CAPACITIVE PERTURBATIONS IN WELL INTERFERENCE TESTING

by Gunnar Bodvarsson, School of Oceanography, Oregon State University. Corvallis, Oregon 97331.

Introduction

Conventional well interference testing is applied to obtain observational data on reservoir parameters such as fluid conductivity, fluid diffusivity and structural inhomogeneities or boundaries. Test results are usually interpreted on the basis of forward type curve-matching methods (Ramey, 1970).

Field procedures are generally based on the use of standard size wells for both injection and response monitoring. The pressure sensors are placed into the wells that serve as observational ports. Obviously, the monitoring wells consititute capacitive inhomogeneities that can perturb the reservoir flow field and thereby distort the pressure readings. In particular, the capacitance of wellbores with two-phase fluids, gas caps or even a free fluid surface is relatively large and the perturbation can then be substantial. Quite erroneous test results may be obtained in such situations. Moreover, analog perturbations can result from the presence of inactive high-capacitance wells and other reservoir "soft spots" in the neighborhood of the test wells. For example, geothermal systems that appear liquid-dominated may actually include local spots with two-phase pore fluids that have a higher compressibility than the pure liquid. In particular, such soft-spots are likely to develop in regions with temperatures close to boiling and/or high gas content liquids.

As a matter of course, the capacitive effects are well known and are in the petroleum industry usually referred to as wellbore storage effects. A considerable literature exists, mainly relating to such effects in single-well pressure-buildup or drawdown testing (see, for example, Ramey, 1970; Earlougher and Ramey, 1973; Raghavan, 1976; Chen and Brigham, 1978; Miller, 1979). For further references, we refer to the monograph by Earlougher (1977). A number of aspects relating specifically to interference testing have been discussed by Prats and Scott (1975), Jargon (1976) and Sandal et al. (1979).

In passing, it is of interest to remark that sensor capacitance is a matter of extremely general relevance. For example, capacitive effects interfere withthe measurement of time-varying temperatures. Just as we refer to temperature gauges as thermometers, we will here apply the term pressometers for the pressure monitoring devices. In interference testing, the pressometer consists of the entire monitoring well setup.

The purpose of the present short note is to discuss the capacitive effects from a rather general point of view and, in partiular, to derive some basic expressions to enable us to correct for pressometer and soft-spot capacitance. The approach will be based on the assumption of a forward type interpretational procedure. In other words, the development is based on definite field models that lead to a well-posed problem setting. By varying the model parameters, the solutions yield the type-curves that are used to interpret field data. Data interpretation on the basis of so-called inverse procedures is usually not feasible and would lead to a practically impossible problem setting.

Notation and basic equations are as given in the paper by Bodvarsson (1978).

An ultrasimple model

In the case of slowly varying fields, well pressometers can quite often be lumped into an equivalent admittance (conductance) A and an equivalent capacitance C. That is to say, that given the ambient time-varying pressure field to be measured p(t) and the pressometer reading $p_m(t)$, the mass flow into the meter system satisfies the following equations

$$q = A(p-p_m), \qquad q = \rho C D p_m \tag{1}$$

where D = d/dt and ρ is the density of the fluid. Let $t_o = \rho C/A$ be the pressometer relaxation or response time and the above equations can then be combined into one equation

$$p_m + t_o D p_m = p \tag{2}$$

including only the parameter t_o. It is convenient to introduce the correction pressure p_1 that has to be added to p_m to obtain the ambient field p such that $p = (p_m + p_1)$. We have then the relation

$$p_1 = t_o D p_m \tag{3}$$

Depending on a number of circumstances such as the flow and phase situation in the well, the parameters A, C and t_o can be taken to be constant over a limited range of pressure. Equation (2) is then a simple differential equation in p_m and the relation (3) involves only a single differentiation.

In interference testing, we can usually take that pressure monitoring proceeds from an equilibrium situation where $p_m = p$ and because of linearity, we can then put $p_m(0) = p(0) = 0$, that is, the system is causal. In operational form, the solution of (1) is then

$$p_m = (1 + t_o D)^{-1} p \tag{4}$$

which yields a Taylor series in the operator $t_o D$.

An injection/monitoring well pair in a distributed reservoir model

Consider now a more general situation involving a porous and permeable fluid-saturated reservoir model with a given fixed boundary Σ where prescribed conditions are to be applied. Let $c = \beta/\nu$ be the fluid conductivity operator where β is the formation permeability operator and ν the kinematic viscosity of the fluid. The density of the fluid is ρ, the wet formation capacitivity or storage coefficient is s and hence the fluid diffusivity $a = c/\rho s$. Let $P = (x,y,z)$ be the general field point.

Two wells have been drilled into the reservoir, one for injection purposes and the other is to be applied as a pressometer that is assumed to have a known capacitance C taken to be constant within the pressure range of interest. Moreover, the distance between the two wells is taken to be very large compared with the dimensions of the formation/well contact openings such that for mathematical convenience the injection zone, as seen from the monitoring well, can be lumped into a point Q. This situation is easily generalized to the case of a distributed source.

The problem setting is now the following. The system is initially in equilibrium and starting at $t = 0$ the mass flow $f(t)$ is being injected into the reservoir at Q. In the case of fluid withdrawal the sign of $f(t)$ is negative. The fluid injection raises the reservoir pressure leading to the reading $p_m(t)$ at the pressometer well. We are interested in the pressure $p(P,t)$ at the monitoring well as unperturbed by the pressometer capacitance and will therefore derive the correction pressure p_1 such that at the pressometer $p = p_m + p_1$. As compared with the simple situation in the preceding section, the present case is more complex in that the correction pressure is a field function $p_1(P,t)$ that has to be derived by the integration of a diffusion type PDE.

To derive the pressure field equations, we simplify the topology of the reservoir by neglecting the conductivity perturbance of the pressometer and replace it by an equivalent capacity function $su(P)$ such that the space integral over this function is equal to C. Obviously, the function $u(P)$ is localized in that it is zero everywhere except at the pressometer well. Moreover, let $\Pi(c)$ be the generalized Laplacian that in the case of a homogeneous and isotropic medium simplifies to $\Pi(c) = -c\nabla^2$.

In this setting with the pressometer well included, the total pressure field $(p-p_1)$ satisfies the equation

$$\rho s(1+u)\partial_t(p-p_1) + \Pi(c)(p-p_1) = f\delta(P-Q), \tag{5}$$

where $\delta(P-Q)$ is the spatial delta-function centered at Q. The pressure field p unperturbed by the pressometer capacitance satisfies

$$\rho s\partial_t p + \Pi(c)\, p = f\delta(P-Q), \tag{6}$$

and hence the correction field p_1 satisfies

$$\rho s \partial_t p_1 + \Pi(c) p_1 = \rho s u \partial_t (p - p_1) \ , \tag{7}$$

To cope with this equation, we observe that the pressure within the pressometer is constant and equal to the observed pressure p_m. Since p_m represents the total field there, we take that $p_m = (p-p_1)$over the support of u(P) and equation (7) can thus be expressed

$$\rho s \partial_t p_1 + \Pi(c) p_1 = \rho s u D p_m \ , \tag{8}$$

where D = d/dt and the expression on the right is now a known function in space and time. Moreover, it is quite obvious that $(p-p_1)$ and p should satisfy the same boundary conditions on Σ and p_1, therefore satisfies homogeneous conditions there. It follows that equation (8) can be integrated to obtain the perturbation pressure p_1. Let the diffusion operator on the left of (7) be expressed

$$H = \rho s \partial_t + \Pi(c), \tag{9}$$

and H^{-1} be its inverse at the conditions specified. The solution of (8) is thus formally

$$p_1(P,t) = \rho H^{-1}(s u D p_m) \ , \tag{10}$$

This equation takes now the place of equation (3) which holds only in the much simplifed lumped case of constant A. In fact, in the case of fields varying so slowly that the time-derivative on the right of (7) can be neglected, equation (8) reduces to a potential equation that can be integrated to yield an expression for p_1. For the field pressure at the pressometer, this integral then reduces to the same form as (3).

It is of importance to remark that to correct the pressometer reading $p_m(t)$, the pressure $p_1(t)$ has to be evaluated at the source of this field. The result is therefore strongly dependent on the selection of a correct local model for the pressometer system. We will refrain from entering into a detailed discussion of the integral (10), and limit our remarks to perhaps the simplest case relevant in the present context. We assume a homogeneous and isotropic reservoir of such an extent that as viewed from the pressometer, it can be taken to be infinite. Moreover, the pressometer system consists of, or is equivalent to, a spherical cavity of radius R. To investigate the response of a system of this type, we turn to a spectral type of analysis and investigate the integral

(10) when $p_m = p_o \exp(i\omega t)$ and ω is the circular frequency. These assumptions simplify the procedure very considerably. Omitting details, we obtain for the amplitude of the correction pressure p_1 at the cavity

$$p_1 = i\omega\rho C p_o / A_s[(1+i)(R/d) + 1] , \qquad (11)$$

where C is the capacitance of the pressometer, $A_s = 4\pi cR$ its static admittance and $d = (2c/\rho s\omega)^{\frac{1}{2}}$ is the skin depth of the pressure field at the frequency ω. This expression is useful in that it gives the amplitude, of the spectral components of p_1. The dominant physical factor is the ratio R/d. Expression (11) is analog to (3) above.

Soft spots

As already stated, even small reservoir soft spots, that are sufficiently close to the pressometer, can perturb the pressure readings, For example, there may be an inactive well with a free liquid surface in the close vicinity of the monitoring well. Considering such a case that has a known capacitance K, we are interested in some estimates of the resulting perturbation of $p_m(t)$. Here, it is appropriate to make the simplifying assumption that multiple pressure field scattering can be neglected. In other words the secondary fields due to the pressometer and the soft spot do not scatter and their perturbation of the primary field is therefore additive. Hence, to obtain the perturbation due to the soft spot at the pressometer we can neglect the capactance of the pressometer.

Under these circumstances, it is possible to proceed in much the same way as above. Let $p_2(p,t)$ be the perturbation pressure field due to the soft-spot. The field has then to satisfy an equation of the same type as (7) above. There is, however, the important difference in that there is no monitoring device in the soft spot and the pressure there is now unknown. The integration expressed by (10) can therefore not be performed. There are nevertheless, the ameliorating circumstances that we are only interested in the value of p_2 at the pressometer. As viewed from this distance, details of the model at the soft-spot are less important and we can in many practically relevant cases resort to a perturbation approach where the pressure field at the soft-spot is taken to be equal to the primary field at this position. On this basis the integration prescribed by (10) can be performed by equating p_m with the primary field and we have then an estimate of p_2 that can be evaluated at the pressometer well.

A variety of situations are of practical interest, but we will refrain from a detailed discussion. A simple investigation on standard size wells shows that in interference tests, the action radius of inactive wells is relatively small. Beyond distances of the order of a very few hundred meters,open inactive wells can for the most practical purposes be neglected.

References

Bodvarsson, G., 1978, Mechanism of reservoir testing, 4th Workshop on Geothermal Reservoir Engineering, December 1978, Stanford University Stanford, California.

Chen, H.K., W.E. Brigham, 1978, Pressure buildup for a well with storage and skin in a closed square, J. of Petr. Tech., January, 1978, 141-146.

Earlougher, R.C., Jr., 1977, Advances in well test analysis, Soc. of Petr. Eng. of AIME, New York, N.Y., and Dallas, Texas.

Earlougher, R.C., Jr., and H.J. Ramey, Jr., 1973, Interference analysis in bounded systems, J. Can. Pet. Tech., Oct.-Dec., 1973, 33-45.

Jargon, J.R., 1976, Effect of wellbore storage and wellbore damage at the active well on interference test analysis, J. Petr. Tech., August, 1976, 851-858.

Miller, C.W., 1979, Wellbore storage effects in geothermal wells, Soc. of Petro. Eng. of AIME, SPE 8203.

Prats, M. and J.B. Scott, 1975, Effect of wellbore storage on pulse-test pressure response, JPT Forum, J. of Petro. Tech. 707-709.

Raghavan, R., 1976, Some practical considerations in the analysis of pressure data, J. of Petro. Tech., October, 1976, 1256-1268.

Ramey, H.J., Jr., 1970, Short-time well test data interpretation in the presence of skin effect and wellbore storage, J. of Petro. Tech., January 1970, 97-104

Sandal, H.M., Horne, R.N., Ramey, H.J., Jr., and J. Wright, 1979, Interference testing with wellbore storage and skin effect at the produced well, Soc. of Petro. Eng. of AIME, SPE 7454.