Theoretical models of infrasonic emission of HC reservoirs in the ANCHAR technology

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Summary. Considered is the theory of ANCHAR phenomenon – emission of intrinsic infrasonic waves by a HC reservoir upon its stimulation by a field of elastic vibrations [1-3]. Presented is a brief review of publications devoted to this phenomenon. Considered is a drop-bubble model of the ANCHAR effect [4]. A principle agreement of experimental spectral power characteristics of ANCHAR microseism and theoretical ones is demonstrated. From this theory it follows that the frequency range of ANCHAR microseism is independent of a pore geometry and reservoir properties.

Introduction

ANCHAR is a Russian low-frequency seismic (infrasonic) technology of oil and gas exploration which allows directly detect the presence of hydrocarbons in geological structures. The ANCHAR technology is based on the phenomenon of emission of intrinsic infrasonic waves by a HC reservoir upon its stimulation by a field of elastic [1-3] (Fig.1).

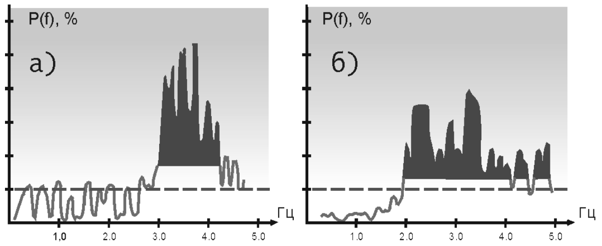

Fig.1. Spectral power of the HC emission of HC reservoirs rated to the background (Cis-Ural trough): (a) – gas reservoir; (b) – gas-condensate reservoir.

Since 1993 the ANCHAR method has been applied in industrial scale. During the last years the ANCHAR geophysical survey projects were implemented for GAZPROM, ONAKO and other petroleum companies in Russia and abroad. Overall, the infrasonic emission fields were studied over the area above 9000 sq km and prediction of hydrocarbons was made for 150 structural and non-structural traps. The prediction results were validated by deep drilling for 40 prospecting targets and the ANCHAR prediction reliability makes up 85%.

Only a few theoretical publications are known shedding light on the ANCHAR phenomenon. Attempts of microscopic description of ANCHAR effect are presented in [4-10]. In paper [5] the author relates the low-frequency phenomenon of the ANCHAR type to a so-called "slow wave" which appears as a result of external acoustic wave and is transported through a reservoir like in a waveguide. The author of [5] demonstrates the proximity of the ANCHAR frequency range to the series of intrinsic frequencies of the slow waves. Moreover, in [5] a similarity principle is applied to experimental modeling of generation and propagation of slow waves under laboratory conditions. In paper [6] which confirms some of experimental results which were firstly obtained in pioneer papers [1-3], a brief review of theoretical papers is present. In [7] the ANCHAR phenomenon is related to intrinsic oscillations of fluid in pores. The papers [5,7] are of a particular interest since, they, at least, propose theoretical approaches to a microscopic description of "slow" processes taking place in the "reservoir-fluid" system. Besides in some publications considered are mechanisms of generation of various microseism with characteristics similar to ANCHAR microseism. In [8] considered is tremor arising before and the volcano eruptions, and existing for some period of time afterwards. Frequency of such oscillations lies in the range of 1-10 Hz. Some features specific of the ANCHAR phenomenon (particularly, the independence of ANCHAR frequency range on the pore geometry) are beyond these theories.

One of the basic hypotheses describing the ANCHAR effect is the assumption that in a HC reservoir there exist localized domains, characterized by a meta-stable state [2-3]. Under particular conditions, fluctuations of the geomedium parameters and external acoustic stimulation can switch these domains into a thermodynamic state with a lower internal energy. A difference between the energy of these two states is converted to the energy of emitted infrasonic wave. Both the natural factors – tectonics, earthquakes of different origin and intensity and technogenic factors may act as an external acoustic stimulation. Thus, either spontaneous (caused by fluctuations) or induced emission is produced which forms an additional infrasonic flux of energy to the background flux. This extra flux is a manifestation of ANCHAR phenomenon.

The above-presented complies with the drop-bubble theory of ANCHAR phenomenon. This model relates ANCHAR phenomenon to the processes of evaporation and condensation of fluids in the presence of electric charges stabilizing a new phase. This model is in a good agreement with observations and gives clear illustration of the ANCHAR phenomenon.

Drop-bubble model of the ANCHAR phenomenon

As mentioned above, the drop-bubble model (DBM) of ANCHAR effect is based on the phenomenon of evaporation / condensation of fluids in pores [4]. Theory presented below describes the ANCHAR phenomenon primarily in gas-condensate and light-weight oil fields. In such fields the fluid consists of methane and its light homologs to the extent of 70-90% and the remainder (30-10%) consists of its heavier homologs [11]. In practice, these are precisely the fields where ANCHAR phenomenon is observed in the most distinct manner. Below is considered a drop-bubble model of ANCHAR phenomenon by an example of formation and dissolution of bubbles on the internal surface of pores in the two- or one-phase fluidal system. Actually the ranges of formation pressure and temperature make up 50-600 atm and 70-200^{0}C, respectively [11]. Under such conditions the fluid has the one-phase (mostly liquid) or two-phase state [12]. Formation of bubbles in a gas system will produce a similar result and there will be no significant difference in the process description.

Process of the bubble disappearance from the pore surface is accompanied by transfer of a pulse to the pore wall. This produces an extra pressure acting on the pore wall in the bubble attachment point. Characteristic frequencies of emission field are defined by a characteristic time of the bubble disappearance. Bubble germs are always present in the liquid phase. Yet, the probability of formation of rather large bubbles is extremely low, it decreases exponentially with the germ size. Besides, such bubbles are instable and do not exist for a long time. Yet, on the internal surface of pores there always exist a certain number of free charges which under particular conditions serve as centers of the germ generation of stable, rather large bubbles in the liquid phase. These bubbles (drops) are under of consideration of DBM.

Assuming that intra-pore thermodynamic parameters and external fields are quite stable, we suppose that there exists an equilibrium between processes of generation and dissolution of stable bubbles being formed on charges. A number of mechanisms may result in dissolution of such bubbles. For example, the departure of a bubble from a charge due to Coulomb forces, fusion of bubbles, etc. Anyway, this results in a randomly distributed in time and space, isotropic (in an isotropic and homogeneous reservoir) field of forces. A composite action of these forces results in generation of a sonic emission (ANCHAR seism), propagating from the boundary of a HC-saturated reservoir. This infrasonic emission arising as a result of detail equilibrium between formation and dissolution of bubbles manifests itself as a spontaneous phenomenon of ANCHAR.

We could assume that the external acoustic stimulation much more speeds up processes of bubble dissolution or evaporation of drops as compared to its effect on the probability of bubble generation. This results in a violation of detail equilibrium between processes of formation and disappearance of active pores (pores inside which evaporation process is taking place). Moreover, a decrease of infrasonic emission in the ANCHAR frequency range, which is observed within a certain time, is a natural consequence of a drastic growth of the number of active pores. The detail equilibrium is restored within a certain characteristic relaxation time only. In addition this results in the flash-up of emission power in the ANCHAR frequency range. This consequence of the drop-bubble model also is in a good agreement with observations and illustrates the induced phenomenon ANCHAR.

Pilot and industrial implementations of ANCHAR technology have suggested a number of empirical propositions concerning the features of ANCHAR phenomenon. Consider some of these propositions.

Proposition 1. Estimated spectral power of displacement makes up about 100 nm/Hz$^{1/2}$

Proposition 2. Frequency range of the ANCHAR phenomenon weakly depend on formation pressure, i.e. depth.

Proposition 3. An increased portion of heavy hydrocarbons results in a shift of the frequency range toward the lower frequencies, i.e., in oil reservoirs the ANCHAR phenomenon manifests itself at lower frequency as compared to that in gas reservoirs.

A theory describing the ANCHAR effect should comply with the above conclusions 1-3. Consider how the DBM deals with these conclusions.

1. Suppose that each active pore is a source of emission of the concentrated force type [13]. Then, within the framework of the drop-bubble model the spectral power displacement on a daylight surface will be described by the following expression [4]:

$$J_\delta(r,\omega) = \frac{NP}{T_u}\frac{2\overline{b_1^2}(DP_0\mu\bar{v}r_0)^2}{(2\rho c_t^2RT)^2}\{1-\gamma_\delta^2(1-\frac{c_t^4}{c_l^4})\}\frac{1}{r^2}\left|\int_{-\infty}^{\infty}dt\exp(-i\omega t)\sqrt{1-\frac{t}{T_u}}\right|^2\frac{\sin^2\frac{1}{2}\omega T_u}{\pi\omega^2} \qquad (1)$$

where N is a number of pores with bubbles (in the first approximation – fluid-filled); P is a probability of the drops fusion; T_u is the bubble dissolution time; D is a coefficient of diffusion in gas; P_0 is the “in-situ” pressure of a saturated vapor; μ is the effective molecular mass of hydrocarbons “in situ”; c_l, c_t is velocity of shear and compression wave of the ANCHAR seism, respectively; R is the universal gas constant; ρ is the effective density of a layer separating the observation point and productive reservoir; T is a formation temperature; r - радиус-вектор точки наблюдения; and γ_δ is a directing cosine. The number of fluid-saturated pores in the reservoir is defined as follows:

$$N = L^3Bg/r_\text{n}^3, \qquad (2)$$

where L is a characteristic size of emitting domain ($L<<\lambda$); r_n is a characteristic size of pores; B is the reservoir porosity; and g is the share of fluid-saturated pores.

Within the framework of drop-bubble model the dependence of frequency range of ANCHAR phenomenon on formation pressure and molecular mass of hydrocarbons is as follows:

$$f_A = \frac{2\rho_0}{\rho_{\text{жс}}q}\frac{P_\text{н}D_\text{н}}{P_0}\left(\frac{T}{T_\text{н}}\right)^{3/2}\left(8\pi(P_{\text{пл}}-P_0)\left(\frac{\varepsilon_\text{г}\varepsilon_{\text{жс}}}{\varepsilon_{\text{жс}}-\varepsilon_\text{г}}\right)\right)^{1/2} \qquad (3)$$

here ρ_0 and P_0 are the density and pressure (respectively) of saturated vapor in situ; D_n and P_n are self-diffusion and pressure under normal conditions; P_f is formation pressure. Using the fact that $D_\text{н} \sim 1/\sqrt{\mu}$ and (3), we get the following expression for frequency f_A:

$$f_A \sim \frac{1}{\sqrt{\mu}}\left(P_{\text{пл}}-P_0\right)^{1/2} \qquad (4)$$

Note that for heavy gases and fluids we will have another relationship:

$$f_A = \frac{2\rho_0}{\rho_{\text{жс}}q}\frac{kT(c_\text{м}\mu_\text{м}+c_{\text{пр}}\mu_{\text{пр}})^{2/3}}{h\rho_{\text{жс}}^{2/3}N_A^{2/3}}(1-\frac{\alpha}{T}(c_\text{м}\mu_\text{м}+c_{\text{пр}}\mu_{\text{пр}}))\left(8\pi(P_{\text{пл}}-P_0)\left(\frac{\varepsilon_\text{г}\varepsilon_{\text{жс}}}{\varepsilon_{\text{жс}}-\varepsilon_\text{г}}\right)\right)^{1/2} \qquad (5)$$

where k,is Boltzmann constant; c_m and μ_m are the molecular share and molecular mass of methane, respectively, in a reservoir rock; c_{np} and μ_{np} are the molecular share and molecular mass of other HC’s, respectively, in a reservoir rock; h is the Planck’s constant; N_A is the Avogadro number; α is a coefficient equal to 261 for HC’s (with the exception of decanes) [15]. When deriving (5) we used the fluid model introduced by Enskiy [15]. Formula (5) presents an evident dependence of f_A on the molecular mass of components.

Formula (1) results in an underestimated displacement as compared to the observed one. To get a correct estimate within the framework of the drop-bubble model it is necessary to apply a concept of correlated localized emission domains. As a result, a multiple will appear in expression (1) equal to a number of pores M included in the correlated domains:

$$M = \frac{L_c^{\,3}Bg}{r_n^{\,3}} \qquad (6)$$

here L_c is a correlation radius. Parameters P and L_c can be found using additional assumptions about the nature of ANCHAR phenomenon. Particularly, a mechanism of formation of active pores and mechanism of formation of correlated emission domains shall be introduced.

2. Consider Propositions 2 and 3. As far as formation pressure changes from one to another field within an order, from (4) it follows that frequency range of the ANCHAR effect will change no more than by coefficient of 3.

3. As for the ANCHAR emission frequency dependence on the effective molecular mass of a mixture, from (4) it follows that in a gas (light component) field the ANCHAR effect will manifest itself at a higher frequency as compared to that in oil fields (featuring a higher portion of heavy molecular components).

Conclusions

It is demonstrated that processes of dissolution of bubbles stabilized by electric charges may result in elastic displacements on the daylight surface comparable in magnitude with observed ones. Relationship (3) is in good agreement with empirical propositions 2 and 3. The ANCHAR emission frequency range has only a weak dependence on the formation pressure and heavy HC components. The dependence character complies with empirical ones.

Dominant mechanisms of generation of free charges inside pores result in a characteristic frequency range of the sonic emission. It is demonstrated that under formation conditions the drop-bubble model provides the low-frequency range of ANCHAR emission. The dominant (from the standpoint of generation rate) mechanisms of generation of charges result in the presence of a certain average number of charges existing inside pores. This, in turn, is responsible for a narrow range of sizes of stable drops (bubbles) and, consequently, for a narrow range of dissolution time which varies in inverse proportion to the emission frequency.

The induced effect ANCHAR can also be described within the framework of the drop-bubble model. The induced effect is owed to an intense growth of the probability of drops fusion a Он связан с сильным ростом вероятности слияния капель P в (1) in the presence of the field of elastic waves. Possibly the field of elastic vibrations triggers other mechanisms resulting in the evaporation of drops. Contrary to the noise character of ANCHAR phenomenon, the growth of the probability of drops fusion P in the field of elastic vibrations can be of a resonance type.

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