Acoustically induced mass transfer in saturated porous media

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Abstract. The paper provides a physical rationale for acoustic flows to occur in porous saturated media. A formula is derived for calculating the velocities of these flows, assuming that all acoustic energy is converted to create flows in a formation. It is assumed that the velocity of acoustic flows depends on the acoustic intensity and the fluid viscosity that saturates pore spaces. With increased fluid viscosity, acoustic velocity decreases. An experimental framework is presented for the effect of combined acoustic and constant electric fields on the permeability of a saturated porous medium.

1. Introduction
The papers [1-3] provides theoretical and experimental studies towards acoustically induced mass transfer in a saturated porous medium. The calculations suggest that primary waves that create acoustic flows in a porous medium are longitudinal P-waves, since the largest portion of elastic energy entering the liquid is related to this type of acoustic waves. A wave has been thought to be flat and the energy absorbed by the medium is entirely used to create an acoustic flow. Stirring fluid motions at frequencies of 10–20 kHz occur only in large pores saturated with water, or with oil that has a viscosity of 10⁻² Pa·s. At high viscosity, stirring motions can occur in large fractures alone. Given that formations are postheated, the viscosity significantly reduces resulting in possible micro-flows to occur in the pores.

A varying wettability rate during fluid motions under the acoustic influence is interconnected with a phenomenon herein defined as wetting hysteresis. The effect is strongly noticeable at the boundaries of various fluids saturating the pores of developed channels. With this in view, the acoustic field in water-saturated reservoirs increases water movements and oil displacement and, the other way around, in oil-wet formations.

2. Materials and methods
Let us evaluate the possibility of creating acoustic flows by an elastic wave in a porous medium. Since the largest portion of elastic energy entering the liquid is associated with P₁ compressional waves, we consider these waves as primary for creating acoustic flows in a permeable porous medium. We consider the entire system of second-order motion, continuity, and state equations [4]. In this case, we admit the presence of a non-zero constant component of travel time. Following the oscillatory averaging, the linear terms vanish, with remaining nonlinear terms to describe non-periodic acoustic flows in the medium.
Assuming that the motion is slow, i.e. neglecting the quadratic terms in the flow velocity, we obtain the acoustic flow equation in the form of Darcy’s law:

\[ B(\bar{v} - \bar{w}) = -\frac{a}{\mu(1 - m)} \nabla \Delta m \]

where \( v \) is the fluid velocity; \( w \) is the solid phase velocity in the wave; \( a \) is the hydraulic coefficient; \( \mu \) is the dynamic viscosity; \( m \) is the coefficient of porosity; \( \Delta m \) is porosity fluctuations; \( B \) is the coefficient subject to the ratio of porosity, density, hydraulic and viscosity oscillating quantities to their unperturbed values; \( p \) is the pressure in the wave. Let us time average the expression (1).

The left-hand side of the equation (1) expresses the acoustic travel time in the medium. The equation indicates that various processes related to elastic energy dissipation influence acoustic flows, including fluid motions in the \( P_1 \) wave relative to the solid phase, non-phase changes in density, porosity, medium permeability and fluid viscosity.

### 3. Results and Discussion

The maximum acoustic velocity can be defined by the formula:

\[ u_{\text{max}} = k \nabla E = \frac{\alpha \vartheta^2}{\nu} d^2 \]

where \( E \) is the total elastic energy of the wave; \( \alpha \) is the attenuation coefficient; \( \nu \) is the kinematic viscosity of the fluid; \( d \) is the pore diameter; \( \vartheta \) is the velocity amplitude; \( k \) is the permeability coefficient.

The expression (2) assumes that the wave is flat and that energy absorbed is entirely used to create an acoustic flux.

A water-saturated medium is calculated with the following parameters: \( k = 10^{-10} \text{ m}^2 \), \( d = 10^{-5} \text{ m} \), \( \nu = 10^{-6} \text{ m}^2/\text{s} \). For a primary wave at \( \alpha = 1 \text{ m}^{-1} \), \( \vartheta = 0.1 \text{ m/s} \), the acoustic velocity is \( u \approx 10^{-6} \text{ m/s} \). With the increased viscosity (in the case of oil-saturated formation, oil viscosity is greater than water viscosity), the acoustic velocity will decrease.

The derived value of the acoustic velocity in the wave is quite comparable with the fluid velocity in the reservoir during its operation.

The calculations suggest that all the absorbed wave energy is spent solely on the acoustic flow. In fact, there are still other acoustic energy losses (for example, thermal attenuation). Therefore, with the acoustic intensity of the order of several tens of kilowatts per 1 m², the acoustic travel time will be negligible. Slight mixing acoustic flows, similar to the ones in the acoustic boundary layer, are likely to occur in the pore, but under certain conditions. In this case, the boundary layer thickness \( \delta \) is determined by the expression:

\[ \delta = \sqrt{\nu / \omega} \]

In this case, the boundary layer thickness should be less than the pore diameter \( d \). For productive strata, the average diameter of a pore channel is within the range \( (1.5 \pm 1) \times 10^{-5} \text{ m} \).

The acoustic boundary thickness is calculated for a set of frequencies 1; 10; 20 and 30 kHz and is given in Table 1.

The data show that, at frequencies of 10±20 Hz, stirring motions are possible in large pores alone (\( d > 2 \delta \)) for water-saturated formations and for oil-saturated formations with an oil viscosity of less than 10-2 Pa•s. For higher viscosity oils, mixing acoustic fluxes are possible in large fractures alone.

Concurrent postheating of the formation leads to a significant decrease in oil viscosity. In this case, the acoustic boundary thickness decreases and microflows are likely to occur in the pores.
Table 1. Acoustic boundary thickness (in 10^{-5} m)

| Fluid               | Frequency, Hz |
|---------------------|---------------|
|                     | 1  | 10  | 20  | 30  |
| Water               | 3.3| 0.9 | 0.7 | 0.6 |
| Oil (if $\mu = 10^{-2}$ Pa·s) | 10.0| 2.8 | 2.2 | 1.8 |
| Oil (if $\mu = 2 \times 10^{-2}$ Pa·s) | 14.0| 4.0 | 3.0 | 2.6 |

With the oscillatory movement of the liquid, the heterogeneity of the pore space leads to the fact that when a fluid element moves forward the amplitude will not be equal to the amplitude to occur when it moves backward. This happens when the displacements are commensurate with the typical length of the pore space articulation. If we take the value of the average pore diameter (10–17 μm) as the latter, then such effects require enormous acoustic intensities (hundreds of kilowatts per 1 m).

However, in addition to the size, the transitional length from a narrow to a wide pore is also significant. With a sharp transition (for example, in fractured reservoirs or reservoirs with angular neo-rounded grains), the articulation parameter can be several micrometers. In these media, the acoustic intensity should be of the order of several tens of kilowatts per 1 m².

The above effect on water drive in an acoustic field is confirmed by experimental data [5, 6]. The water drive was studied experimentally with a low-frequency (50 Hz) elastic effect. The oil recovery in the elastic field increased by 8%. The liquid was found to propagate deep in the fractures and capillaries in the ultrasonic field.

The surface forces at the fluid–formation boundary are also crucial in the filtration processes. The chemical composition of the pore surface is heterogeneous due to differences in rock-forming minerals and due to surface impurities. Hence, the surface forces acting on the fluid in different parts of the surface will be different. In this regard, fluid motions in the pore space near the surface can be represented as the movement in a varying potential field.

The most important role in the movement of a fluid is played by electric and molecular forces, as well as the friction force. The charge of the pore surface is very heterogeneous. Some patches are charged predominantly positively, while others are negatively charged. Similarly, some micro-areas of the surface are well wetted by liquid, while others are poorly wetted.

Acoustic impact on the fluid motion with the varying wettability of local patches of the pore surface is closely related to the wetting hysteresis. It is especially significant when various fluids are in contact in developed pore channels and resides in the fact that the advance angle of the meniscus is greater than the retreat angle. This phenomenon is due to the fact that when the meniscus (or a homogeneous liquid) moves ‘back’, the solid surface is wetted by the advancing liquid. The ‘forth’ movement occurs immediately on the wetted surface. In the acoustic field, the meniscus oscillates and due to the wetting hysteresis the surface in front of the meniscus is already wetted by the moving (displacing) liquid.

For this reason, the acoustic field will promote the advancement of water and the displacement of oil in hydrophilic reservoirs, and the other way around – in hydrophobic reservoirs.

A series of experiments [7, 8] are aimed at the filtration based on porous media models. With the acoustic intensity of several hundred kilowatts per 1 m², there was an increase in the filtration of water and oil through a reservoir model. The authors explain a powerful increase (up to 18 times) of filtration in sandstone caused by the pressure of sound radiation (radiation pressure) and an increase in the number of pores in which the flow deviates from the Poiseuille law. With increasing temperature, the viscosity of oil decreases, which contributes to the reduction in the critical pore diameter. Thus, the fluid movement in its entirety deviates from the classical law in smaller pores.

The study also involved the flow of various liquids – polar and nonpolar (benzene, gasoline), dielectrics and electrolytes (salt solutions) – in an acoustic field with an intensity of 1.9 kW/m² and a frequency of 17 kHz. The filtration rate of liquids having a large dipole moment or low electrical
conductivity was found to increase significantly. At constant hydrodynamic pressure, the increase in filtration is directly proportional to the intensity of the sound field.

Experimental studies were also conducted to evaluate the effect of electric (constant or variable) fields and their combinations with acoustic fields on the filtration characteristics of formations (Fig. 1). Constant electric fields with an intensity $E$ up to $3.5 \text{ kV/m}$ and pressure gradients of $0.87 \text{ MPa/m}$ increased the permeability of the samples by no more than 4 times (Curve 1, Fig. 1). The combination of constant electric ($3 \text{ kV/m}$) and acoustic ($3 \text{ kW/m}^2$) fields made it possible to increase the permeability effect with a pressure gradient in the sample $\Delta P = 100 \text{ MPa/m}$ up to 3.5 times (Curves 2 and 3).

Figure 1. Ratio of formation permeability in acoustic field and gas permeability versus electric field strength

The effect of the acoustic field in combination with a constant electric field makes it possible to increase the processing efficiency by several times as compared with the case when there is no electric impact. The restoration of permeability in ultrasonic and electric fields is obviously associated with the destruction of the diffusion part of the double electric layer in stagnant zones, which reduce the effective cross sections of capillaries.

4. Conclusion
The paper addresses various physical processes occurring in saturated porous media in an acoustic field. In particular, mass transfer of fluid in the formation occurs more intensively when exposed to an acoustic field.

Thus, medium and high acoustic fields (an intensity of over $10 \text{ kW/m}^2$) within the kilohertz frequency range, feature increased permeability of saturated porous media, associated with the advanced mass transfer. With gas bubbles to be present in the liquid, microflows arising in small pulsating bubbles can apparently play a certain role in such mass transfer.

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