INFLUENCE OF THE VIBRATION ON THE ABSOLUTE PERMEABILITY OF POROUS MEDIA SATURATED WITH WATER

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Abstract. *In the present work, the effects of mechanical vibration on the absolute permeability of porous media saturated with water were experimentally verified for the case in which there is superposition of a uniform flow externally imposed to the vibration. After the identification of a driving range within which indirect effects of the vibration – such as those due to ultrasonic heating of the system and to the mechanical disintegration of the rock matrix – are excluded, it was possible to verify that the vibration, at ultrasonic frequencies, reduces the pressure drop across the sample, and reduces, in transient state, the flow rate through the sample. The combination of magnitude of these two effects may result in an increase in absolute permeability, being such changes dependent on the velocity of the flow externally imposed besides being also a function of the frequency. Analysis of the problem according to the acoustics approach permitted formulating a physical model based on the concept of the viscous skin depth inversely proportional to the oscillation frequency. The mechanism is consistent with the obtained experimental results, making it possible to suppose that the effects result of the fact that the acceleration introduced by the vibration, changes the viscous friction between the solid and liquid phases which compose the solid lattice and the fluid that fills the porous medium and flows through it.*

Keywords*: porous media, absolute permeability, mechanical vibration, ultrasound, viscous skin depth*

1. Introduction

Porous media are present in natural and in artificial accumulations – such as aquifers, petroleum reservoirs, and infiltrations in buildings or implants in organisms for a continuous liberation of drugs.

Capillary forces control imbibitions, being the permeability one of the basic properties of the porous medium. Permeability is a measure of the capacity of the medium to transmit fluids, and is proportional to the conductivity of the porous medium to the flow of a fluid. In the definition given by Darcy's law (Amyx, 1960), analogous to Poiseuille's law, permeability relates the pressure gradient, which causes a liquid with certain viscosity to flow with a given velocity. Absolute permeability is that determined when a single-phase fluid that occupies the whole void volume of the porous medium, flows through it under conditions of viscous flow.

Some references in the literature mention the dependence between the absolute permeability and the frequency of vibration of a porous medium. The importance of gaining a better understanding of such variation lies in the fact that this might contribute to the development of yet other techniques for the additional recovery of fluids stored in porous media.

Our preliminary experimental results showed that some effects other than those of direct interest for this work may result of the ultrasonic irradiation of the porous medium, mainly the heating due to dissipation of the ultrasonic energy for prolonged periods, and the partial destruction of the solid matrix by the flow field. Selection of samples with higher mechanical resistance – which also possess lower nominal permeability – and the adjustment of test conditions that could lead to an appreciable effect, within a short period of irradiation, permitted the isolation of an effect of the mechanical vibration on the hydrodynamic properties not related to the heating or disintegration of the porous medium. This can be assured because the observed effects proved to be instantaneous and reversible. On the other hand, analysis of the problem according to acoustics theory permitted the identification of a satisfactory explanation for the experimental results obtained.

Thus, besides the experimental verification of the effect of the frequency of vibration, this work proposes a physical model describing how the absolute permeability changes with vibration in a saturated porous medium through which a uniform flow also occurs.

Changes in the permeability itself or in the flow rate through porous media under vibration mentioned in the literature range from the behavior of water or oil wells after earthquakes to laboratory scale. There are also a wide variety of conditions under which the observations may have been made, such as, under constant flow rate or under constant pressure; under conditions of single-phase flow or under some proportion of multiphase flow; vibrating the sample supported over the vibration source or with the vibrations source coupled to the sample's inlet face, such as the configurations used by Fairbanks and Chen (1971) or by Poesio *et al*. (2002). The idea is that supporting the sample over the vibrations source constitutes a way of simulating the transmission of vibrations produced in the surface to the subsurface reservoir rock. Coupling the source to one of the faces of the sample would simulate bottom hole applications. In the field scale, surface applications are usually used to stimulate not too deep reservoirs, up to 1500 m.

In a comprehensive review, Beresnev and Johnson (1994) observe that the existing papers in general contain experimental verifications of the fact that, most of the times, the application of elastic waves causes an increase in the absolute permeability of saturated porous media and an increase in the permeability to oil – apparently if this happens to be the less abundant phase in relation to the water saturation. But they list reports of cases in which the effect results indifferent and even negative, depending on the frequency and on the state of saturation of the porous medium.

Fairbanks and Chen (1971) verify experimentally that the ultrasonic irradiation promotes an increase in the flow across a porous medium. The increase proved to be dependent on the driving frequency. They observe an increase in the temperature during the irradiation of the system, but find that the increase in the flow rate is much greater than what could be attained only due to the respective decrease in the viscosity of the liquid if the flow is supposed to remain of the viscous type. Thus they propose that the phenomenon is one of a capillary nature and speculate that the effect of the ultrasonic irradiation is to cause a decrease in the solid-liquid interfacial tension in the system. On the other hand, Poesio *et al*. (2002) notice that high power (2,0 kW and 0,7 kW) elastic waves, with frequencies of 20 kHz and 40 kHz respectively, applied with an acoustic horn in a direction parallel to the flow, have a significant effect on the pressure gradient of the constant rate flow through samples of the Berea sandstone with permeability ranging from 100 mD to 300 mD (1 *darcy* (D) = $9{,}869 \times 10^{-13}$ m^2). They concluded that the pressure gradient reduction is only due to the heating produced by the dissipation of ultrasonic energy in the fluid with the consequent reduction of its viscosity.

Cherskiy *et al*. (1977) verify experimentally an increase in permeability as a direct function of the intensity of the ultrasound applied simultaneously to a steady flow through the porous medium Vogler and Chrysikopoulos (2002) verify experimentally that the application of acoustic waves with frequencies from 60 to 245 Hz to the flow through porous medium under constant pressure gradient improves the transport of solute in relation to the transport promoted only by the flow. Iassonov & Beresnev (2003) notice that low intensity (0,2 to 125 W/m^2) elastic waves with frequencies up to 100 Hz improve the flow of fluids through porous media mainly as referred to the multiphase flow in which one non-aqueous liquid phase is displaced by the aqueous phase. Westermark *et al*. (2001) list several papers reporting the application of vibrations under a wide range of frequencies – from 1 Hz to 5 MHz – and describe a down hole tool capable of producing vibrations up to 200 Hz with which they intend to carry out field-scale tests. They present experimental results showing that there is better oil recovery – under water injection – from porous media submitted to vibrations, and even better recovery if the vibration is intermittently applied.

Aarts *et al*. (1999) attribute an ultrasound-induced flow in a capillary tube filled by a liquid – experimentally verified – to the deformation of the pore wall, under the form of transverse waves, producing a peristaltic mechanism of transport. However, they notice that the mechanism was not capable of totally explaining the phenomena, for example regarding the results upon changes in rigidity of the capillary wall.

While satisfactory physical models have not been proposed for explaining the observed effects of the mechanical vibration on the permeability of saturated porous media, on the other hand linear continuum mechanics permits relating the modes of propagation of elastic waves to the physical properties of the propagation medium. This way, it becomes possible to predict that if, for example, low-amplitude, compression waves (also named *P*-waves or longitudinal waves) are incident upon an elastic, homogeneous and isotropic solid – and/or shear waves (also named *S*-waves or transverse waves) – then waves of the same nature (*P* or *S*) will propagate through the solid with amplitudes, velocities, frequencies and phase angles proportional to the mechanical properties of the solid, *i. e*., proportional to the deformation characteristics of that solid under the specific configuration of application of stresses.

Biot (1956a, b) extends these principles of propagation of mechanical waves through continuous media by formulating the theory as applied to saturated porous media. The theory predicts that besides the compression (*P*) wave and the shear (*S*) wave, a second compression, slower wave (thus more sensitive to attenuation), also named slow *P*-wave will propagate. This is due to the differential deformation between the continuous and interpenetrated solid and liquid phases of which the system is composed.

As we will may conclude, the mechanism that gives rise to the second-type *P*-wave constitutes a change of the viscous friction between the solid and liquid phases, which is responsible for the change in the pressure gradient associated to the movement of the liquid through the porous medium.

2. Interfacial tension

The free surface of a liquid in contact with a solid adheres to the solid surface if the intermolecular, attractive interactions in the solid-liquid interface are higher than the intermolecular attractive interactions within the fluid (Probstein, 1994). The solid-liquid interfacial adhesion due to surface tension forces are given rise to balance the contact between different phases, and is more intense the higher the interfacial tension in relation to the surface tension of the liquid – or the lower the contact angle, θ, between the solid and the liquid –, as given by the Young's equation, $\cos\theta = \dfrac{\sigma_{sg} - \sigma_{ss}}{\sigma}$, where σ is the surface tension (or liquid-vapor interfacial tension), σ_{sg} is the solid-gas interfacial tension, and σ_{sl} is the solid-liquid interfacial tension. Thus, the interfacial adhesion due to interfacial tension forces is an interaction of a static nature and does not play any role in the single-phase flow through porous media.

3. Interfacial friction

When there is either a uniform movement of the solid phase, with velocity $\dot{u}$, relatively to the liquid phase, or a movement of the liquid phase, with velocity $\dot{U}$, relatively to the solid phase, a friction force, of viscous nature, is given rise at the interface, because this is the case of the viscous transport of momentum between the phases (Probstein, 1994). This force is given by

$$F = \beta\dot{u}\,, \tag{1}$$

or $F = \beta\dot{U}$, since $\dot{U} = \dot{u}$, in this case. The resulting action of this force also manifests as an interfacial adhesion, causing one phase to drag the other. The interfacial friction – or drag – force is, thus, an interaction of a dynamic nature.

If besides being viscous the liquid is also incompressible, then the substitution of the uniform displacement by the vibration of an interface changes the interfacial drag force. In this case, if the interface is taken to be an infinite plane, it will be sufficient to represent the change in the interfacial friction as a change in the friction coefficient, thus resulting (Landau, 1987):

$$F(t) = \left(\beta_1 + i\beta_2\right)\dot{u} = \beta_1\dot{u} - \frac{\beta_2}{\omega}\ddot{u}\,, \tag{2}$$

where the vibration substituting the uniform movement of the interface is represented by the harmonic movement of the solid surface, given by

$$\dot{u}(t) = \dot{u}_0\cos\left(\omega t + \gamma\right). \tag{3}$$

Thus, the introduction of an accelerated movement in the interface changes the adhesion between the phases, due to the interfacial friction, and phases out this force in relation to the velocity of the mobile phase – in this case the solid surface with velocity $\dot{u}$.

The out of phase component of the interfacial friction force corresponds to the inertial reaction of the liquid phase to being dragged by the solid phase and, actually, constitutes a differential movement of the liquid phase (with velocity $\dot{U}$) in relation to the solid phase (with velocity $\dot{u}$) as will be seen in the following.

4. Vibrant liquid skin

The vibration of the solid-viscous liquid interface, to which the change in interfacial friction is associated, also causes the change in the viscous, interfacial momentum transfer, giving rise to a longitudinally vibrating liquid layer instead of the uniform drag of the liquid phase – *i. e.* a vibrant liquid layer with depth $\delta_s(\omega)$, contiguous to the solid surface. Since if it is considered that the solid phase is the mobile phase with velocity $\dot{u}$, then the momentum transfer transverse to the solid surface – *i. e.*, within the fluid – is given by (Landau, 1987):

$$\dot{U}_y(x,t) = \dot{u}_0\, e^{-\frac{x}{\delta_s}}\, e^{i\left(\frac{x}{\delta_s} - \omega t\right)}, \tag{4}$$

where $\delta_s(\omega) = \sqrt{\dfrac{2\mu}{\rho_f \omega}}$, which means that gradient of velocities $\dot{U}_y(x,t)$ of the vibrant, viscous liquid skin $\delta_s(\omega)$ decays exponentially from the solid surface to within the fluid.

5. Transition frequency within capillaries

A consequence of the vibrant viscous skin on the movement of the liquid comes when the oscillating solid-liquid interface is not an infinite plane but a capillary tube filled by the viscous liquid: the vibrant layer forms an annular with depth $\delta_s(\omega)$, contiguous to the inner wall of the capillary with radius *a*, giving rise to a transition frequency, ω_t, given by:

$$\omega_t = \frac{2\mu}{\rho_f a^2}. \tag{5}$$

While the vibration frequency is low enough for it to be around the value of ω_t, so that the vibrant skin depth is greater than, equal to or of the order of *a*, the vibrating skin spans the distance of the diameter of the capillary tube. The amplitude decay in velocity within de fluid is given by $\dot{U}_y(x,t)$ (Eq. (4)), which may be taken as approximately parabolic. Within this low frequency range all of the fluid along the capillary's diameter is viscously coupled to the vibration of the capillary, and the pressure gradient along the capillary's length, associated with the movement of the liquid, is of the type given by Poiseuille's law (Bird, 1987),

$$\dot{U}_{ext,y}(x) = \frac{x^2}{4\mu}\left(1 - \frac{x^2}{a^2}\right)\frac{\partial p}{\partial y}, \tag{6}$$

which linearly relates the pressure gradient to the velocity of movement of the liquid within the tube, predicting a parabolic profile of transverse distribution of velocities.

At frequencies greater than ω_t the movement of the liquid deviates from the Poiseuille-type and, as frequency gets higher, an ever increasing fraction of the fluid mass within the capillary is free of the influence of the vibration transmitted via the interfacial friction.

To our best knowledge, the pressure gradient associated to this vibrant liquid movement within the tube has not been directly treated throughout the literature, mainly in the high frequency range, in which the gradient of velocities does not span throughout the capillary's diameter. Indirectly, however, there is the acoustics treatment, which describes the analogous propagation of elastic disturbs through saturated porous media.

6. Acoustics approach

The mathematical modeling developed by the acoustics approach is not concerned with the problem of the effect of the vibration on the pressure gradient associated to the movement of the liquid phase through porous media, because the pressure gradient is undetectable by usual acoustic methods – these consist of the detection of displacements. Neither is the formation of the vibrant viscous skin detectable by acoustic methods.

Yet, according to the acoustics approach, within the low frequency range, at frequencies lesser than ω_t, the Poiseuille-type interfacial friction causes that the movement of the fluid out of phase with – *i. e.*, which takes place relatively to – the solid surface behaves as the slow diffusion of a pressure dissipation in the direction of propagation of compression disturbs (with velocity V_{P1}) through the system.

Within the high frequency range, at frequencies greater than ω_t, the deviation in interfacial friction from the Poiseuille-type implies that the movement of fluid relatively to the solid surface – and out of phase with it – behaves as the propagation of a true compression (longitudinal) wave, in the direction of propagation of the compression disturbs through the system and with a velocity of propagation of an order comparable to theirs.

In both frequency ranges the movement of the liquid phase (with velocity $\dot{U}$) out of phase with the solid surface (with velocity $\dot{u}$) constitutes the propagation of a second type of compression disturb (with certain diffusion coefficient (Plona, 1980), within the low frequency range, or with velocity V_{P2}, within the high frequency range) through the porous medium saturated with viscous liquid. For this reason, the acoustics of saturated porous media may be approximated, from a macroscopic point of view, as an equilibrium problem of a continuum composed by two continuous, interpenetrated phases.

For the same limiting problems, Jones (1962) considered only the description of the component of the interfacial, relative movement out of phase with the friction force as the propagation of a transverse wave – *i. e.* a wave from the solid surface to within the fluid. This additional wave is given rise within the saturated porous medium under vibration and to which an external uniform flow, $\dot{U}_e$, is superposed. He did not consider the problem of predicting the effect of an additional wave on the pressure gradient across the porous medium. Jones' study does not divide the behavior of such additional shear wave, say V_{S2}, into low and high frequency ranges. Such a wave would be equivalent to $\dot{\delta}_s$.

Thus, the change in the pressure gradient is a result of the change in the interfacial friction associated with the out of phase movement between the solid and liquid phases in viscous contact. These are the same mechanisms initially described – and experimentally verified – by the acoustics approach of the problem. In this sense, the analogy between the problems will make it possible that flow experiments come to constitute an indirect method for the verification of Jones' V_{S2} wave.

7. Porous medium

When the solid-liquid interface is used to represent the saturated porous medium through which a uniform flow, with velocity $\dot{U}_e$, externally imposed takes place, the interfacial friction (Eq. (1)) gives rise to the pressure gradient as given by Darcy's law (*e. g.* for one-dimensional flow):

$$\frac{\partial p_e}{\partial x} = \frac{\mu}{K}\dot{U}_e, \tag{7}$$

which makes it possible to approximate the porous medium, from a macroscopic point of view, as a bundle of tortuous, interconnected capillaries.

In this case, submitting the saturated porous medium through which an externally imposed, uniform flow takes place to the vibration $\dot{u}(t)$ reduces the pressure gradient to

$$\frac{\partial}{\partial x} p_e(t) \propto F(t) = \beta_1\left(\dot{U}_e - \dot{u}\right) - \frac{\beta_2}{\omega}\left(\ddot{U}_e - \ddot{u}\right) \tag{8}$$

due to the change in interfacial friction. This is so because part of the pressure gradient $\frac{\partial p_e}{\partial x}$ associated to the uniform flow externally imposed, $\dot{U}_e$, is used to constitute the friction force (given by the inertial component in the last part of Equations (2) and (8)) associated to the formation of the vibrant liquid skin ($\delta_s(\omega)$).

In its turn, the formation of $\delta_s(\omega)$ is debited, in transient state, in $\dot{U}_e$. It means that, as part of the mass of fluid provided by $\dot{U}_e$ is utilized during and for the formation of $\delta_s(\omega)$, there is a transient reduction of $\dot{U}_e$ in the downstream face of the porous medium. This $\dot{U}_e$ transient at the downstream face of the porous medium is also due to the inertial term in Eqs. (2) and (8), to which a mathematical model has not yet been derived, to our best knowledge.

8. Experimental results

When performing experiments for the verification of the effects of vibrations on the saturated porous medium to which an external uniform flow is superposed (Pompeo, 2004), we indeed noticed that the transient of change in pressure gradient is followed by a transient reduction in flow rate at the outlet port of the sample, as can be respectively seen in the graphs of $p(t)$ and of $Q_s(t)$ shown in Fig. 1(a). [Data were acquired in a computer via the output of a pressure transducer and of a scale, respectively]

The transient reduction in $Q_s(t)$ seems to be related to the period of formation of the vibrant viscous skin ($\delta_s(\omega)$), whose depth is inversely proportional to the frequency of vibration. Data shown in Fig. 1(a) were acquired in experiments of injection of an aqueous solution in cylindrical samples of porous media constituted of sedimentary rocks (Brazilian Botucatu sandstone) fully saturated with the same fluid.

In a sample with absolute permeability K = 8 mD (1 *darcy* (D) = 9,869 $\times$ 10^{-13} m^2), the solution was injected, at constant rate, during 300 s, causing a pressure drop, $\Delta p(t)$, of approximately 48 PSI (330,86 kPa) to build up across the sample while the flow rate registered at the outlet face of the sample, $Q_s(t)$, was constant and equal to the injection rate at the inlet face, $Q_e(t)$ = 0.0225 cm^3/s. During the following 300 s (from 300 s through 600 s), the sample was submitted to an irradiation of frequency ω = 40 kHz, while the injection of brine continues superposed at the initial, constant value, Q_e. During the next 300 s the sample continues solely under injection of brine at the initial inlet Q_e.

Thus, it is possible to define relative variations of these variables as the ratio between the difference of the final and the initial values to the initial value, $\frac{\Delta X}{X} = \frac{X_f - X_i}{X_i}$, being the initial value that of the variable without the influence of vibration, and the final value that of the maximum variation registered under application of vibration.

The registered reduction in $Q_s(t)$ apparently only could be detected because of the association of the low initial permeability of the sample to the high frequency of vibration. But also mainly due to the measurement – and registering – of the flow rate at the outlet face of the sample along the time, $Q_s(t)$, as can be seen in Fig. 1(a).

In shorter tests (steps of 120 s) so that the samples did not undergo irreversible changes, some tendencies could be forwarded for the relative variation of the pressure drop (Fig. 1(b)) and of the relative variation of flow rate at the outlet face of the sample (Fig. 1(c)) as a function of the flow rate at the inlet face and providing variations in the initial permeability of the samples (8 mD and 70 mD) and in the frequency of the vibration sources (25 kHz and 40 kHz).
With these two sets of data, it was possible to calculate the relative variations of the absolute permeability of the samples under the respective test conditions, as can be seen in Fig. 1(d). Notice that there is an apparent tendency of decaying increase of the permeability, as a direct function of the external flow rate and as an inverse function of the frequency (within this narrow range). This trend seems to be able to evolve into increasing reduction of K, as in the case of the 8-mD sample under irradiation of 25 kHz. This kind of behavior has already been reported in the literature (Beresnev, 1994).

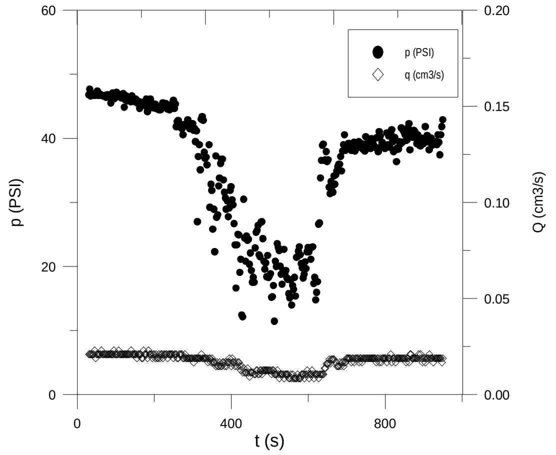
9. Conclusions

It is possible to draw the conclusion that the vibration, in this work tested within the range of ultrasonic frequencies, does affect the conditions of a uniform flow externally imposed to a porous medium saturated by the flowing viscous liquid.

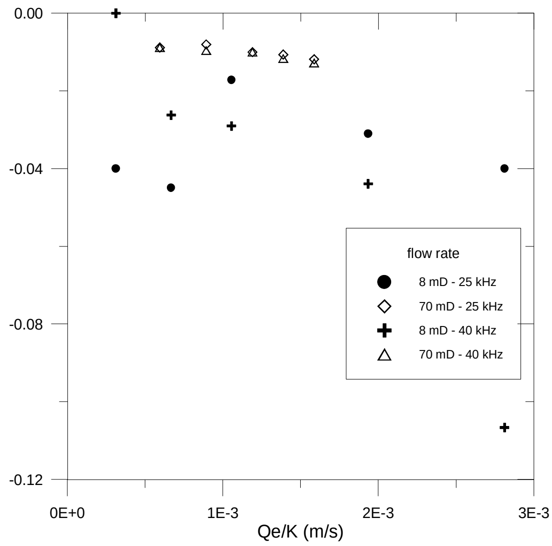
Analysis of the problem by means of the acoustics approach – and comparison with the experimental results – permits formulating the hypothesis that the acceleration introduced by the vibration promotes a viscous momentum transfer from the solid phase to the liquid phase, which, in steady state, changes the friction forces between the phases. The experimental results are consistent with the available phenomenological description.

Despite the argument according to which the vibration in the ultrasonic range may be of difficult implementation in eventual applications in field scale, this range seems adequate to the basic research, in laboratory scale, of the involved mechanisms.

In works to appear elsewhere we intend to extend the range of frequencies of vibration so as to include the sonic region, as a means of figuring out more broadly its effect on the variations in permeability. Perhaps under low frequencies the variation in Q_s is not as easily noticeable due to the probably much longer transient duration – with the lower rate of variation of $\Delta p(t)$ and, consequently, of Q_s –, neither perhaps will the amplitude of variation of Δp be that large. We also intend to model the transient formation of $\delta_s(\omega)$ and its influence on $Q_s(t)$ and consequences in $\frac{\partial}{\partial x} p(t)$.



(a)



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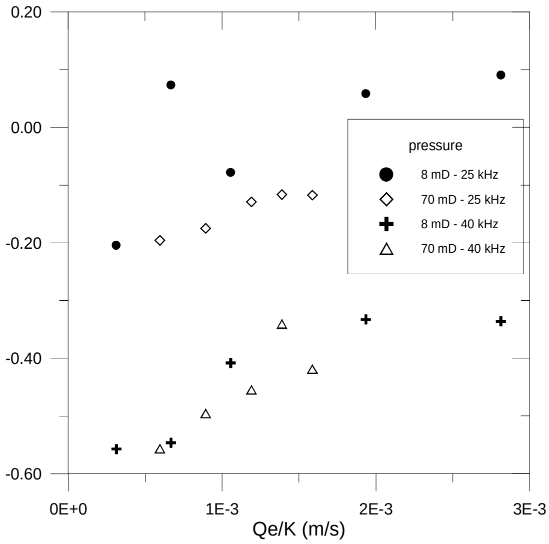
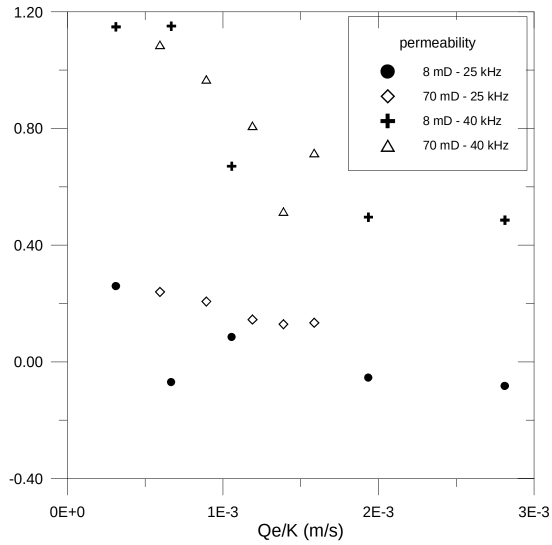


(b)



(d)

Figure 1. (a) – Buildup of the pressure drop, $\Delta p(t)$, and registering of the outlet face flow rate, $Q_s(t)$, during the brine injection experiment with constant inlet rate, Q_e. Beginning of irradiation at t = 300 s; end at t = 600 s. (b) – Relative variation of the pressure drop ($\frac{\Delta(\Delta p)}{\Delta p}$) as a function of the flow rate at the inlet face Q_e, given the changes in initial permeability K of the samples and of the frequencies of vibration. (c) – Relative variation of the flow rate at the outlet face of the sample ($\frac{\Delta Q_s}{Q_s}$) as a function of the flow rate at the inlet face Q_e, given the changes in initial permeability K of the samples and of the frequencies of vibration. (d) – Relative variation of the absolute permeability of the sample ($\frac{\Delta K}{K}$) as a function of the flow rate at the inlet face Q_e, given the changes in initial permeability K of the samples and of the frequencies of vibration.

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