent Systems. LSMS ICSEE 2021. Communications in Computer and Information Science, vol. 1468, p. 37. Springer, Singapore (2021). https://doi.org/10.1007/978-981-16-7210-1_37

[6] Shen, T., Chen, Y., Liu, W., *et al.*: Morphological analysis and intelligent optimization of the fusion zone in electrofusion welding of pe pipes. The International Journal of Advanced Manufacturing Technology **145**, 2643–2660 (2026) https://doi.org/10.1007/s00170-026-18485-9

[7] Kulikova, T.G., Trufanov, N.A.: Numerical solution of the boundary value problem of thermomechanics for a crystallizing viscoelastic polymer. Computational Continuum Mechanics **1**(2), 38–52 (2008). [in Russian]

[8] Chebbo, Z., Vincent, M., Boujlal, A., *et al.*: Numerical and experimental study of the electrofusion welding process of polyethylene pipes. Polymer Engineering & Science **55**(1), 123–131 (2015)

[9] Spina, R., Spekowius, M., Hopmann, C.: Simulation of crystallization of isotactic polypropylene with different shear regimes. Thermochimica Acta **659**, 44–54 (2018)

[10] Spina, R., Spekowius, M., Hopmann, C.: Multiphysics simulation of thermoplastic polymer crystallization. Materials & Design **95**, 455–469 (2016)

[11] Rong, Y., He, H., Cao, W., Shen, C., Chen, J.: Multi-scale molding and numerical simulation of the flow-induced crystallization of polymer. Computational Materials Science **67**, 35–39 (2013)

[12] Samarskii, A.A., Vabishchevich, P.N.: Computational Heat Transfer. Editorial URSS, Moscow (2003). [in Russian]

[13] Hughes, T.J.R.: The Finite Element Method: Linear Static and Dynamic Finite Element Analysis. Dover Publications, New York (2012)

[14] Zienkiewicz, O.C., Taylor, R.L., Zhu, J.Z.: The Finite Element Method: Its Basis and Fundamentals. Butterworth-Heinemann, Burlington (2005)

[15] Zienkiewicz, O.C., Taylor, R.L.: The Finite Element Method: Solid Mechanics. Butterworth-Heinemann, Burlington (2000)

[16] Logg, A., Mardal, K.-A., Wells, G.N.: Automated Solution of Differential Equations by the Finite Element Method: The FEniCS Book, p. 723. Springer, Heidelberg (2012)

[17] The FEniCS Project: FEniCS Project. http://fenicsproject.org/ (2024)

[18] Gmsh Developers: Gmsh: A 3D finite element mesh generator. http://geuz.org/gmsh/ (2024)

[19] Kitware, Inc.: ParaView: An Open-Source, Multi-Platform Data Analysis and Visualization Application. http://www.paraview.org/ (2024)

[20] Mokarizadeh, M.: Evolution of the crystalline and amorphous phases of high-density polyethylene subjected to equal-channel angular pressing. Polymer Bulletin **77**, 2115–2131 (2020)