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INVESTIGATION OF THE COOLING OF TWO-LAYER CORRUGATED POLYMERIC PIPES

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Physical and mathematical models of the one-side and two-side cooling of two-layer corrugated polymeric pipes in the process of their production by coextrusion are considered. The models proposed allow one to determine the rational regimes of work of the coolers used in a line for production of such pipes, providing a required output of this line. Results of a mathematical simulation of the one-side and two-side cooling of the indicated pipes are presented. The results of calculations were compared with the corresponding experimental data.

Keywords: *polymer, two-layer corrugated pipes, two-side cooling, mathematical simulation, experiment.*

Introduction. Two-layer corrugated polymeric pipes (TLCPP), due to their high strength and annular rigidity and low specific consumption of materials, have found wide application in different industries, first of all, in cable service lines and head-free liquid systems. In such a pipe, the outer corrugated layer provides a required value of its annular rigidity and the smooth inner layer is responsible for the hydrodynamics of the liquid in the pipe [1].

In the production of a TLCPP, a limiting stage is the cooling of a round billet, because the inner layer of the pipe is cooled mainly due to the heat conduction on its outer sider. In this case, the length of a production line can reach several tens of meters; however, the line output remains insufficiently high [2, 3].

A promising method of intensification of the cooling of a TLCPP in the process of its production is the removal of heat from its inner surface. Combined cooling of the outer and inner surfaces of a TLCPP will make it possible to substantially decrease the length of the cooling zone of a production line and increase its output [2] as well as to stabilize the shape of the pipe and increase the quality of its inner surface [4].

The auxiliary equipment of lines for production of corrugated pipes (corrugators, cooling vats) are most frequently designed on the basis of experience on the use of these equipment. This approach to the determination of rational regimes of work of the indicated equipment leads to large expenditures of energy and material resources, especially when passing to the production of pipes of different standard sizes or with the use of different materials.

Thus, there is a need to develop physical and mathematical models of cooling of a TLCPP in the process of its production for the purpose of analyzing this process and designing the auxiliary equipment of lines for production of such pipes, for obtaining of pipes with rotational parameters, as well as for the elimination of unjustified expenses of energy, material, and human resources.

The aim of the present work is to develop physical and mathematical models of cooling of extruded TLCPPs, taking into account the possibility of cooling of their inner and outer surface, and to investigate the two-side cooling of such pipes.

Mathematical Simulation of the Cooling of a TLCPP. The formation of a TLCPP and the preliminary cooling of a round billet to temperature at which the properties of the polymer provide the retention of the shape of the pipe in the process of its further processing are carried out in corrugators (Fig. 1). This pipe is finally cooled in a cooling vat by a water flow around the outer surface of the pipe.

In the general case, the cooling of a TLCPP is defined by the energy equation

$$\rho_i(T)\, c_i(T)\, \frac{dT}{d\tau} = -\nabla q + q_V \,. \tag{1}$$

Since the shrinkage of the material of a pipe in the process of its cooling is insignificant, the term q_V defining the dissipation in Eq. (1) can be disregarded.

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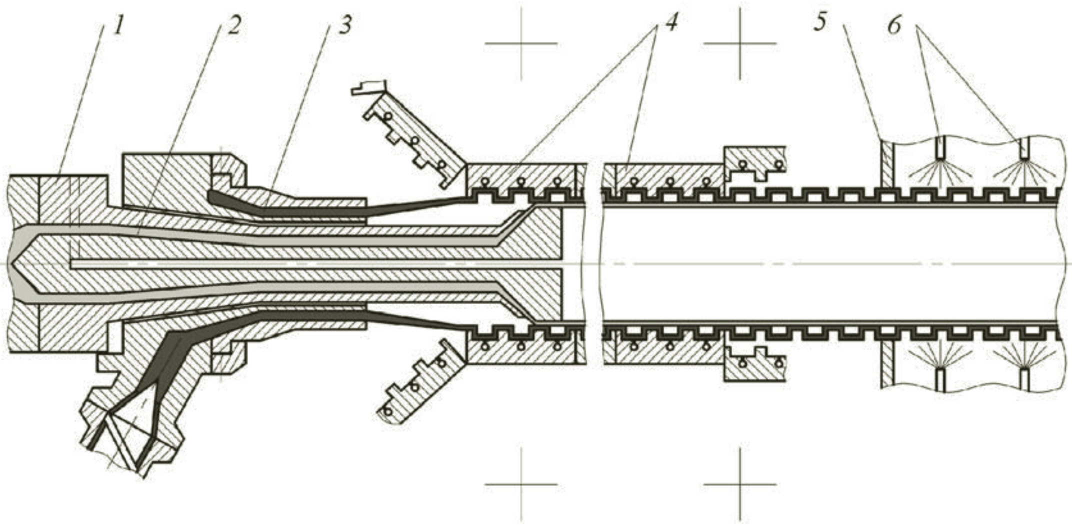

Fig. 1. Scheme of production of a TLCPP: 1) direct-flow extrusion head; 2) angular extrusion head; 3) round billet of the outer layer of the pipe; 4) half-moulds of a corrugator; 5) cooling vat; 6) injectors.

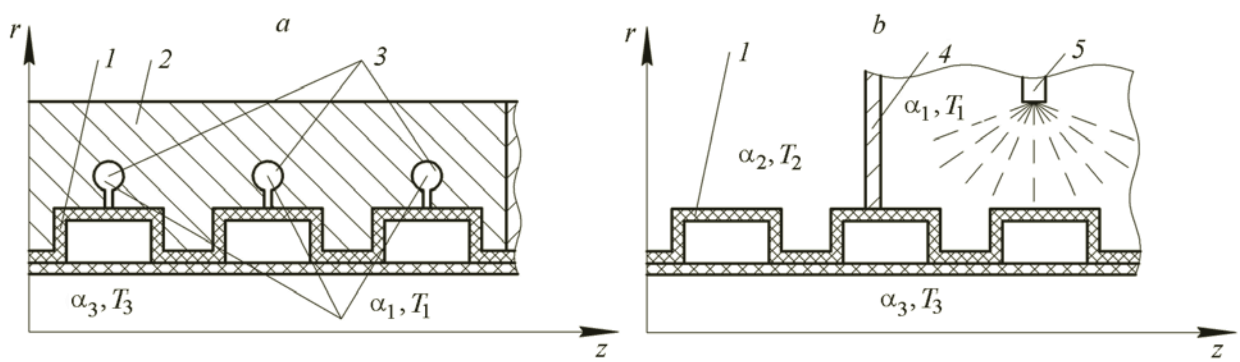

Fig. 2. Scheme of cooling of a TLCPP in a corrugator (a) and in a cooling vat (b): 1) pipe; 2) half-mould of the corrugator; 3) channels for cooling water; 4) cooling vat; 5) injector.

It makes sense to perform numerical simulation of the cooling of a TLCPP in an immovable cylindrical coordinate system (Fig. 2). In this case, only the rate of cooling of the pipe along the z axis w_z can be assumed to be nonzero. This rate is determined by the geometric parameters of the cross section of the pipe and the capacity of the extrusion equipment. The cooling process being considered was analyzed on the following assumptions:

1) the process of cooling of a TLCPP is axially symmetric, i.e., the temperature at the diametric cross section of the pipe is independent of the angular coordinate;

2) the fourth-order boundary conditions are realized at a contact of two neighboring layers of the pipe;

3) the heat transfer in each layer of the pipe material and in the air contained in the corrugations of the pipe is due to the heat conduction;

4) the thermophysical properties of the material of the pipe and the air contained in the corrugations are determined by the temperatures of the pipe and the corrugators.

Equation (1) written in the cylindrical coordinates with account for the above-indicated assumptions has the following form:

$$w_z \rho_i \left(T\right) c_i \left(T\right) \frac{\partial T}{\partial z} = \lambda_i \left(T\right) \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right). \qquad (2)$$

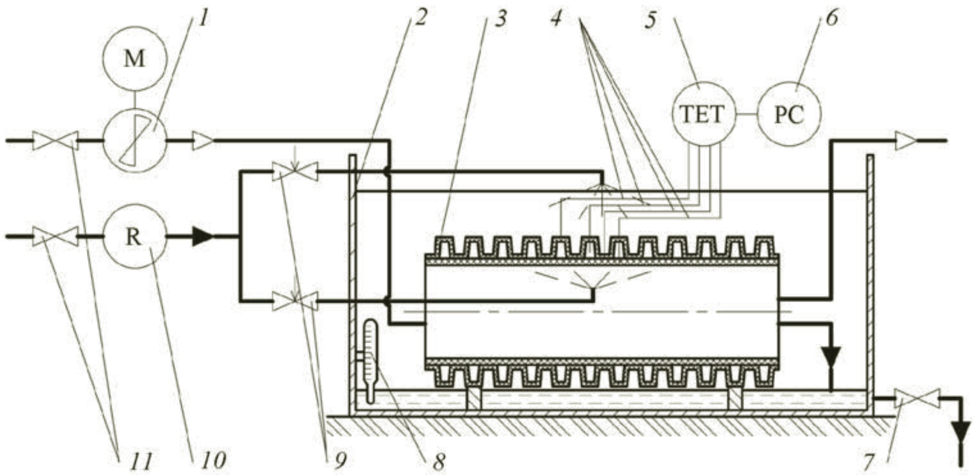

Fig. 3. Scheme of the experimental setup: 1) fan; 2) cooling vat; 3) pipe; 4) thermocouples; 5) thermoelectric temperature transducer; 6) computer; 7, 11) cocks; 8) thermometer; 9) valves; 10) rotameter.

Since the thermophysical properties of a polymer change substantially in the process of its cooling, Eq. (2) is conveniently written in the enthalpy form:

$$\frac{\partial H}{\partial \tau} = \frac{1}{r}\frac{\partial}{\partial r}\left[r\lambda_i\left(T\right)\frac{\partial T}{\partial r}\right] + \frac{\partial}{\partial z}\left[\lambda_i\left(T\right)\frac{\partial T}{\partial z}\right], \quad i = \overline{1, n}\,. \tag{3}$$

The initial condition of the process of cooling of a TLCPP is determined by the initial temperature distribution in it. Since modern extrusion equipment provide a satisfactory temperature homogeneity of a melt, it may be assumed that, at the initial instant of time, the temperature distribution over the thickness of a round billet at the output of a die head is homogeneous:

$$T\left(r, z\right)\Big|_{\tau=0} = T_0\,. \tag{4}$$

It is assumed that the fourth-order boundary conditions are fulfilled at the contact boundary between the layers in the wall of the pipe as well as between its outer surface and the corrugators:

$$\{T\} = 0\,, \quad \{\mathbf{n}\cdot\mathbf{q}\} = 0\,, \tag{5}$$

and the third-order condition is fulfilled at the contact between the pipe and the cooling medium:

$$\mathbf{n}\left(-\lambda_i\left(T\right)\nabla T\right) = \alpha_k\left(T\right)\left(T - T_k\right), \quad i = \overline{1, n}, \quad k = \overline{1, m}\,. \tag{6}$$

Equation (3) with the initial condition (4) and the boundary conditions (5) and (6) represents a mathematical model of cooling of a TLCPP that is conveniently solved by the finite-element method [5]. This allows one to develop a computational program for determining the temperature fields in the wall of a TLCPP and in the spaces of its corrugations at all the stages of the cooling of the pipe (i.e., to take into account the complex geometry of the system) as well as to determine the rational regimes of work of the cooling equipment.

Experimental Investigations. In the case of a two-side cooling of a TLCPP, heat is removed from the outer surface of the pipe by water, and heat is removed from its inner surface by air, water, or an air-water mixture (WAM). In this case, it makes sense to cool the inner surface of a TLCPP by water only in the case where it has a small diameter because, with increase in the pipe diameter, not only does the flow rate of the cooling water substantially increase, but also there arise purely design difficulties of realization of such cooling.

An experimental setup for investigating the efficiency of different methods of cooling of a TLCPP and verification of the adequacy of models of this cooling has been developed at the Faculty of Machines and Apparatuses for Chemical and

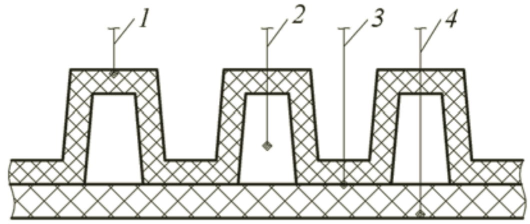

Fig. 4. Scheme of disposition of thermocouples (1–4) in the wall of a pipe.

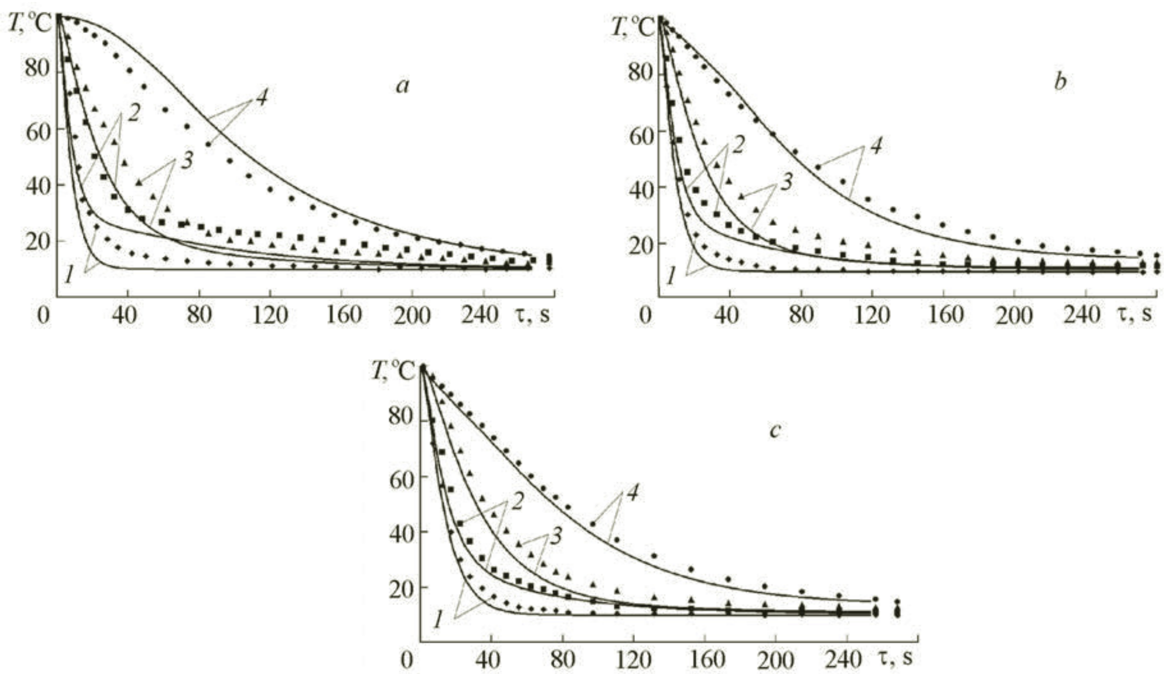

Fig. 5. Temperature fields in the wall of a pipe in the case of external water cooling (a) and two-side cooling: external cooling by water and internal cooling by air (b) and external cooling by water and internal cooling by a water-air mixture (c): 1–4, numbers of thermocouples as in Fig. 4; points, experimental data; lines, calculation.

Petroleum-Refining Productions of the National Technical University of Ukraine "Kiev Polytechnic Institute." A diagram of this setup is presented in Fig. 3. The investigations were carried out with a polyethylene pipe of the B-P-U/SN8/DN/ID200/176/6000/DSTU B V.2-32:2007 type. Immediately before the cooling of the pipe, it was heated in a heat chamber (which is not shown in the figure). To prevent a loss in the shape of the pipe and in its sizes, the maximum temperature of heating was maintained at a level not higher than 100^{o}C. After the pipe was homogeneously heated to the required temperature, it was connected to a cooling system.

The temperature in the wall of the pipe was measured by thermocouples 4 (the diagram of disposition of the thermocouples in the wall of the pipe is presented in Fig. 4) and was recorded by the thermoelectric temperature transducers 5 connected to a personal computer 6 (see Fig. 3). The degree of digitization of the temperature measurements was 1 s. The temperature changes were analyzed using a program written in the graphical programming LabVIEW 8.5 medium. The difference between the measured and calculated values of the temperature of the pipe wall did not exceed 25% and the deviation of the measured time of cooling from the calculated one comprised 10% (Fig. 5), which points to the fact that the mathematical model developed adequately defines the cooling process being considered.

In the case where the outer surface of a TLCPP was cooled by water from 100 to 15^{o}C and its inner surface was cooled by air, the cooling time was decreased by approximately 12%, and, in the case where the inner surface of the pipe was

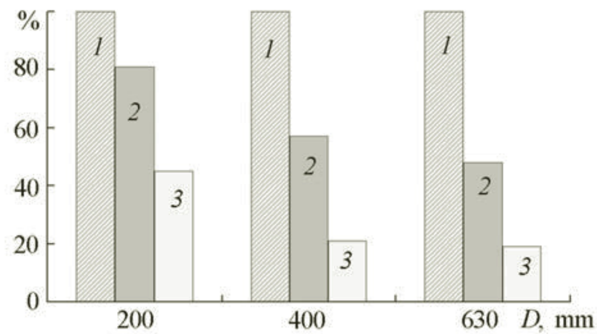

Fig. 6. Results of numerical simulation of the efficiency of cooling of pipes different in diameter for a definite period of time depending on the cooling method: 1) one-side external cooling by water; 2) two-side cooling: external cooling by water and internal cooling by air; 3) two-side cooling: external cooling by water and internal cooling by a water-air mixture.

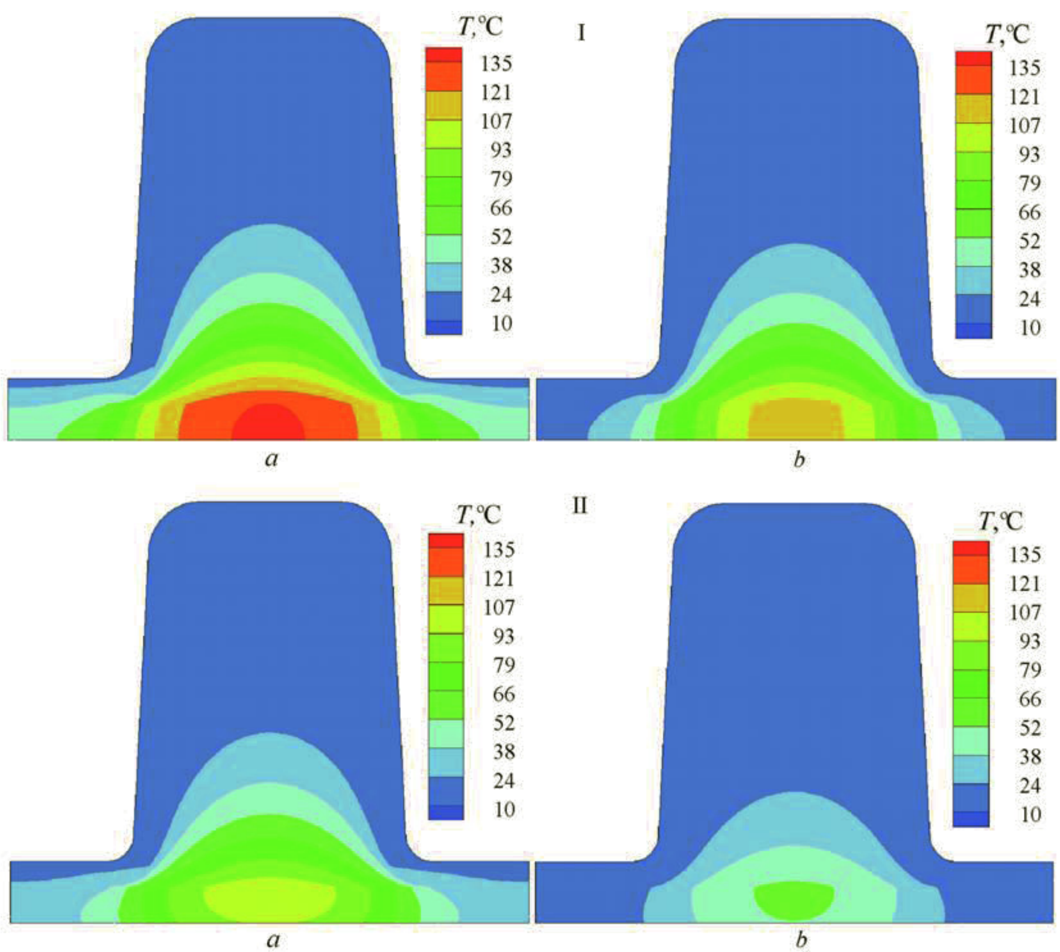

Fig. 7. Temperature fields of a polyethylene TLCPP with inner and outer diameters of 200 and 176 mm, thicknesses of the outer and inner layers of 0.8 and 1.1 mm, and an initial temperature of 160°C within 30 (a) and 60 s (b) after the beginning of the cooling: I) one-side external cooling by water with a temperature of 10°C; II) two-side cooling: external cooling by water with a temperature of 10°C and internal cooling by a water-air mixture.

cooled by a water-air mixture, the cooling time was decreased by 44%. This allows the conclusion that the two-side cooling of TLCPPs is a highly efficient method of cooling of such pipes.

When a TLCPP is cooled by a water-air mixture, the water is used more rationally than in the case of convective water cooling. When the surface of such a pipe has a temperature higher than 100°C, the cooling water is transformed into the fine-dispersed state (a fog) and, therefore, is rapidly cooled and evaporated, with the result that the cooling process is substantially intensified. In this case, the vapor-air mixture formed in the space of the pipe can be easily removed through the vacuum channel in a die head: the vacuum formed in the space of the pipe provides reliable removal of the vapor-air mixture from the pipe practically independently of its dimensions.

To estimate the efficiency of the two-sided cooling of TLCPPs, we performed numerical simulation of the cooling of such pipes differing in diameter from 160 to 40°C (Fig. 6). At higher temperatures, the effect of the two-side cooling of a TLCPP with a diameter of 200 mm was increased by 7% in the case where air was used for cooling, and by 11% in the case of cooling of this pipe with the use of a water-air mixture. The efficiency of the cooling of TLCPPs also increases with increase in their dimensions.

In the case where the external cooling of a TLCPP is fairly intensive, the air inside the corrugations of the pipe exhibits a large thermal resistance. Therefore, the regions of the inner layer of the pipe, which are located under the corrugations, remain practically noncooled during a fairly large period of time, while the temperature of the outer layer of the pipe reaches a required value (Fig. 7, I). If in this case the cooling process is terminated, the inner and outer layers of the pipe wall can be heated progressively due to the further redistribution of the heat flow between them, which, in turn, can cause a loss in the shape of the tube. To prevent this effect, it is necessary to further cool the pipe, which, in the case of a one-side external cooling, leads not only to an increase in the cooling time, but also to an increase in the amount of water necessary for the cooling process.

In the case of a two-side cooling of a TLCPP, the regions of the inner layer of the pipe, located under the corrugations, are cooled directly (on the inner side of the pipe), which can lead to a significant decrease in the cooling time; this is especially true for large-diameter pipes (Fig. 7, II). In the process of production of small-diameter TLCPPs, it is best to use air for cooling of the inner surface of a pipe, and a water-air mixture is more suitable for cooling of large-diameter TLCPPs.

Conclusions. Mathematical models of one-side and two-side coolings of two-layer corrugated polymeric pipes were considered. A comparison of the results of calculations by these models with the corresponding experimental data has shown that the models proposed adequately define the real process of cooling of the indicated pipes. The expediency of the use of a two-side cooling in the process of production of two-layer corrugated polymeric pipes was substantiated. It was shown that it is advantageous to use a water-air mixture for cooling of pipes with large diameters. Since in the air contained in the corrugations of two-layer corrugated pipes there arises a large temperature gradient, in further works we plan to investigate the influence of the convective heat transfer in the corrugations of such pipes on the temperature field in their wall depending on the angle coordinate of the diametrical cross section of a pipe.

NOTATION

c, mass heat capacity, J/(kg·K); D, diameter of the pipe, mm; H, enthalpy, J/kg; n, normal to the outer surface of the pipe; q, surface density of the heat flow, W/m^2; q_V, volume density of the heat flow from the internal energy sources, W/m^3; r, current radius, m; T_k, temperature of the cooling medium, °C; w, linear rate of cooling of the pipe, m/s; z, longitudinal axis of the cylindrical coordinate system, m; α_k, coefficient of the convective heat transfer, W/(m^2·K); λ, heat conduction, W/(m·K); ρ, density, kg/m^3; τ, time, s; ∇ , Hamiltonian. Subscripts: 0, initial state; i, number of a layer of a multilayer pipe ($i = \overline{1, n}$); k, number of a cooling medium ($k = \overline{1, m}$).

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