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ON THE POSSIBILITY OF ACOUSTIC PROBING OF GAS WELLS

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The possibility of probing the critical areas of gas wells using acoustic signals is analyzed. The results of investigations on the evolution of acoustic waves in cylindrical channels with permeable portions surrounded by a porous space are presented. The quantitative and qualitative features of the dynamics of waves as a function of the state of an inhomogeneous porous medium are established. Results showing that the state of the reservoir characteristics of rocks has a substantial influence on the evolution of acoustic signals are obtained.

Introduction. To improve the reservoir characteristics of the critical areas of oil- and gas-bearing beds one uses different methods of treatment: physicochemical, thermal, and hydrodynamic ones. Acoustic methods related to the distinctive features of the evolution of wave pulses propagating over the gas in the well with different permeabilities of rocks around the walls seem one efficient means for monitoring routinely the state of the critical areas of wells before and after the treatment.

The propagation of high-frequency acoustic waves in wells surrounded by a porous medium was first theoretically analyzed in [1]. Most investigations [2, 3] have been devoted to studying hydraulic waves in cased wells, i.e., in such wells that do not have a permeable portion. The reservoir properties, as far as the parameters of damping of high-frequency waves in tubes are concerned, have been considered in [4–6] theoretically and in [7–9] experimentally. The influence of fractured porous media on the dynamics of waves in liquid-filled channels has been shown in [10, 11]. The basic developments in the long-wave range of the acoustic waves used (the wave-pulse length is much larger than the channel diameter $\lambda >> 2r_0$) have been performed in [12]. Certain aspects of propagation and damping of acoustic waves in channels surrounded by a homogeneous space have been considered in [13–16].

Below, we discuss the remote method of acoustic monitoring (Fig. 1a): the initial signal is created at a certain distance from the portion inspected and is conveyed by a waveguide, for which one can use, e.g., a cased well wall. The duration of the probing signal is assumed to be much shorter than the time of its propagation over the permeable well portion under study. In this problem, we must single out the following zones of propagation of the acoustic wave: a waveguide, a permeable portion (uncased well wall), and a porous bed around the well (Fig. 1b).

The propagation of a disturbance in the waveguide is influenced by the processes related to the presence of internal friction (viscosity) and heat conduction in the wall layer of the well. At the boundary between the cased and naked (uncased) zones of the well, we have a partial reflection of the acoustic signal and its transmission by the boundary. Consequently, in propagation over the uncased zone, the wave signal is damped due to the filtration of the gas in the surrounding porous medium. Therefore, we must consider the problem in the porous medium, which is external in relation to the well, and to determine the missing physical parameters (such as the rate of gas filtration through a permeable well wall bordering the porous bed).

From the parameters of the echo of the wave signal from the critical area of the well we can primarily judge the permeability and porosity of the bed. Furthermore, the signals reflected from the boundary of the cased and uncased zones and from the bottom of the uncased zone carry information on the length and occurrence depth of the permeable bed.

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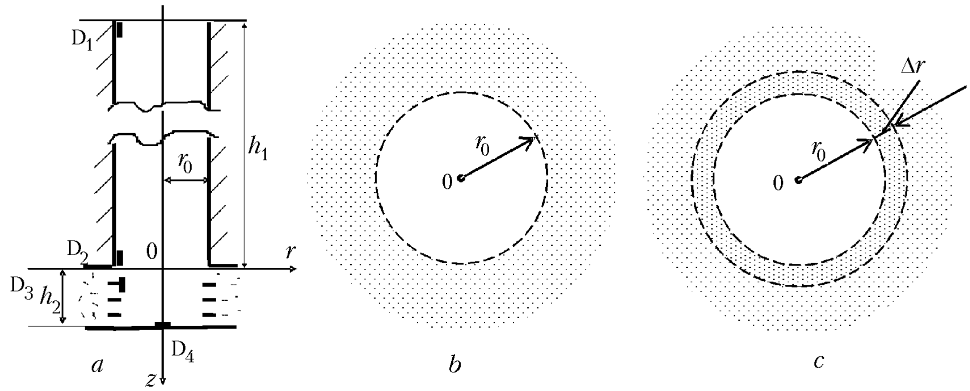

Fig. 1. Diagram of a channel with a permeable portion (a) and different possible structures of a porous medium surrounding the channel: homogeneous structure (b) and that with a "crust" (c): D_1–D_4, sensors.

Basic Equations. We will consider disturbances whose duration is much shorter than the time of their propagation over the portion with permeable and impermeable walls. The process of evolution of such disturbances may be subdivided into individual steps characteristic of the propagation of the disturbances over the cased and uncased portions respectively. Furthermore, separate account must be taken of the process of transmission of wave signals by the boundary between these portions.

The coordinate axis will be guided vertically downward. The origin of coordinates is coincident with the boundary dividing the well into portions with permeable ($z > 0$) and impermeable ($z < 0$) walls.

Let us write the continuity equation for the "cased" portion with impermeable walls ($-h_1 < z < 0$)

$$\frac{\partial \rho}{\partial t} + \rho_0 \frac{\partial w}{\partial z} = 0 \,. \tag{1}$$

We assume that the compression and expansion of the gas in propagation of disturbances in the well occur in a nearly adiabatic regime, whereas the temperature difference between the gas and the well wall is realized in a thin boundary layer near the wall. Then, on the basis of the first law of thermodynamics, we obtain the following equation:

$$\frac{\partial \rho}{\partial t} = \frac{1}{C^2}\left(\frac{\partial p}{\partial t} + (\gamma - 1)\frac{2q}{r_0}\right), \quad q = \sqrt{\frac{\nu^T}{\pi}}\,\frac{\partial}{\partial t}\int_0^t \frac{p\,(z, \varphi)}{\sqrt{t-\varphi}}\,d\varphi\,, \quad C = \sqrt{\gamma \frac{p_0}{\rho_0}}\,,$$

$$\gamma = \frac{c_g}{c_g - R_g}\,, \quad \nu^T = \frac{\lambda_g}{\rho_0 c_g}\,. \tag{2}$$

The continuity equation (1) with account for (2) can be reduced to the form

$$\frac{\partial}{\partial t}\left(p + 2\frac{\sqrt{\nu^T}\,(\gamma - 1)}{r_0\sqrt{\pi}}\int_{t_0}^t \frac{p\,(z, \varphi)}{\sqrt{t-\varphi}}\,d\varphi\right) + \rho_0 C^2 \frac{\partial w}{\partial z} = 0\,. \tag{3}$$

Taking into account that the medium was at rest ($p^{(1)} = p = 0$) at the "initial" instant of time $t_0 \to -\infty$, we rewrite Eq. (3) in a more general form as

$$\frac{\partial}{\partial t}\left(p + 2\frac{\sqrt{\nu^T}\,(\gamma - 1)}{r_0\sqrt{\pi}}\int_{-\infty}^t \frac{p\,(z, \varphi)}{\sqrt{t-\varphi}}\,d\varphi\right) + \rho_0 C^2 \frac{\partial w}{\partial z} = 0\,. \tag{4}$$

The propagation of signals is influenced, in addition to heat transfer, by the process of energy dissipation; these processes are related to the presence of internal friction (viscosity), which manifests itself just in a thin boundary layer near the well wall. An equation describing the propagation of pulses, with allowance for the forces of viscous friction against well walls, has the form

$$\rho_0 \frac{\partial w}{\partial t} + \frac{\partial p}{\partial z} = -\frac{2\tau}{r_0}, \tag{5}$$

where τ can be determined from the relation [17]

$$\tau = \frac{\mu_g}{\sqrt{\pi \nu^{\mu}}} \int_{-\infty}^{t} \frac{\partial w / \partial t}{\sqrt{t - \varphi}} d\varphi, \quad \nu^{\mu} = \frac{\mu_g}{\rho_0}.$$

It is correct to use expression (5), when viscosity manifests itself just in a thin boundary layer near a solid wall of a cylindrical well in propagation of wave disturbances. To do this requires in turn that the time duration of a pressure pulse t_* satisfy the condition $\sqrt{t_* \nu^{\mu}} << r_0$.

The mass equation on the portion with a permeable wall ($0 < z < h_2$) in a linearized approximation can be written as

$$\frac{1}{C^2} \frac{\partial p}{\partial t} + \rho_0 \frac{\partial w}{\partial z} = -\frac{2\rho_0 u}{r_0}. \tag{6}$$

The pulse equation on the portion ($z > 0$) can be represented in the form (5); the action of viscous stresses will be disregarded ($\tau = 0$).

To describe the intensity of the process of filtration of the gas to the surrounding porous space ($0 < z < h_2$ and $r > r_0$) in traversal of the portion with permeable walls by the wave we take the pulse equation with allowance for inertial effects

$$\rho_0 \frac{\partial u^{(1)}}{\partial t} = -m^{(1)} \frac{\partial p^{(1)}}{\partial r} - \frac{m^{(1)} \mu_g}{k^{(1)}} u^{(1)}, \tag{7}$$

and the continuity equation

$$m^{(1)} \frac{\partial \rho^{(1)}}{\partial t} + \frac{\rho_0}{r} \frac{\partial (r u^{(1)})}{\partial r} = 0, \quad r > r_0. \tag{8}$$

For the sake of generality we will assume that the interior surface of a permeable channel portion can be coated with a thin ($\Delta r << r_0$) low-permeability "crust" (see Fig. 1c). Then the boundary conditions on the channel wall ($r = r_0$) for Eqs. (7) and (8) will acquire the form

$$u^{(1)} = u, \quad u = h(p - p^{(1)}), \quad h = \frac{k^{(1)}}{\mu_g \Delta r}. \tag{9}$$

If the hydraulic resistance of the "crust" is disregarded ($h \to 0$), we can write

$$u^{(1)} = u, \quad p^{(1)} = p, \quad r = r_0 \tag{10}$$

instead of conditions (9).

When the channel is surrounded by a porous space of infinite thickness (filtration processes in propagation of disturbances occur in layers whose thickness is much smaller than the thickness of the porous space around the channel), we must supplement the system of equations with the boundary condition

$$p^{(1)} = 0 \; (r \to \infty) \; . \tag{11}$$

When disturbances are transmitted by the boundary dividing the cased and uncased well portions, the evolution of an acoustic signal will be accompanied by partial reflection. Therefore, at the boundary $z = 0$, we must write the relations

$$p^{(\mathrm{O})} + p^{(\mathrm{R})} = p^{(\mathrm{G})} \, , \quad w^{(\mathrm{O})} + w^{(\mathrm{R})} = w^{(\mathrm{G})} \, , \tag{12}$$

following from the conditions of continuity of pressure and the medium.

Dispersion Equations. The solution of the equations on each portion of the well will be sought in the form of a running harmonic wave propagating along the channel axis:

$$W = A_W \exp\left[i\,(Kz - \omega t)\right] , \quad i = \sqrt{-1} \, , \quad C_{\mathrm{ph}} = \frac{\omega}{\mathrm{Re}\,(K)} \, , \quad \delta = \mathrm{Im}\,(K) \, . \tag{13}$$

On condition that solutions of the form (13) are existent, Eqs. (4)–(8) yield the dispersion expression for the cased portion of the well

$$K^{(1)} = \pm \frac{\omega}{C} \sqrt{\left(1 + 2\,\frac{(\gamma - 1)}{y^T}\right)\left(1 + \frac{1}{y^{\mu}}\right)} \, , \quad \left(y^{\mu} = \sqrt{-\frac{i\omega r_0^2}{\nu^{\mu}}} \, , \quad y^T = \sqrt{-\frac{i\omega r_0^2}{\nu^T}}\right) . \tag{14}$$

Here (+) and (–) correspond to the waves propagating in the positive and negative directions in the well.

To obtain the dispersion equation in the uncased portion we must solve the problem on propagation of an acoustic signal in a porous medium. Substituting the solution in the form of a running wave (13) into Eqs. (7)–(9), we obtain the following system of equations:

$$A_u^{(1)} = \frac{-\,m^{(1)} k^{(1)}}{(-\,i\omega\rho_0 k^{(1)} + m^{(1)}\mu_{\mathrm{g}})\, r_0} \, \frac{dA_p^{(1)}(R)}{dR} \, , \quad y^2 A_p^{(1)}(R) = \frac{1}{R}\,\frac{d}{dR}\left(R\,\frac{dA_p^{(1)}(R)}{dR}\right) , \quad R > 1 \, , \tag{15}$$

$$y^2 = -\frac{i\omega r_0^2}{\nu^{\mathrm{p}}} - \frac{\omega^2 r_0^2}{C^2} \, , \quad \nu^{\mathrm{p}} = \frac{k^{(1)}\rho_0 C^2}{m^{(1)}\mu_{\mathrm{g}}} \, , \quad R = \frac{r}{r_0} \, , \quad A_u^{(1)} = A_u \, , \quad A_u = h\left(A_p - A_p^{(1)}\right) , \quad R = 1 \, .$$

We note that the first term in the expression for Y corresponds to the viscous resistance in filtration of the gas in a porous space, and the second term is responsible for inertial effects.

The general solution of Eqs. (15) has the form [18]

$$A_p^{(1)}(R) = A I_0\,(yR) + B K_0\,(yR) \, . \tag{16}$$

For the solution (16) to satisfy boundary condition (11), we must set $A = 0$. Then, on the basis of Eqs. (15), we can determine the constant B:

$$B = \frac{A_p}{K_0\,(y) - \xi y K_0'\,(y)} \, , \quad \xi = \frac{k^{(1)} C^2}{i\mu_{\mathrm{g}} h\,(\nu^B \omega + C^2 i)} \, . \tag{17}$$

The amplitude of the rate of filtration through the well walls with account for (15), (16), and (17) can be represented in the form

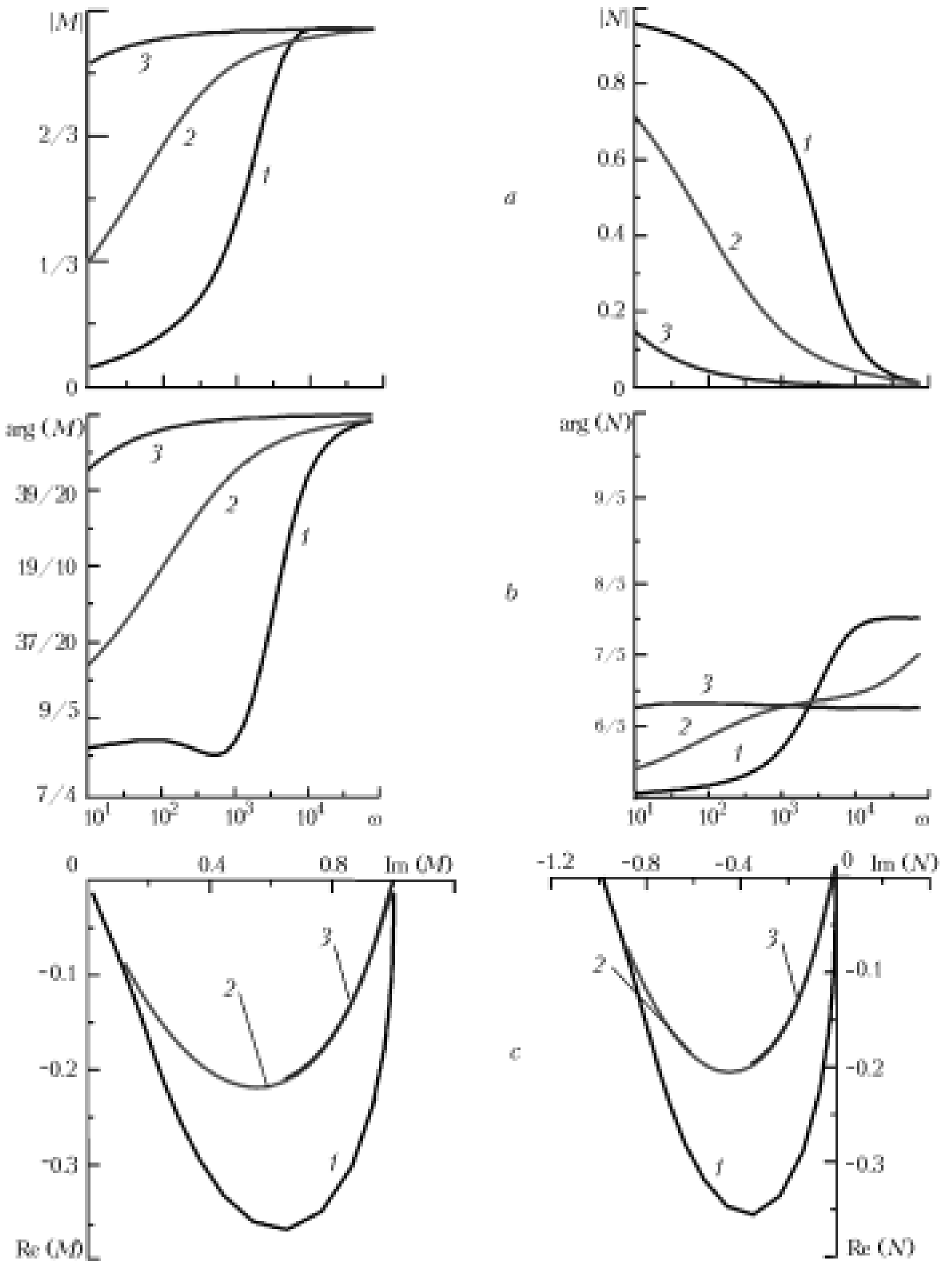

Fig. 2. Moduli (a), arguments (b), and hodographs (c) of the coefficients of transmission and reflection of a wave (T = 380 K and $p = 10 \cdot 10^6$ Pa): 1) $k^{(1)} = 10^{-10}$, 2) 10^{-12}, and 3) 10^{-14} m^2.

$$A_u = -\frac{h\xi y A_p K_0'(y)}{K_0(y) - \xi y K_0'(y)}. \tag{18}$$

Using (17) and (18) for the uncased zone of the well ($z > 0$), we obtain the following dispersion equation:

$$K^{(\mathrm{II})} = \pm \frac{\omega}{C} \sqrt{1 - \left(\frac{2m^{(1)}}{y}\right)\left(\frac{\ln (K_0(y))'}{1 - y\xi \ln (K_0(y))'}\right)}. \tag{19}$$

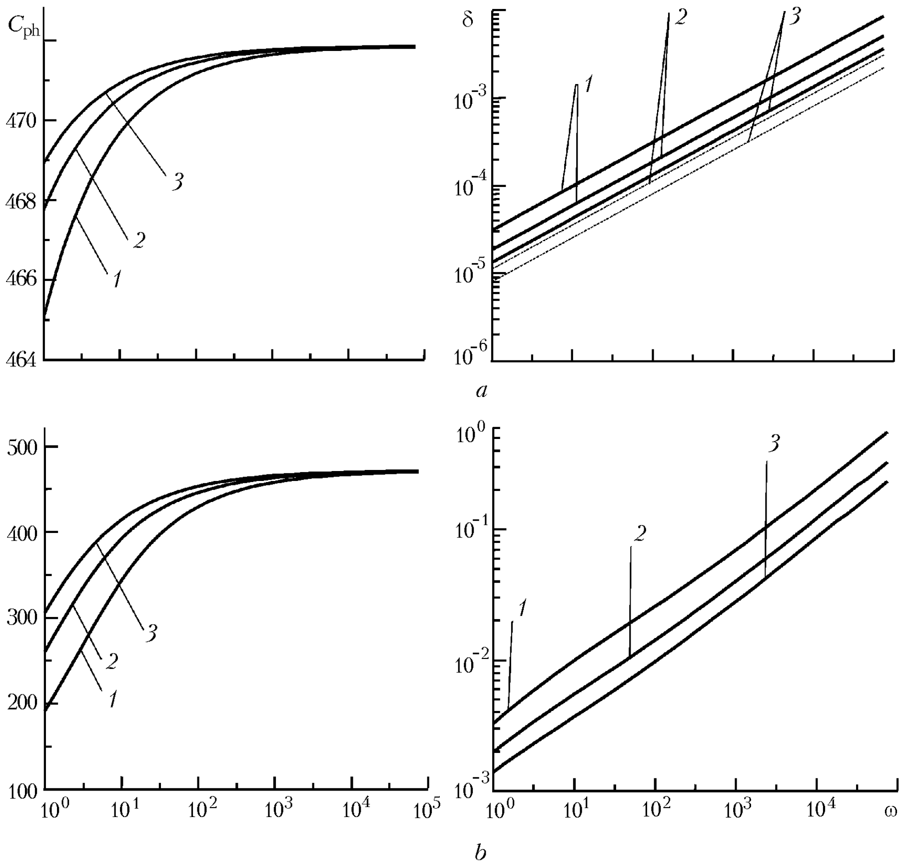

Fig. 3. Phase velocity and damping factor of disturbances vs. frequency for the impermeable (a) and permeable (b) portions, plotted for different radii of the well: 1) $r_0 = 3{\cdot}10^{-2}$, 2) $5{\cdot}10^{-2}$, and 3) $7{\cdot}10^{-2}$ m. The dotted curves are the dependences allowing just for the gas viscosity.

For the coefficients of reflection ($N = A_p^{(R)}/A_p^{(O)}$) and transmission ($M = A_p^{(G)}/A_p^{(O)}$) by the boundary $z = 0$, with account for (12) and (13), we easily obtain

$$N = \frac{K^{(I)} - K^{(II)}}{K^{(I)} + K^{(II)}}, \quad M = \frac{2K^{(I)}}{K^{(I)} + K^{(II)}}. \tag{20}$$

Figure 2 gives the dependences (calculated from expressions (20)) of the moduli $|N|$ and $|M|$ and arguments arg (N) and arg (M) of the reflection and transmission coefficients of waves on their frequency and of the hodographs in methane-filled channels (T = 380 K, $r_0 = 5{\cdot}10^{-2}$ m, $p = 10{\cdot}10^6$ Pa, h_2 = 5 m, and $m^{(1)}$ = 0.2). The modulus of the reflection coefficient varies from 1 to 0 throughout the frequency range. For the region of high frequencies ($\omega \to \infty$), the reflection coefficient is $N \to 0$, and the transmission coefficient is $M \to 0$. The plots presented show that the real part of the reflection coefficient is a positive quantity throughout the frequency range (arg (N) $> \pi$). The modulus of the transmission coefficient of the acoustic signal grows with the permeability coefficient of the surrounding porous medium, whereas the modulus of the reflection coefficient decreases. In the frequency range presented in Fig. 2 for low-permeability media ($k^{(1)} \le 10^{-14}$ m^2), the transmission is nearly complete ($M \to 1$) and accordingly the acoustic signal "does not feel" the permeable portion, i.e., the reflection coefficient tends to zero ($N \to 0$).

Above, we have presented the dependences of the phase velocity C_{ph} and the damping factor δ of acoustic disturbances on frequency in the impermeable (Fig. 3a) and permeable (Fig. 3b) portions surrounded by a porous medium ($k^{(1)} = 10^{-12}$ m^2 and $m^{(1)}$ = 0.2) for different values of the well radius. From these plots, we infer that viscosity

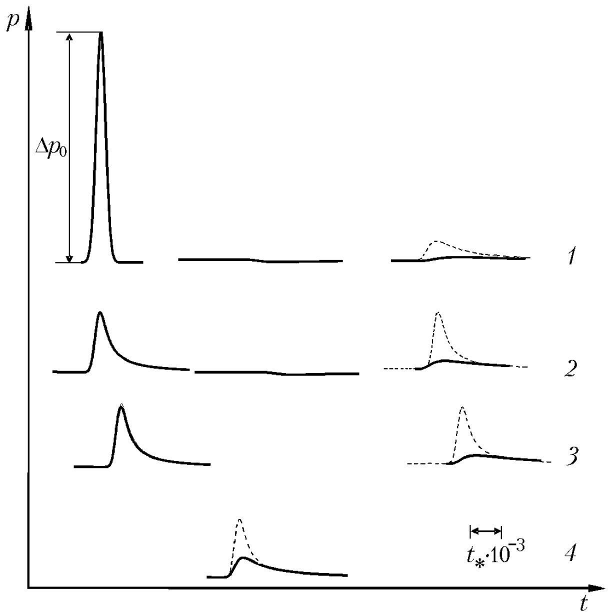

Fig. 4. Dynamics of a pulsed signal in the well at $p = 10{\cdot}10^6$ Pa and $T = 380$ K.

and thermal conductivity in the cased zone cannot substantially perturb the signal. Figure 3 shows that the phase velocity grows with well radius, whereas the damping factor decreases. The damping factor of a disturbance in the uncased zone of the well is two orders of magnitude higher throughout the frequency range than that in the cased zone. Therefore, the filtration of the gas influences the damping of acoustic disturbances much more strongly than viscosity and thermal conductivity. This fact enables us to obtain information on the reservoir characteristics of a bed. Comparing the solid and dotted curves in Fig. 3a, we note that the damping factor is dependent on the viscosity of the gas more strongly than on its thermal conductivity.

Dynamics of Waves of Finite Length. On the basis of expressions (20) for the reflection and transmission coefficients and of the dispersion relations (14) and (19), we consider the evolution of waves of finite length in traversal of the permeable portion of a cylindrical channel. Let a signal of finite duration $p = \tilde{p}^{(O)}(t)$ be actuated from the boundary of two portions ($z < 0$) through the boundary $z = -h_1$ in the left region. Then, using the Fourier transformation, for the pulse that has reached the boundary ($z = 0$) we have

$$p^{(O)}(0, t) = \frac{1}{\pi} \int_0^{\infty} \int_{-\infty}^{\infty} \tilde{p}^{(O)}(\varphi) \exp(iK(\omega) h_1) \exp[i\omega(t - \varphi)]\, d\omega d\varphi .$$

Analogous relations can be written for the pulse reflected from the boundary and the pulse transmitted by the boundary $z = 0$:

$$p^{(R)}(0, t) = \frac{1}{\pi} \int_0^{\infty} \int_{-\infty}^{\infty} p^{(O)}(0, \varphi)\, N(\omega) \exp[i\omega(t - \varphi)]\, d\omega d\varphi ,$$

$$p^{(G)}(0, t) = \frac{1}{\pi} \int_0^{\infty} \int_{-\infty}^{\infty} p^{(O)}(0, \varphi)\, M(\omega) \exp[i\omega(t - \varphi)]\, d\omega d\varphi .$$

We take a bell-shaped pressure pulse with an amplitude Δp_0: $\tilde{p}^{(O)} = \Delta p_0 \exp\left(-\left(\frac{t - t_0}{t_*/6}\right)^2\right)$ as the initial wave signal.

Figure 4 gives the calculated oscillograms illustrating the evolution of a wave signal actuated at the distance h_1 = 1000 m from the permeable portion. The permeable portion is near the well bottom. Oscillograms 1, 2, 3, and 4 correspond to the readings of sensors D_1, D_2, D_3, and D_4 located at the point of actuation of the signal, near the boundary at $z < 0$, at the beginning of the permeable portion, and at the bottom. The initial signal represents a bell-shaped pressure pulse of unit amplitude. The time length of the initial pulse is equal to $t_* = 1 \cdot 10^{-3}$ sec. For the example presented, the porous medium ($m^{(1)} = 0.2$ and $k^{(1)} = 10^{-13}$ m^2) surrounding the cylindrical channel (r_0 = $5 \cdot 10^{-2}$ m) is homogeneous; the length of the permeable portion is h_2 = 5 m. The first burst on the oscillogram of sensor D_1 expresses the initial signal actuated at a distance from the permeable portion. This pulse reaches the permeable portion, being somewhat attenuated because of the manifestation of the gas viscosity and the heat loss in the process of its propagation in the channel (first burst on the oscillogram of sensor D_2). The second burst on the same oscillogram is a signal reflected from the permeable portion. Next, part of the signal returns to sensor D_1 (second burst on the oscillogram of sensor D_1), whereas the other part propagates over the portion of the well with permeable walls (first burst on the oscillogram of sensor D_3). In the waveguide (cased zone), viscosity and thermal conductivity weakly perturb an acoustic signal. As this signal propagates over the open portion, it is damped by filtration effects. The signal that has reached the rigid wall (first burst on the oscillogram of sensor D_4) propagates in the opposite direction after the reflection. If the amplitude of the signal is sufficiently large, it reaches the boundary of the permeable portion (second burst on the oscillogram of sensor D_3). Next, the situation is repeated: part of the signal is reflected from the boundary, and part of it is transmitted by the boundary (third burst on the oscillogram of sensor D_2). If the signal transmitted has a pronounced amplitude, it returns to the signal sounce (third burst on the oscillogram of sensor D_1). The dynamics of reflection of secondary waves in the uncased zone continues until the acoustic signals are completely damped by the filtration of the gas to the surrounding porous medium. The dashed curves correspond to the case where a permeable portion is absent. The calculated oscillograms presented illustrate the possibility of evaluating the occurrence depth of a permeable bed (by the second burst on the oscillogram of sensor D_1) and its length (third burst on the oscillogram of sensor D_1). Furthermore, from the values of the amplitudes of return signals, we can judge the reservoir characteristics of a permeable portion (permeability and porosity).

Conclusions. The given results of calculations of acoustic waves in gas wells show that in most cases the cased portion is a waveguide perturbing acoustic signals only slightly. In the uncased portion, the state of the reservoir characteristics (porosity, permeability, etc.) of the surrounding rocks exerts a pronounced influence on the evolution of signals in some cases. This fact makes us hopeful that the ideas considered here can be used under certain situations for monitoring of the reservoir characteristics of the near-well region of rocks.

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NOTATION

A, arbitrary constant; A_W, amplitude of the parameter W; B, arbitrary constant; C, velocity of sound in the gas, m/sec; c_g, specific heat of the gas, J/(kg·K); C_{ph}, phase velocity, m/sec; h, hydraulic resistance of the "crust", m^2·sec/kg; h_1, length of the cased portion of the well, m; h_2, length of the uncased portion of the well, m; i, imaginary unit; $I_0(yR) = J_0(iyR)$, Bessel function of zero order; K, wave vector representing a complex number, m^{-1}; $k^{(1)}$, coefficient of permeability of the space surrounding the channel, m^2; $K_0(yR) = \int_0^\infty \exp(-yRch(\varphi))d\varphi$, Macdonald function of zero order; M, coefficient of transmission of an acoustic wave; $m^{(1)}$, porosity of the space surrounding the channel; N, coefficient of reflection of an acoustic wave; p, pressure in the well, Pa; $p^{(1)}$, pressure in the saturated porous medium around the well, Pa; Δp_0, amplitude of the initial pressure pulse, Pa; q, heat flux per unit area of the well wall, W/m^2; R, self-similar variable; r, horizontal coordinate, m; r_0, well radius, m; Δr, "crust" thickness, m; R_g, reduced gas constant, m^2/(K·sec^2); t_*, characteristic time length of a pressure pulse, sec; t, time, sec; T, gas temperature, K; u, rate of filtration of an acoustic wave through the well wall, m/sec; W, parametric disturbance; w, velocity of the medium, m/sec; z, vertical coordinate, m; γ, adiabatic exponent of the gas; δ, damping factor, m^{-1}; φ, variable under the integral sign; λ, wavelength, m; λ_g, thermal conductivity, W/(m·K); μ_g, dynamic viscosity of the gas, kg/(m·sec); ρ, density of the medium, kg/m^3; $\rho^{(1)}$, density of the medium around the well, kg/m^3; τ,n tangential viscous stress on the interior channel-wall surface, kg/(m·sec^2); ν^{μ}, kinematic viscosity of the gas, m^2/sec; ν^{p}, piezoelectrical conductivity, m^2/sec; ν^{T}, thermal diffusivity, m^2/sec; ω, angular frequency, sec^{-1}. Subscripts: 0, initial state; g, gas; p, at constant gas pressure; u, gas-filtration rate. Superscripts: I, zone of the cased well; II, zone of the well with a permeable portion; 1, porous space around the channel; G, values of the parameters in the transmitted wave; O, values of the parameters in the incident wave; R, reflected wave; p, piezoelectrical conductivity; ph, phase.

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