

# **An Investigation of Thermodynamic Effects in Porous Media Saturated with Fluids**

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## **Introduction**

Recent years have witnessed an extensive application of thermal methods for investigating wells when monitoring the development of oil and gas fields [1]. Temperature changes in the formation are brought about by manifestations of the adiabatic and the Joule-Thomson effects, as well as by the heat of fluid degassing when the pressure in the well is reduced below the one of saturation of oil with gas [2].

The paper presents the research data on the influence of the adiabatic and the Joule-Thomson effects and the heat of fluid degassing on the temperature field in the porous medium.

To calculate the formation of the temperature field with due account taken of the above effects one has to know thermodynamic coefficient for actual formation fluids. With this aim in view, an experimental installation was developed based on the PVT bomb to determine the coefficients of the Joule-Thomson and the adiabatic effects, as well as to obtain the specific heat of oil degassing. The thermodynamic coefficients thus obtained are used for investigating a non-stationary temperature field in the porous medium for various conditions of pressure gradient and the content of gas dissolved in the fluid.

## **1. Experimental Determination of Thermodynamic Coefficients**

### *1.1. The Joule-Thomson Coefficient*

The value of the Joule-Thomson coefficient  $\varepsilon$  is effected by the physical and chemical properties of the percolating fluid, and it is different for the fluids found in different fields. Therefore, to determine the value of the Joule-Thomson coefficients for formation fluids of specific oil fields, an experimental installation was developed whose diagram is presented in Fig. 1. It consists of the main units as follow: the choking element I, the temperature regime measuring circuit II, and the system to create a pressure gradient III. The choking element is a controllable (allowing to change the aperture width) needle valve, whose chamber (A) is connected to a standard pressure gauge 1, whereas chamber (B) is maintained at atmospheric pressure. To reduce heat exchange of the choking fluid with the body, the heat-insulating ebonite sleeve 3 was squeezed into the chamber (B). Temperature transducers 2 are implanted into the chambers. Semiconductor diodes incorporated in a direct-shift bridge circuit are used as temperature sensors. The temperature characteristic of the measuring circuit is linear in a wide temperature range. This measuring circuit enables one to measure both temperature difference in chambers and absolute temperatures in each of the choker chambers. The system to create the pressure gradient is the commercially available UIPK-1M installation for determining rock permeability, this installation comprising the principal parts as follow: two electric motor-driven presses 4, the piston separator 5, tanks for the investigated fluid 6 and the working fluid 7, the standard pressure gauge 1.

Due to the fine adjustment of the presses, the amount of fluid which passes through the choke can be precisely determined, whereas a wide range within which the speed of the presses can be controlled enables one to maintain flow rates of up to  $0.67 \cdot 10^{-6} \text{ m}^3/\text{day}$ . It should be underlined here that the flow is strictly constant at constant speed. The UIPK-1M can create pressure gradients of up to 30 MPa. If we assume that  $\left(\frac{\partial \varepsilon}{\partial T}\right)_p$  and  $\left(\frac{\partial \varepsilon}{\partial P}\right)_T$  are small in relation to  $\varepsilon$  with one measurement taken, then, measuring the pressure gradient ( $\Delta P$ ) and temperature gradient ( $\Delta T$ ) in the choker chambers with the fluid choking established, one can determine the Joule-Thomson coefficient according to the formula  $\varepsilon = \Delta T / \Delta P$ .

The analysis demonstrates that the Joule-Thomson coefficient is practically independent of pressure, whereas  $\left(\frac{\partial \varepsilon}{\partial T}\right)_p = 6 \cdot 10^{-4} \text{ MPa}^{-1}$ . Under such conditions, measuring the temperature change which follows from the final pressure gradient under constant enthalpy, is sufficient for a direct evaluation of  $\varepsilon$ . Several values (experimental and calculated) of the Joule-Thomson coefficients are presented in Table 1.

Table 1

Values of the Joule-Thomson Coefficients

Fluid under Study	$\varepsilon_{\text{calculated, K/MPa}}$	$\varepsilon_{\text{experimental, K/MPa}}$
Fresh Water	0.220	0.216
Mineralized Water	-	0.225
Transformer Oil	0.46	0.410
Arlan Crude (Bashkiriya)	-	0.415
Fyodorovskaya Crude (Western Siberia)	-	0.337

### 1.2. Adiabatic Coefficient

The value of the temperature change under the adiabatic process is proportional to the pressure change  $\Delta P$  in the system:  $\Delta T = \eta \Delta P$ .

In practice, the adiabatic processes comprise the so-called fast processes during which no significant heat exchange with the environment takes place, as well as the processes in large-volume thermodynamic systems (in the atmosphere, for example).

The proportionality coefficient  $\eta$  bears the name of the adiabatic one, and it can be calculated using the expression  $\eta = \frac{\alpha T}{C_p \rho}$ .

The sign of  $\eta$  coincides with that of  $\alpha$ , usually  $\alpha > 0$  ( $\alpha < 0$  only for water within the  $0^\circ$  to  $4^\circ\text{C}$  temperature range). The value and the pattern of the system temperature change due to the adiabatic effect depend primarily on the velocity, the value of the pressure change in the system and are determined by the fluid's physical and chemical properties. The determination of the adiabatic coefficient for the fluid involves measuring temperature depending on the pressure change subject to constant entropy. The latter means that a pressure change should take place within such a period of time as to enable one to ignore any heat exchange with the environment. To

investigate the adiabatic effect, the authors employed the heat-insulated piston-type separator 5 of the UIPK-1M installation (Fig. 1). The chamber (C), which is filled with the fluid under study, is provided with a tube with the temperature sensor 12. The STZ-19 thermoresistor with the time constant of not more than 1 sec is used as a sensor.

The pressure generated by the installation is fed through the valve 9 and piston 8 into the chamber (C). With the valves 11 and 13 closed, the opening of the valve 10 immediately releases pressure in the chamber (D) and, correspondingly, in the chamber (C). By measuring pressure and temperature changes before and after the pressure release and bearing in mind that temperature in the chambers equalizes with the ambient temperature within the period of 900-1200 seconds, whereas the duration of temperature measurement is 3–5 seconds, the adiabatic coefficient can be determined.

The installation and the measurement technique thus developed enabled the authors to experimentally determine the value of adiabatic coefficients with an error not exceeding 2%.

Table 2 presents experimental and calculated values of the coefficient for certain fluids.

Table 2

Values of Adiabatic Expansion Coefficient for Fluids

Fluid under Study	$\eta_{\text{calculated}}$ , K/MPa	$\eta_{\text{experimental}}$ , K/MPa
Fresh Water	0.015	0.016
Mineralized Water ( $\rho=1.18 \text{ g/cm}^3$ )	-	0.030
Transformer Oil	0.097	0.098
Arlan Crude (Bashkiriya)	-	0.134
Tuimazy Crude (Bashkiriya)	-	0.059
Fyodorovskaya Crude (Western Siberia)	-	0.137

As opposed to the Joule-Thomson effect, the adiabatic effect both in liquids and in gases acts in one direction, i.e. their temperature increases when they are compressed and decreases when they expand.

### 1.3. Phase Transition Heat

When the pressure (P) drops below the saturation pressure ( $P_{\text{sat}}$ ) there takes place in the porous medium a degassing of the fluid or a release of the gas dissolved in the fluid. This taking place, energy is absorbed which brings about a change in the system temperature. This process is characterized by latent phase transition heat or degassing heat (L, J/kg). When gas is dissolved the corresponding amount of energy is produced. Estimates are known of phase transition heat when formation crude is degassed, these estimates ranging between 100 and 300 kJ/kg [3,4].

To estimate specific heat of fluid degassing the authors created an experimental installation whose principal diagram is shown in Fig. 2. The principal element is the thermally insulated vessel I (PVT bomb). The vessel is filled with a liquid and a gas. Pressure inside the vessel is built up by the manual press 2 and is registered by the pressure gauge 4. Opening the valve 6, one can reduce the pressure inside the cylinder down to  $P_1 < P_0$ , where  $P_0$  is the pressure inside the vessel before the valve is opened, whereas  $P_1$  is the one after the valve is opened. When the pressure drops below the saturation pressure, gas starts to emanate from the liquid, i.e. the degassing process commences. The volume of gas that has been released is measured using the gas meter 10. Temperature changes in the vessel were measured using 2 copper-constantan

thermocouples. One thermocouple 9 was located in the vessel 1, whereas the other one – in the thermostatic vessel 14. Temperature was measured using the micro-voltmeter 15. Temperature variations were logged by, an automatic recorder.

The technique for evaluating specific heat of fluid degassing is as follows. Let us assume that there is some liquid in the vessel of volume  $V$  with a gas dissolved in this liquid. The volume is completely filled with the gassed fluid. The pressure in the system is reduced by the value of  $\Delta P$ . In doing so, a temperature change takes place by the value of  $\Delta T$  brought about by the adiabatic effect and that of degassing. Let us assume that the mass of the gas thus released is small, so we shall ignore the change in the fluid mass in the unit of volume. We shall apply here the linear law of Henry of isothermal solubility of gas in liquid.

The process of adiabatic expansion of the gas-liquid mixture can be divided into two stages: the first one involves a reduction of pressure from the initial to the saturation one, whereas the second one comprises a reduction of pressure below the saturation one. Let us investigate both of these stages in a greater detail. We shall start with the first one, i.e. when  $P > P_{sat}$ . The liquid over-saturated with gas is under the pressure  $P_1$  which is greater than the saturation pressure  $P_{sat}$ . The temperature change which results from the adiabatic expansion of the gas and liquid mixture can be presented using the adiabatic coefficient  $\eta_l$  for the liquid  $\Delta T = \eta_l \Delta P$ . When the pressure in the mixture is equal to the saturation pressure, i.e.  $P = P_{sat}$ , the mixture temperature will change by the value of  $T = -\eta_l (P_1 - P_{sat})$ . Let us now consider the second stage, i.e. at  $P < P_{sat}$ . At some moment of time  $t$ , the liquid and the gas are at the temperature  $T(t)$ . Within the time  $\Delta t$ , at the moment of time  $t + \Delta t$ , the pressure will change by  $\Delta P$ . The liquid temperature will change by  $\eta_l \Delta P$ , whereas the gas temperature will change by  $\eta_g \Delta P$  due to the adiabatic process. Besides, the issuing gas will change its temperature by the value of  $L/C_g$ , where  $L$  is specific latent heat of the phase transition, and  $C_g$  is specific heat capacity of the gas. After simple transformations we shall obtain  $L = C_l m_l \Delta T / m_g$ , where  $m_l = \rho_l V_l$ ,  $C_l$  is specific heat capacity of the liquid;  $V_l$  is the volume of the liquid;  $\Delta T$  is the change of the mixture temperature;  $V_g$  is the volume of gas released under normal conditions.

When calculating the heat of the phase transition or the heat of degassing, the authors used the experimental values which are presented in Table 3 and which were obtained using the installation (Fig. 2).

Table 3

$V_l$ cm <sup>3</sup>	$\rho_l$ g/cm <sup>3</sup>	$\Delta T$ C	$V_g$ , cm <sup>3</sup>	$\rho_g$ g/cm <sup>3</sup>	$L$ kJ/kg
600	0.99	0.3	6.28	1.84	65.27
		0.51	7.02		99.26
		0.24	3.07		106.81
		0.21	3.11		92.26
		0.19	1.73		150.06
		0.15	2.19		93.58
		0.13	1.33		128.71
		0.1	0.49		178.84

## 2. An Investigation of Temperature Fields Brought About by Thermodynamic Effects in Porous Media

### 2.1. Single-phase Non-stationary Movement of Liquid

The temperature change in a porous medium when a liquid is choked is determined by convective transfer and the thermodynamic effects which accompany percolation, these effects being the choking effect, the adiabatic expansion effect and that of phase transitions.

The mathematic formulation of the problem to calculate the temperature field with no account taken of the fluid degassing in a uniform porous medium with a single-phase percolation has the form

$$\frac{\partial T}{\partial t} + u(r,t) \frac{\partial T}{\partial r} = -\varepsilon u(r,t) \frac{\partial P}{\partial r} + \eta \Pi \frac{\partial P}{\partial t} \quad (1)$$

$$T(r,0) = 0 \quad (2)$$

Здесь  $u(r,t)$  is the velocity of convective heat transfer, m/sec;  $u(r,t) = cv(r,t) = -c \frac{k}{\mu} \frac{\partial P}{\partial r}$ , where  $c = C_1/C_p$  is the ratio of volume heat capacity of the

fluid and that of the porous medium saturated with this fluid,  $\varepsilon$ ,  $\eta$  are the Joule-Thomson and the adiabatic expansion coefficients of the fluid, K/Pa;  $\Pi = mc$  is the parameter which takes into account instantaneous heat exchange between the fluid and the skeleton of the porous medium;  $P(r,t)$  is the pressure at the distance  $r$  from the well axis at the moment of time  $t$ , which is obtained by solving the corresponding boundary-value problem of piezo-conductance.

A general solution of (1) - (2) along the characteristics  $r_t(t, r_1)$  can be written as

$$T(r_t, t) = \varepsilon [p(r_1, 0) - p(r_t, t)] + (\varepsilon + \eta \Pi) \int_0^t \frac{\partial p(r_\tau, \tau)}{\partial \tau} d\tau \quad (3)$$

Obviously, the first term is unambiguously determined by the initial and the current values of pressure, whereas the second one points at the dependence of temperature change on the nature of pressure change versus time along the fluid path.

The calculations show that upon a lapse of some time after choking the main contribution to the value of temperature change is made by the choking effect, and the following formula can be used for estimating calculations (for  $t \leq t_0$ )

$$T(r_c, t) \approx \frac{\varepsilon \Delta P}{2 \ln R} \ln \left( 1 + c \frac{qt}{\pi r_c^2} \right); \quad R = \frac{R_k}{r_c} \quad (4)$$

where  $R_k$  is the radius to the border of the porous medium;  $r_c$  is the well radius,  $q$  is specific flow,  $\Delta P$  is the pressure gradient.

Fig. 3 demonstrates the results of calculating, using the formula (4), of the temperature change brought about by the choking effect when the crude and water flow in under the influence of the constant depression  $\Delta P = 5.0$  MPa at:  $R = 100$ ,  $\varepsilon_o = 0.5$  K/MPa,  $\varepsilon_w = 0.2$  K/MPa,  $c_o = 0.8$ ,  $c_w = 1.2$ ,  $q_o = 1$  m<sup>3</sup>/day m,  $q_w = 100$  m<sup>3</sup>/day m. It is evident from the figure that initially water is heated more than oil. Thereafter, one can observe a "normal" change of oil and water temperature ( $T_o > T_w$ ). In this sense one can talk about an inversion in time of the value of the choking-induced temperature anomaly within the intervals of oil and water inflow. This is primarily explained by different

mobilities of oil and water: the more mobile water, within the same period of time, covers a larger portion of the depression funnel and, in spite of the lower value of the Joule-Thomson coefficient, it is heated more than oil.

## 2.2. Multi-phase Non-stationary Movement Accompanied by Liquid Degassing

A two-phase movement of oil and gas is observed when the pressure is reduced below the one of saturating oil with gas. The mathematical model for calculating the temperature field in a non-stationary pressure field with due account taken of the Joule-Thomson effect, the adiabatic effect and the heat of fluid degassing in a porous medium is written as:

$$\begin{aligned}
 m \frac{\partial \rho_i^0 c_{ik} S_i}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} \left( r \rho_i^0 c_{ik} \frac{k K_i}{\mu_i} \frac{\partial P}{\partial r} \right) &= 0 \quad i=1,2,3; k=1,2 \quad (5), \\
 \frac{\partial}{\partial t} [(1-m) \rho_0 C_0 T + m \sum_{i=1}^3 \rho_i^0 C_i S_i T + m \rho_1^0 S_1 L] + \\
 + \frac{1}{r} \frac{\partial}{\partial r} r [ \sum_{i=1}^3 \rho_i^0 m S_i v_i C_i T + m \rho_1^0 S_1 v_1 L ] + \\
 + \sum_{i=0}^3 \rho_i^0 C_i \varepsilon_i m S_i v_i \frac{\partial P}{\partial r} - \sum_{i=1}^3 \rho_i^0 C_i S_i \eta_i \frac{\partial P}{\partial t} &= 0 \quad (7)
 \end{aligned}$$

Different  $i$  indices correspond to different phases, namely: 0 - rock, 1 - gas, 2 - water, 3 - oil;  $S_i$  and  $v_i$  are saturation and motion speed of the  $i$ -th phase;  $C_{ik}$  is concentration of the  $k$ -th component in the  $i$ -th phase;  $\rho_i$  is density of the  $i$ -th phase;  $K$  is absolute permeability;  $k_i$  is phase permeability;  $\mu_i$  is viscosity of the  $i$ -th phase;  $m$  is porosity;  $P$  is pressure;  $T$  - температура;  $C_i$  is heat capacity;  $\varepsilon_i$  is the Joule-Thomson coefficient;  $\eta_i$  is the adiabatic coefficient;  $L$  is degassing heat.

Fig 4. shows the dependencies for the values of thermodynamic parameters of phases as follow:  $C_0 = 800$  J/(kg K),  $C_1 = 3000$  J/(kg K),  $C_2 = 4000$  J/(kg K),  $C_3 = 2000$  J/(kg K);  $\varepsilon_1 = -4$  K/MPa,  $\varepsilon_2 = 0.2$  K/MPa,  $\varepsilon_3 = 0.4$  K/MPa;  $\eta_1 = 20$  (K/MPa,  $\eta_2 = 0.015$  K/MPa,  $\eta_3 = 0.13$  K/MPa.

The value of phase transfer heat during degassing oil is taken as  $L = 100$  kJ/kg. The viscosities of the gaseous, gassed aqueous and oil phases are, respectively:  $\mu_1 = 0.01$  mPa·sec,  $\mu_2 = 0.2$  mPa·sec,  $\mu_3 = 0.4$  mPa·sec.

Let us consider the peculiarities of forming the temperature field in the porous medium in a non-stationary pressure field. Curves 1-3 correspond to the following values of the established ratio of the dissolved gas volume to the volume of the fluid: 50, 100, 150 m<sup>3</sup>/m<sup>3</sup>. It is seen from Fig. 4, that at the instantaneous pressure drop at the initial moments of time one can observe a reduction in temperature resulting from the manifestation of the adiabatic effect and the heat of fluid degassing. As time passes, the formation of the heat field is effected by the choking heating of the fluid and gas cooling. It is obvious, that as the portion of gas in the flow increases one can observe more intensive cooling of the fluid which is connected with degassing gas choking heat. For the sake of comparing the influence of degassing heat on the temperature field, Curve 4 in Fig. 4 ignores the heat of fluid degassing.

Thus, when the pressure is instantaneously reduced below the one of saturation of oil with gas, at the initial moments the main contribution to forming the temperature field is made by the adiabatic cooling of the fluid and the heat of fluid degassing. Thereafter, the contribution of the choking effect increases. The extent of the temperature drop is affected by the value of fluid degassing heat, the Joule-Thomson coefficient and that of the adiabatic effect, by gas solubility and the pressure gradient. The combined influence of the cooling and heating effects results to the formation of a temperature minimum on the temperature curve. As this takes, depending on the amount of gas dissolved in the fluid and on the pressure gradient, the stationary distribution of temperature may feature both positive (Curves 1 and 2) and negative (Curve 3) temperature anomalies.

The results thus obtained can be employed in the technologies of thermal methods of well surveys.

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Fig. 1. Diagram of the experimental installation to determine the Jopule-Thomson coefficient.

Fig. 2. Principal diagram of the installation

1 - thermally insulated container (PVT bomb), 2 - piston separator, 3 - pressure gauge, 4 - thermostatic container, 5 - temperature sensor, 6 - gas canister, 7 - ice-filled reservoir.

Fig. 3. Dependence of temperature on time.

Fig. 4. Dependence of temperature on time with due account taken of fluid degassing. Volume content of gas: 1 -  $50 \text{ m}^3/\text{m}^3$ , 2 -  $100 \text{ m}^3/\text{m}^3$ , 3 -  $150 \text{ m}^3/\text{m}^3$ , 4 - without taking into account degassing heat,  $150 \text{ m}^3/\text{m}^3$ .

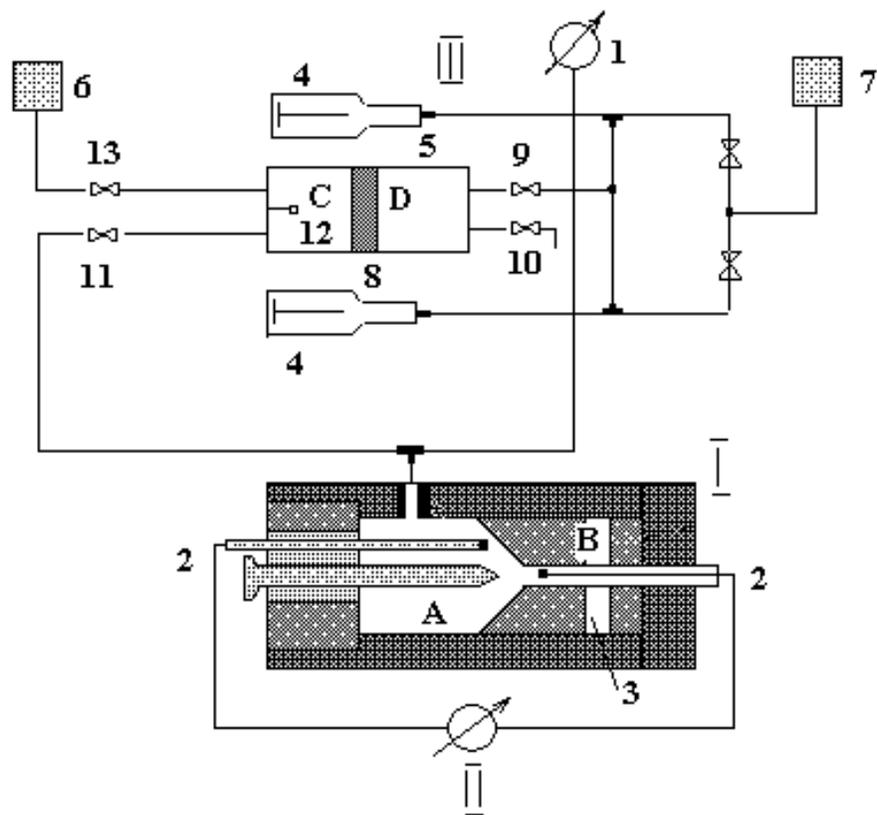


Fig. 1.

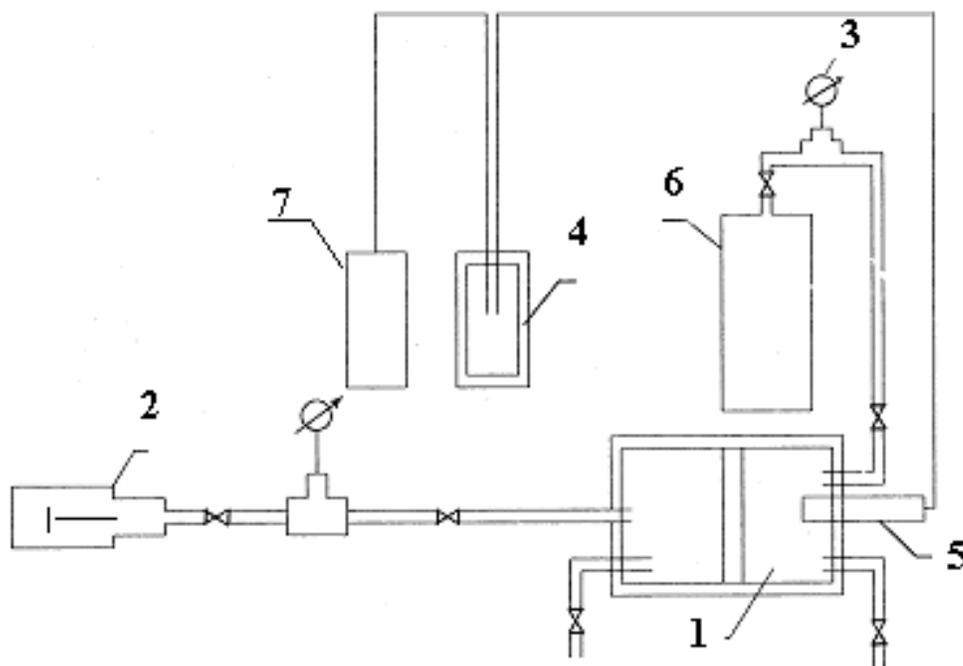


Fig. 2.

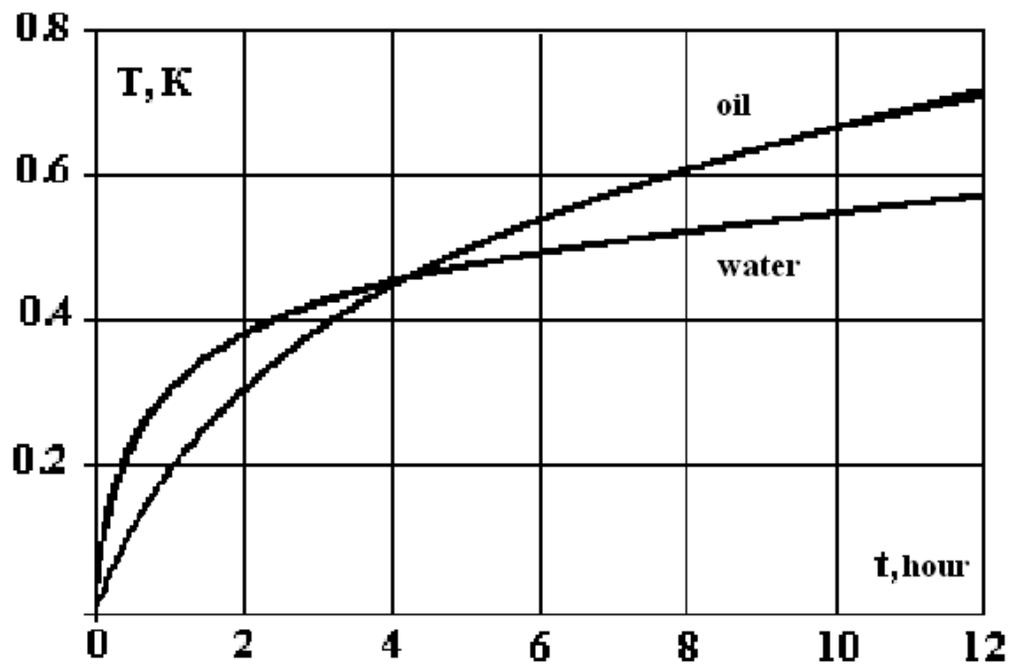


Fig. 3.

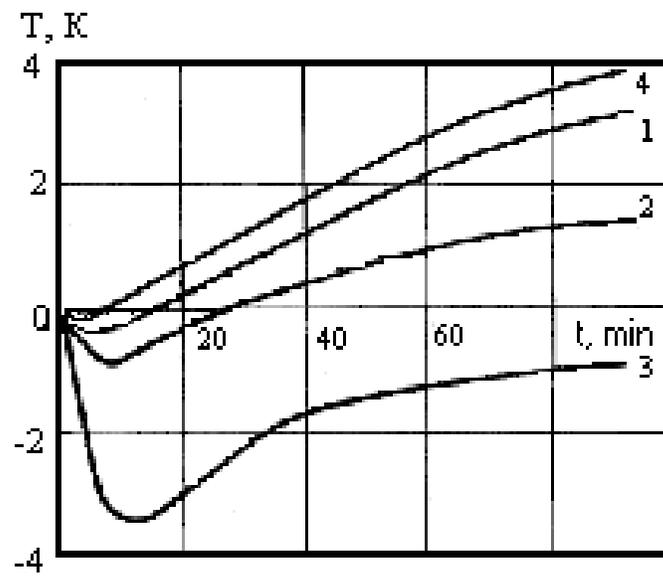


Fig. 4.