

Heating Duration of Polyethylene Pipes for Unwinding from Bays during Construction and Installation Works at Low Temperatures

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Abstract. The present paper proposes a technique for determining duration of heating coiled polyethylene pipes with hot air for laying and installation operations in construction of gas pipelines in conditions of low temperatures. A mathematical model of the thermal process of heating polyethylene pipes with hot air is considered. Herewith, it is assumed that a turbulent flow of heated air courses inside the pipe along its entire length. A laminar sublayer is formed in the pipe wall through which heat is transferred by means of molecular thermal conductivity. The rest of the pipe section is filled with turbulent flowing air (turbulent core). Heat is transferred in a turbulent flow not only by thermal conductivity, but also by turbulent pulsations. The coefficient of turbulent thermal conductivity is determined on the basis of the temperature data of the full-scale experiment at a certain ambient air temperature. The thickness of the laminar sublayer, which is the thermal resistance, is regulated by the known formula. The results of a calculation study of duration of the heating of polyethylene pipe in the temperature range of the ambient air at a known air flow rate fed into the pipe are presented. The effectiveness of the proposed method for determining the duration of heating polyethylene pipes in coils is confirmed experimentally.

1. Introduction

Most papers devoted to the problem of heat transfer in round pipes do not consider the problem as a nonstationary conjugate problem. For example, the heat exchange coefficient is determined in works [1-2] with a linear change in temperature along the pipe wall taken into account. The study [3] presents a solution to the conjugate problem in a round pipe at a one-dimensional description of the processes in the heat-transfer agent and formulas for determining the heat transfer coefficient inside the pipe, which depends on the axial coordinate. An engineering method for calculating the heating and cooling processes of the pipeline has been developed under the assumption that there is no heat exchange outside the pipeline and at the known heat transfer coefficient. The calculation procedure is reduced to the use of the corresponding nomograms.

The most complete formulations of nonstationary conjugate heat transfer problems for laminar and turbulent fluid and gas flows in pipes of infinite length and solutions using the Fourier transform are obtained in [4]. Despite the great versatility of methods for solving the problems of non-stationary heat transfer in pipes, they are not always convenient and rational for solving some practical problems.



According to the regulatory documents, unwinding of long-length polyethylene pipes from coils for the gas pipelines is performed at an ambient temperature of +10 °C and above. At a lower air temperature, the pipes in the coils are heated to the required temperature by placing them for a period of at least 4 hours in a heated construction or are heated with a blower until the temperature of the outer and inner surfaces of the coil are not lower than (15 ± 5) °C [5].

The given paper focuses on a hot air heating of a long-length polyethylene pipe in a coil that has an outside air temperature and covered with an airtight material (polyethylene film). The air temperature inside the construction is maintained higher than the outside temperature and the heated air is fed inside the pipe. The temperature of the hot supplied air and the air under the cover do not exceed 60 °C. Naturally, duration of the heating of a pipe will vary greatly depending on the length of the pipe, the wall thickness, the ambient temperature, the flow rate of the supplied air, its temperature, etc. In practice, the number of nominal sizes of heated pipes is often very limited, the flow rates of the supplied air are constant. In connection with this, the paper considers the problem of calculation and experimental determination of duration of heating pipe of a given diameter by a stream of heated air at a given rate.

2. Modeling of thermal process

When studying the heating of a long-length polyethylene pipe, we estimate the length of the starting hydrodynamic section as insignificant. Thus, a hydrodynamically and thermally stabilized turbulent flow occurs along the entire length of the pipe. We also assume that the heat-transfer agent is incompressible, its physical parameters are constant, friction heat and energy dissipation can be neglected. Typically, the heat transfer coefficient in bent pipes is obtained by introducing correction factor to the heat transfer coefficient for the straight pipe. Therefore, the pipe is considered straight to simplify the conjugate heat exchange problem. Parameters obtained in the experiment for heating the coiled pipe are used in mathematical model. It is known that a laminar layer is formed near the pipe wall during turbulent motion, and the heat is transferred through this layer by molecular thermal conductivity [2, 4, 6]. The rest of the pipe section is filled with turbulent flowing air (turbulent core). The heat is transferred in a turbulent flow not only by thermal conductivity, but also by turbulent pulsations. Since the thermal conductivity of air is much less than the thermal conductivity of polyethylene, molecular heat transfer along the axial variable is considered negligibly small within the pipe. Under these assumptions, the system of equations for non-stationary heat transfer in the case of a turbulent flow of heated air in a round pipe is as follows:

$$C_1(U) \left(\frac{\partial U}{\partial t} + v(r) \frac{\partial U}{\partial z} \right) = \frac{1}{r} \frac{\partial}{\partial r} \left(r(\lambda_1(U) + \lambda_T(U)) \frac{\partial U}{\partial r} \right), \quad (1)$$

$$0 < r < R_1 - \delta, \quad 0 < z < L, \quad 0 < t \leq t_m,$$

$$C_1(U) \left(\frac{\partial U}{\partial t} + v(r) \frac{\partial U}{\partial z} \right) = \frac{1}{r} \frac{\partial}{\partial r} \left(r\lambda_1(U) \frac{\partial U}{\partial r} \right), \quad (2)$$

$$R_1 - \delta < r < R_1, \quad 0 < z < L, \quad 0 < t \leq t_m,$$

$$C_2(T) \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(r\lambda_2(T) \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left(\lambda_2(T) \frac{\partial T}{\partial z} \right), \quad (3)$$

$$R_1 < r < R_2, \quad 0 < z < L, \quad 0 < t \leq t_m,$$

$$T(r, z, 0) = U(r, z, 0) = T_0, \quad (4)$$

where U , T are the air temperatures inside the pipe and in the wall; t_m is estimated time; r , z are radial and axial coordinates; R_1 , R_2 stand for internal and external radii of the pipe; L is the length of the pipe; C_1 , C_2 is specific volumetric heat capacity of air and material of the pipe wall; λ_1 , λ_2 is

coefficient of thermal conductivity of air and material of the pipe wall; λ_T is the turbulent thermal conductivity of air; $v(r)$ is velocity distribution along the cross-section of the pipe; T_0 is the ambient air temperature; δ is the thickness of the laminar sublayer.

The temperature of the supplied heated air T_N is set on the left end inside the pipe; the condition of convective heat exchange with air inside the construction with temperature T_C is arranged on the outer surface of the pipe. The usual conditions for an ideal thermal contact between different layers and the condition for the boundedness of solution on the tube axis are also established.

The initial boundary value problem (1) - (4) is solved by the method of finite differences using splitting with respect to spatial variables and physical processes [7-8]. So equation (1) splits into two equations in physical processes:

$$C_1(U) \frac{\partial U}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(r(\lambda_1(U) + \lambda_T(U)) \frac{\partial U}{\partial r} \right), \quad (5)$$

$$\frac{\partial U}{\partial t} + v(r) \frac{\partial U}{\partial z} = 0. \quad (6)$$

Homogeneous difference scheme is used when solving the heat equation with respect to the radial variable (5). The one-dimensional transport equation (6) is solved using an explicit scheme on the three-point template [9]. Similar transport equations can be solved by other methods, including the Cabaret method [10-14].

The two-dimensional equation (3) for the pipe wall splits in space variables [8, 15-16]. Thus, the following equations are solved for transition to the next time layer: the transport equation inside the pipe, the equation of thermal conductivity along the radial variable for all nodes of the axial coordinate, the equation of thermal conductivity along the axial coordinate in the pipe wall for all $R_1 \leq r \leq R_2$.

3. Calculation results

Tests for heating long-length polyethylene pipe in the coil with hot air were accomplished to determine the unknown parameter of the mathematical model. The diameter of the pipe was 90 mm, the length was 100 m. The heating of the coiled pipe was performed in covered structure with a temperature of $T_C = 15$ °C. The temperature of the supplied heated air T_N was 54 °C. The tests were accomplished at an outdoor temperature of $T_0 = -25$ °C.

Cold air was heated by an electric heater with a capacity of 1.2 kW to a temperature of 60 °C in a special construction and fed into the pipe. Pump at the other end of the pipe was used to increase the flow speed of the supplied heated air. The average velocity of air flow on the axis of the pipe was $v_0 = 16$ m/s.

The thickness of the laminar layer, which is the thermal resistance, was determined by the formula [17]:

$$\delta = \frac{65 \cdot R_1}{\text{Re} \cdot (0,0032 + 0,221 \cdot \text{Re}^{-0,237})} \quad (7)$$

where Re is the Reynolds number, R_1 is the inner radius of the pipe.

The coefficient of turbulent thermal conductivity λ_T was determined from the condition of minimum deviation of the calculated values of the temperatures T from experimental T^{exp} , as in [18].

The problem of determining the nonstationary temperature field in turbulent airflow in a circular pipe was solved with the following initial data: the internal radius of the pipe $R_1 = 0.0368$ m; outer radius of pipe $R_2 = 0.045$ m; coefficient of thermal conductivity of air $\lambda_1 = 0.029$ and of polyethylene $\lambda_2 = 0.38$ W/(m · °C); specific volumetric heat capacity of air $C_1 = 1065$ and of polyethylene – $C_2 = 1.8 \cdot 10^6$ J/(m³ · °C); coefficient of heat exchange on the outer surface of the pipe $\alpha = 15$ W / (m² · °C).

The time step $\tau = 0.015625$ seconds was selected from the condition that the Courant number is equal to one, $\gamma = \frac{v_0 \cdot \tau}{h} = 1$. In a time equal to one step, a particle of air is transported at a speed v_0 exactly one step along the axial coordinate. With this choice of time step, there is no instability of the calculation scheme used.

The velocity distribution has a three-dimensional character and it is asymmetric in the bent pipe. This is due to the influence of the centrifugal force, which acts along the normal to the direction of the main flow and causes displacements of the velocity maximum from the center [6, 19]. A general formula for determining the velocity distribution over the pipe cross section, taking into account this phenomenon, has not been obtained. The distribution of velocities along the pipe cross-section was determined from the well-known formula [20]:

$$v(r) = v_0 \left(1 - \frac{r}{R_1} \right)^{\frac{1}{6.7}}. \quad (8)$$

The thickness of the laminar sublayer equal to $\delta = 0.002$ m is found for the given initial data. At $\lambda_T = 4 \text{ W / (m}^\circ\text{C)}$, the calculated temperature dependences satisfactorily describe the experimental ones. Figure 1 demonstrates the results of comparing the calculated and experimental temperature dependences on time on the outer surface of the pipe at a different distance from the heated air inlet of the pipe. Calculations reveal that the heating time, defined by the time necessary to reach a temperature of 15°C in the wall at the end of the pipe, is 51 minutes.

Calculations with assumptions taken into account show that the temperature field is practically uniform in the turbulent core. At the beginning of the process of heating with hot air, the wall temperature on the outer surface of the pipe is higher than on the inner wall of the pipe. This effect is exerted by the temperature maintained inside the construction. After a certain time, the temperature is equalized over the thickness of the pipe. The temperature decreases with increasing radius in the layer of molecular thermal conductivity (Figure 2).

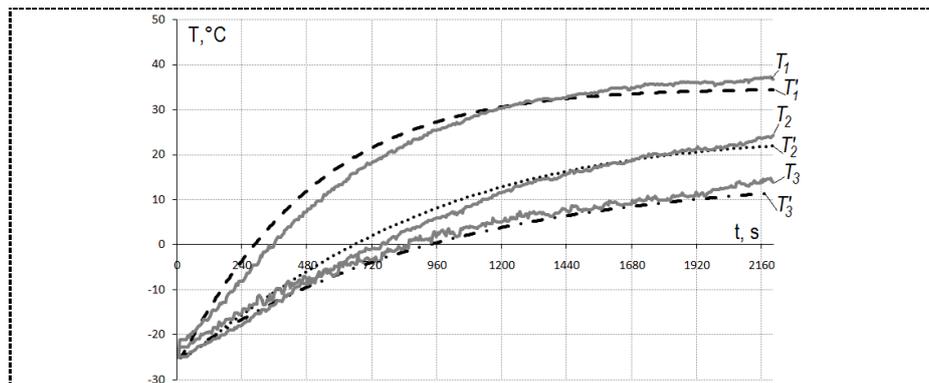


Figure 1. Comparison of calculated T'_1 , T'_2 , T'_3 and experimental T_1 , T_2 , T_3 temperature dependences in the middle of the pipe at different distances from the outlet: T_1 , T'_1 – temperature measurements at 8 m; T_2 , T'_2 – temperature measurements at 30 m; T_3 , T'_3 – at the point of 100 m.

Figure 3 shows the change in temperature in the turbulent core along the length of the tube at different times. The graphs demonstrate that the temperature of the supplied heated air decreases significantly along the length of the pipe. At the beginning of the heating process (2 s), the flow does not reach the end of the pipe - the air temperature in the pipe is equal to the temperature of the outside air. The temperature of the supplied air at the outlet from the pipe rises rather slowly, reaching 15°C in 40 minutes.

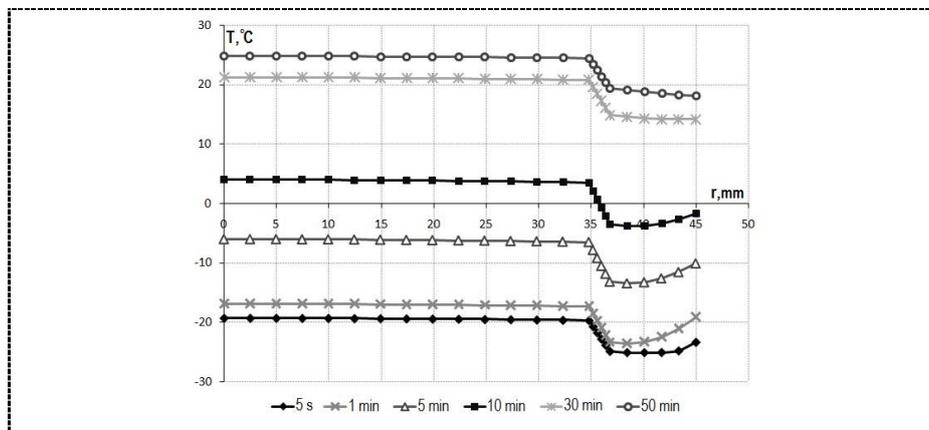


Figure 2. Temperature distribution over the radius at $z = 50$ m at different times

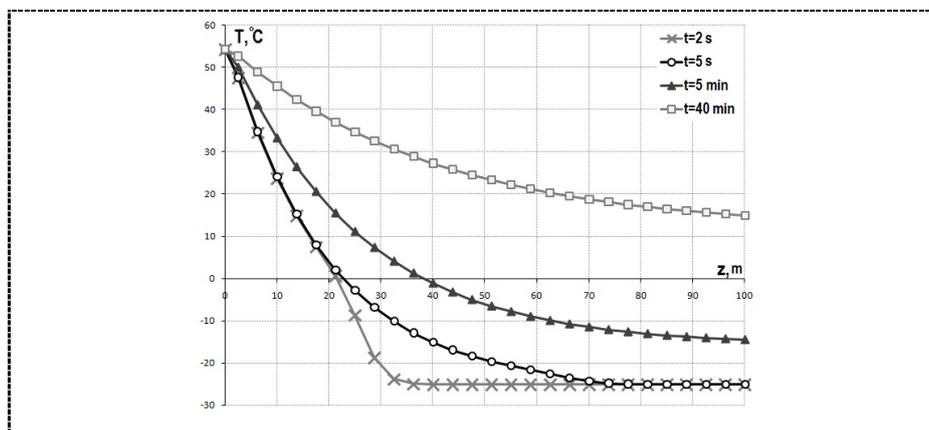


Figure 3. Change in air temperature in the pipe along the length of the pipe at different times

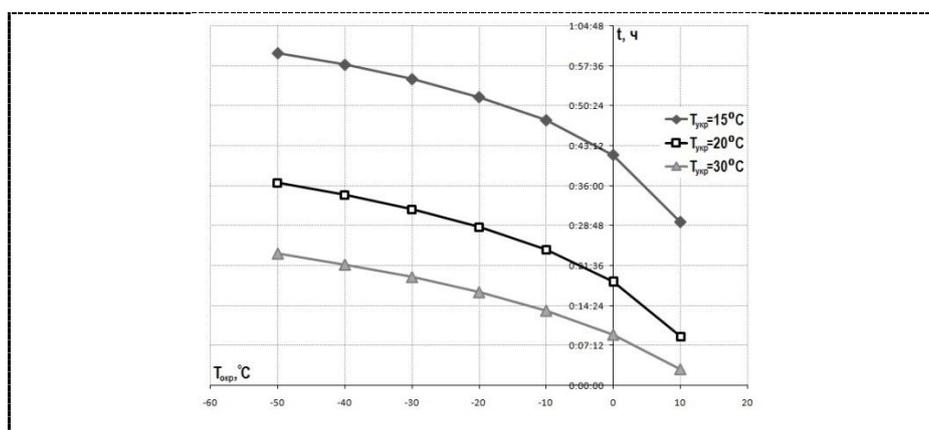


Figure 4. Duration of heating the coiled pipe with hot air at a flow velocity $v_0 = 16$ m / s and $T_N = 60$ °C at various ambient temperatures T_0 (horizontal axis) and in heated constructions T_C (rows with markers)

Heating duration at which the desired temperature of 15 °C is provided on the considered pipe wall at various ambient air temperatures and in constructions is shown in Figure 4. The calculation results reveal that the temperature maintained in heated constructions significantly affects the duration of heating.

4. Conclusion

Assuming that the structure of the turbulent flow does not change strongly with change in the temperature of pipe wall, the mathematical model with the calculated parameters (the thickness of the laminar layer and the coefficient of turbulent thermal conductivity) can be used to predict the duration of heating coiled pipe at various temperatures of the ambient air. It is necessary to determine the parameters of the model by calculation and experiment when the flow velocity is changed. The proposed approach for the approximate calculation of the temperature change in the pipe wall at forced air flow in a circular pipe can be used to calculate the duration of heating polyethylene pipes of various sizes when determining the parameters of a mathematical model by comparing the calculated and experimental temperature data.

5. References

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