JOURNAL OF
ENVIRONMENTAL HYDROLOGY

The Electronic Journal of the International Association for Environmental Hydrology
On the World Wide Web at http://www.hydroweb.com

VOLUME 11 2002

DETERMINATION OF THE SKIN FACTOR IN THE EARLY PORTION OF AN AQUIFER TEST

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Unsteady flow to a single well fully penetrating a confined aquifer (homogeneous and isotropic) is analyzed. The well is assumed to be located in an infinite system; that is, the effect of boundaries is not considered. The line source solution presented first by Theis assumes that the storage capacity of the flowing well and skin region around the pumping well are negligible. For a "real" well, the effect of wellbore storage and skin on the pumping well is significant. If wellbore storage dominates drawdown data, and testing has been conducted long enough, two semilogarithmic straight lines can be obtained. If boundary effects do not interfere, then the second straight line is the "correct" line to be evaluated by semi-logarithmic analysis. In this contribution, a procedure for determination of the skin factor from pumping test data at a single well (no observation well is available) dominated by wellbore storage and the skin effect is presented.

INTRODUCTION

The additional resistances and finite volume of a wellbore are the two main factors which influence pumping test data measured at a well. The drawdown caused by additional resistance (the skin effect) was noted for the first time by van Everdingen (1953). Since then many authors in petroleum engineering and groundwater hydraulics have published articles giving their attention to the problem of the influence of skin effect and wellbore storage on the measured value of the real drawdown at a well. In 1970, Agarwal et al. (1970) introduced the idea of a log-log type curve matching to analyze pressure data at a well dominated by wellbore storage and skin effect. McKinley (1971) and Earlougher-Kersch (1974) presented two other type curve methods for analyzing this problem. A new method for evaluation of transmissivity, T, and skin factor, W, from the early time portion of pumping test data was published by Garcia-Rivera (1979).

Here we derive a method for the evaluation of skin factor, W, on a single well fully penetrating a confined aquifer (no observation well is available) from the early time portion of a pumping test. This method can be applied if the Jacob semi logarithmic part of pumping test is not achieved. The solution of the general partial differential equation of liquid flow through porous media in Laplace space was used. The Laplace transform was inverted in terms of algorithm 368 of Stehfest (Stehfest, 1970). Here we derive a correlation of the dimensionless intersection time as a function of the dimensionless wellbore-storage constant and skin factor.

THEORY AND ASSUMPTIONS

The following dimensionless parameters are used:

Dimensionless drawdown

$$s_{WD}(t) = \frac{2\pi T s_W(t)}{Q} \tag{1a}$$

where s_W is drawdown at a well, T is transmissivity, t is time, and Q is well discharge.

Dimensionless time

$$t_D = \frac{Tt}{r_W^2 S} \tag{1b}$$

where r_W is well radius and S is storativity.

Dimensionless radius

$$r_D = \frac{r}{r_W} \tag{1c}$$

where r is radial location.

Dimensionless wellbore storage constant

$$C_D = \frac{C}{2\pi\, r_W^2 S} \tag{1d}$$

where C is unit storage factor (Ramey , 1970).

Dimensionless skin factor

$$W = \frac{2\pi\, T\, s_W}{Q} \tag{1e}$$

Dimensionless intersection time

$$t'_D = \frac{Tt'}{r_W^2 S} \tag{1f}$$

where t' is intersection time.

THE SKIN EFFECT

The drawdown at a well depends on the resistance of the formation, the viscosity of the fluid and the additional resistance concentrated in an infinitesimally thin skin zone around the well. The additional resistance is due to hydromechanical, chemical, and biological factors that occur during drilling or completion operations, and during the exploitation of a well. These include such things as well perforations, partial penetration, fractures of various types, non-Darcy flow, and so on. This additional resistance causes an "additional" drawdown at a "real" well (here denoted s_{SK}). More details about the skin effect and its influence on pumping test data evaluation can be found in van Everdingen (1953) and Agarwal et al. (1970).

If the additional drawdown, s_{SK} is taken into account then the total drawdown at a "real" well can be written in the following form (Figure 1).

$$s_W = s_{TE} + s_{SK} \tag{2}$$

where s_W is measured drawdown at a "real" well, s_{TE} is drawdown at an "ideal" well (W = 0), and s_{SK} is additional drawdown at a well caused by additional resistance.

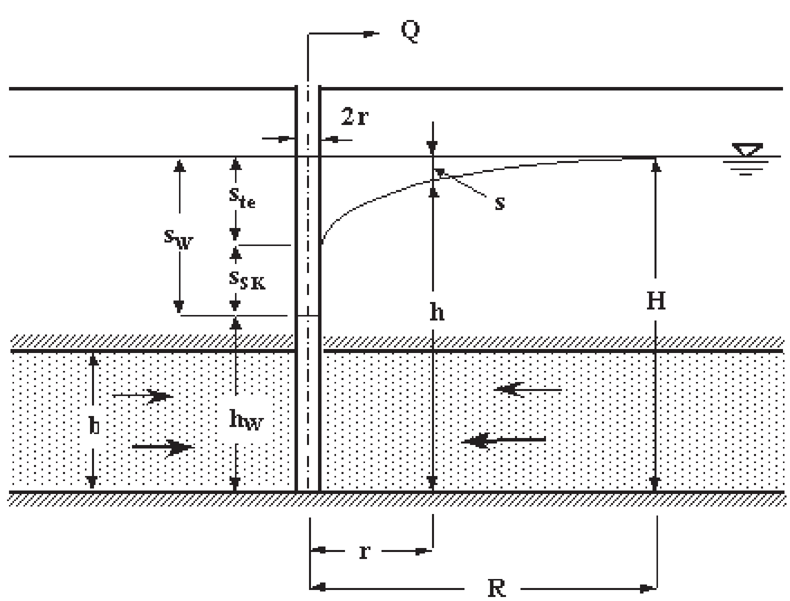

Figure 1. Drawdown around a production well with skin effect.

Equation (2) indicates that the drawdown at a "real" well differs from drawdown at an "ideal" one by an additive amount (van Everdingen, 1953):

$$s_{SK} = \frac{Q}{2\pi T} W \tag{3}$$

where Q is pumping rate, T is transmissivity, and W is skin factor.

WELLBORE STORAGE

Wellbore storage, also called wellbore loading or unloading, has long been recognized as affecting short-time transient hydraulic head behavior. Ramey (1970) discussed this problem in detail. When pumping starts (pumping rate Q = const.) the first liquid produced will be that stored in the well bore, and the initial flow rate from the formation to the well, Q_{IN} will be zero. With increasing flow time, at constant surface producing rate, Q, the down-hole flow rate will approach a constant value.

$$Q_{IN} = Q - C\frac{dh_V}{dt} \tag{4}$$

where Q_{IN} is flow rate from the formation to a well, Q is constant surface producing rate, and C is unit wellbore storage factor (Ramey, 1970).

The basic assumptions of the problem considered are identical to those examined by Agarwal et al. (1970). For the solved problem it is assumed that the aquifer is uniform, homogeneous and isotropic (gravitational forces are neglected). The well is located in an infinite system; that is, the effect of boundaries is not considered. The influences of wellbore storage and skin effect on pumping test data are taken into account.

The partial differential equation describing radial flow to a well fully penetrating confined aquifer is

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial s}{\partial r}\right) = \frac{S}{T}\frac{\partial s}{\partial t} \tag{5}$$

where s is drawdown and r is radial distance.

SOLUTION

Expressed in terms of the dimensionless variables (Equations 1 a, b and c), Equation (5) may be written in the form:

$$\frac{\partial^2 s_D}{\partial r_D^2} + \frac{1}{r_D}\frac{\partial s_D}{\partial r_D} = \frac{\partial s_D}{\partial t_D} \tag{6}$$

As was shown by Agarwal (1970), the complete solution to the problem under consideration may be obtained by the application of the Laplace transformation technique. The Laplace transform is inverted numerically using the Stehfest algorithm 368 (Stehfest, 1970). Wei Chun Chu (1980) proved that this algorithm may be used to numerically invert for skin factor $W > 0$ and dimensionless wellbore storage, $C_D > 100$.

Using a FORTAN computer program, values of dimensionless drawdown at a well, s_{WD} , were evaluated for a range of values of skin factor, W, (0, 2, 4, 6, 8, 10, 12, 15, 20, 25, 30, 35, 40, 45, 50, 60, 70, 80, 90, and 100) and dimensionless wellbore storage, C_D ,(10^2, $5x10^2$, 10^3, $5x10^3$, 10^4, $5x10^4$, 10^5, $5x10^5$, 10^6, $5x10^6$, and 10^7).

As can be seen in Figure 2, two semilogarithmic straight lines are obtained. They agree with the results obtained by Garcia-Rivera (1980). The second straight line represents part of the pumping test, which can be evaluated by means of the Jacob semilogarithmic method. The dimensionless intersection times, t_D', (dimensionless time where the first straight line in the semilog graph (s_{WD} vs. log t_D) intersects the axis log t_D (s_{WD} = 0, see Figure 2) were determined by means of the computer program. It was found that the dimensionless intersection time, t_D', is a unique function of the dimensionless wellbore storage constant, C_D, and the skin factor, W.

This correlation is shown in Figure 3. It is now possible to express the general equation of these straight lines in the form

$$t_D' = a_T W + b_T \tag{7}$$

where a_T and b_T are coefficients.

The coefficients a_T and b_T in Equation (7) for all straight lines were evaluated by the least squares method. As can be seen in Figure 3, these coefficients are functions of skin factor, W. The function dependence $a_T = f(W)$ and $b_T = f(W)$ were derived from the following equations:

$$a_T = \frac{n\sum_{i=l}^{n} W_i \left(t_D'\right)_i - \sum_{i=l}^{n} W_i \sum_{i=l}^{n} \left(t_D'\right)_i}{n\sum_{i=l}^{n} \left(W_i\right)^2 - \left(\sum_{i=l}^{n} W_i\right)^2} \tag{8a}$$

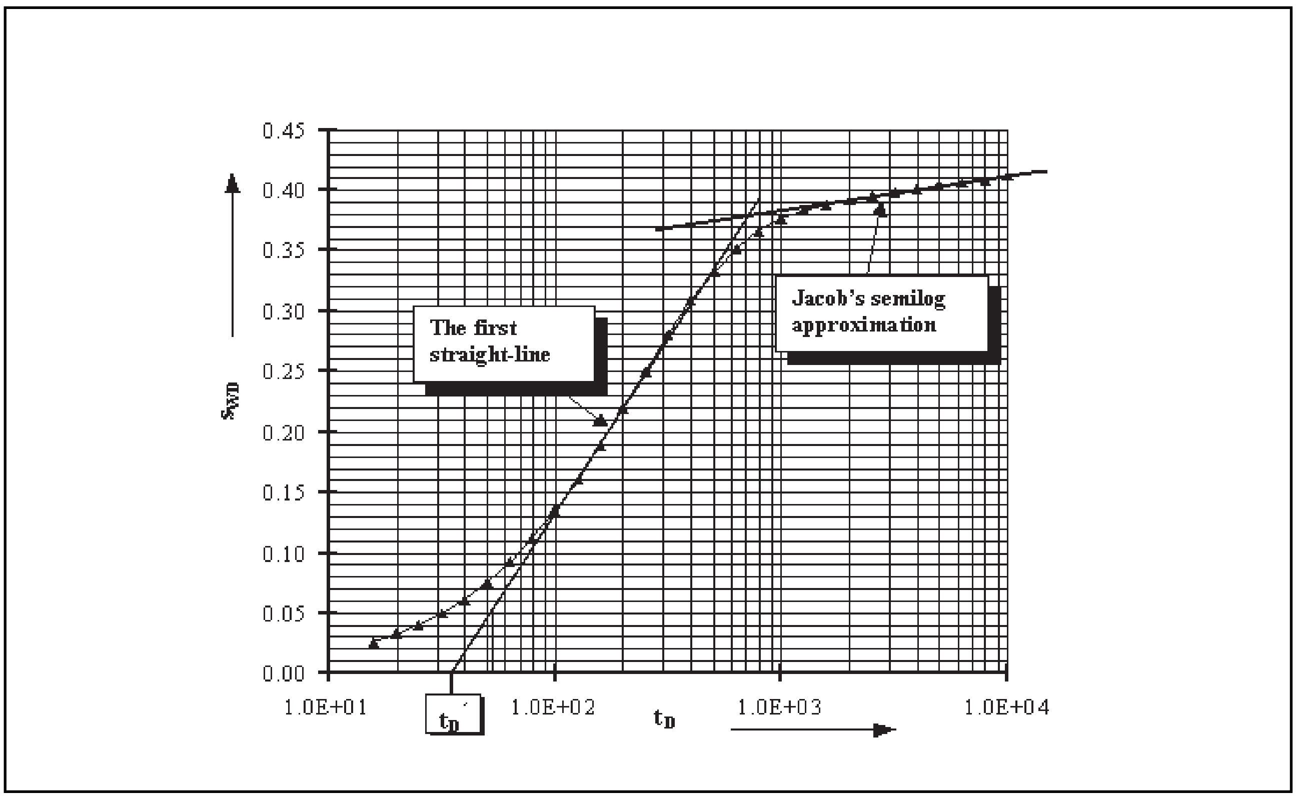

Figure 2. Graph of s_{WD} vs. log t_D for a wellbore storage and skin factor (for C_D=100; W=10).

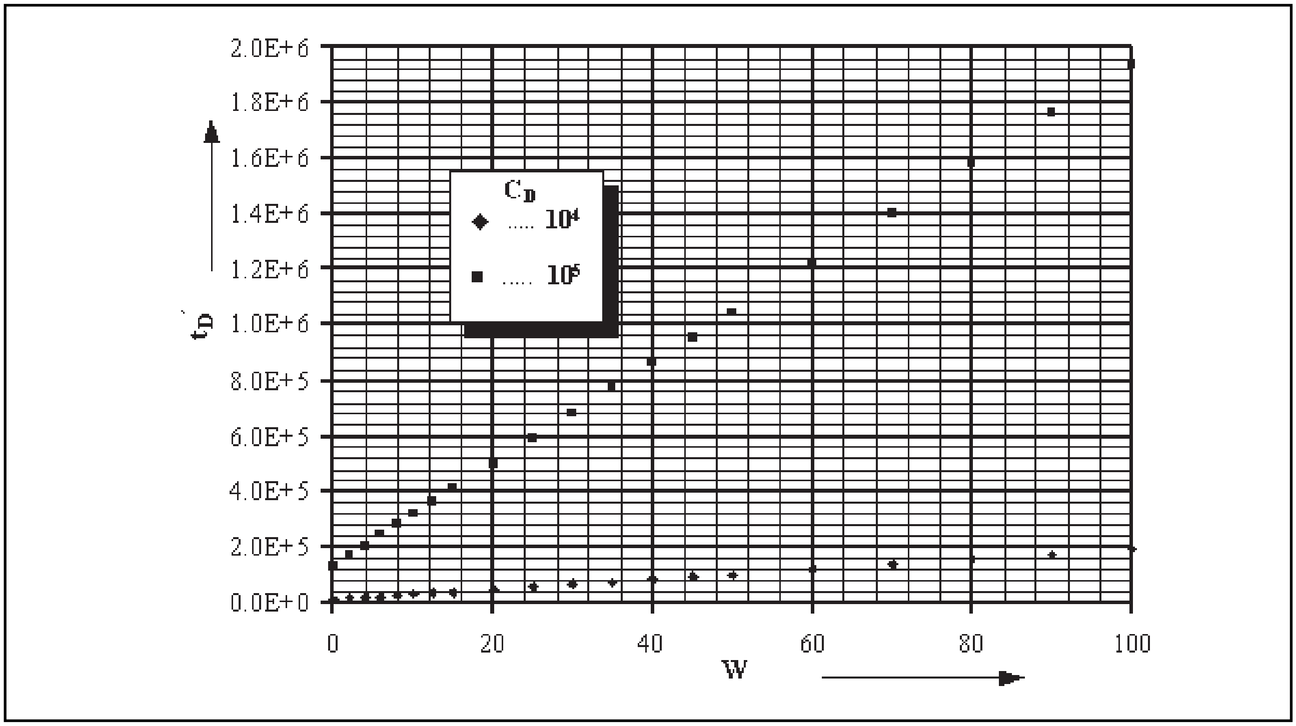

Figure 3. Graph of t_D' vs. W for C_D=10^4 and C_D = 10^5 .

$$b_T = \frac{n\sum_{i=l}^{n}(W_i)^2\sum_{i=l}^{n}\left(t_D'\right)_i - \sum_{i=l}^{n}W_i\sum_{i=l}^{n}W_i\left(t_D'\right)_i}{n\sum_{i=l}^{n}(W_i)^2 - \left(\sum_{i=l}^{n}W_i\right)^2} \tag{8b}$$

Evaluations are given in graphic form in Figures 4 and 5.

The straight lines in Figure 4 and Figure 5 can be expressed as

$$\log a_T = a_{1T}\log C_D + a_{2T} \tag{9a}$$

and

$$\log b_T = b_{1T}\log C_D + b_{2T} \tag{9b}$$

where

a_{1T}, a_{2T}, b_{1T}, and b_{2T} are coefficients.

Coefficients were evaluated from equations similar to (8a) and (8b). For a_{1T} and a_{2T} they have the forms

$$a_{1T} = \frac{n\sum_{i=l}^{n}(\log C_D)_i(\log a_T)_i - \sum_{i=l}^{n}(\log C_D)_i\sum_{i=l}^{n}(\log a_T)_i}{n\sum_{i=l}^{n}\left[(\log C_D)_i W_i\right]^2 - \left(\sum_{i=l}^{n}(\log C_D)_i\right)^2} \tag{10a}$$

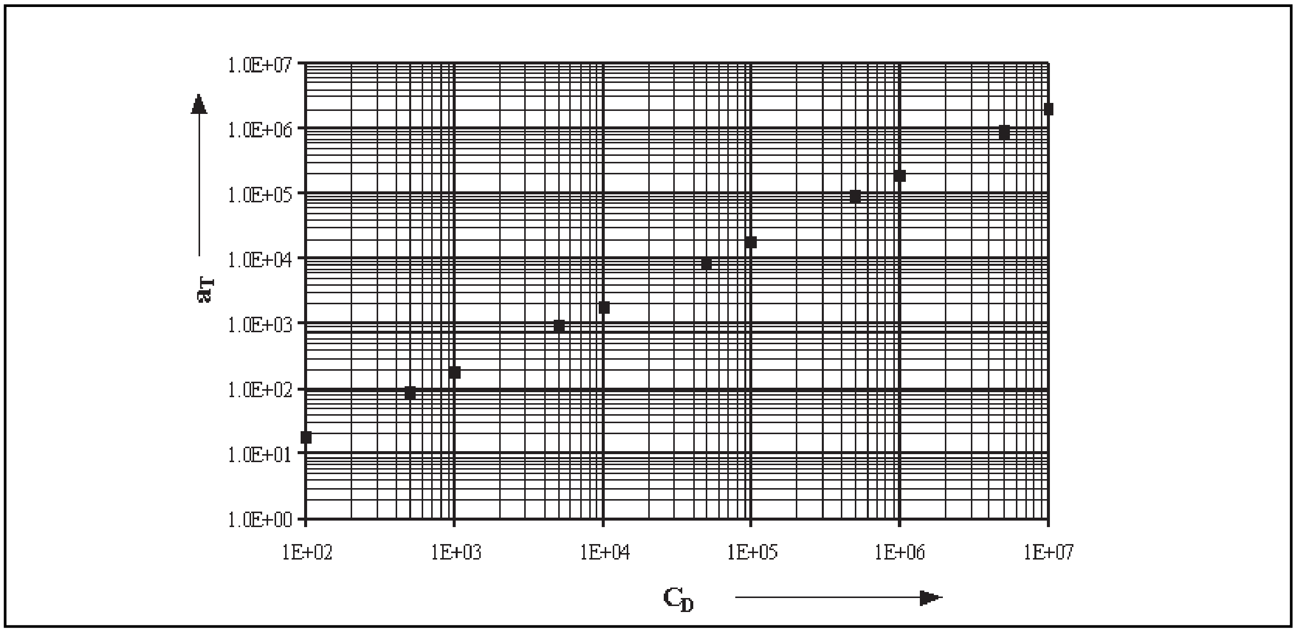

Figure 4. Graph of coefficient log a_T vs. log C_D.

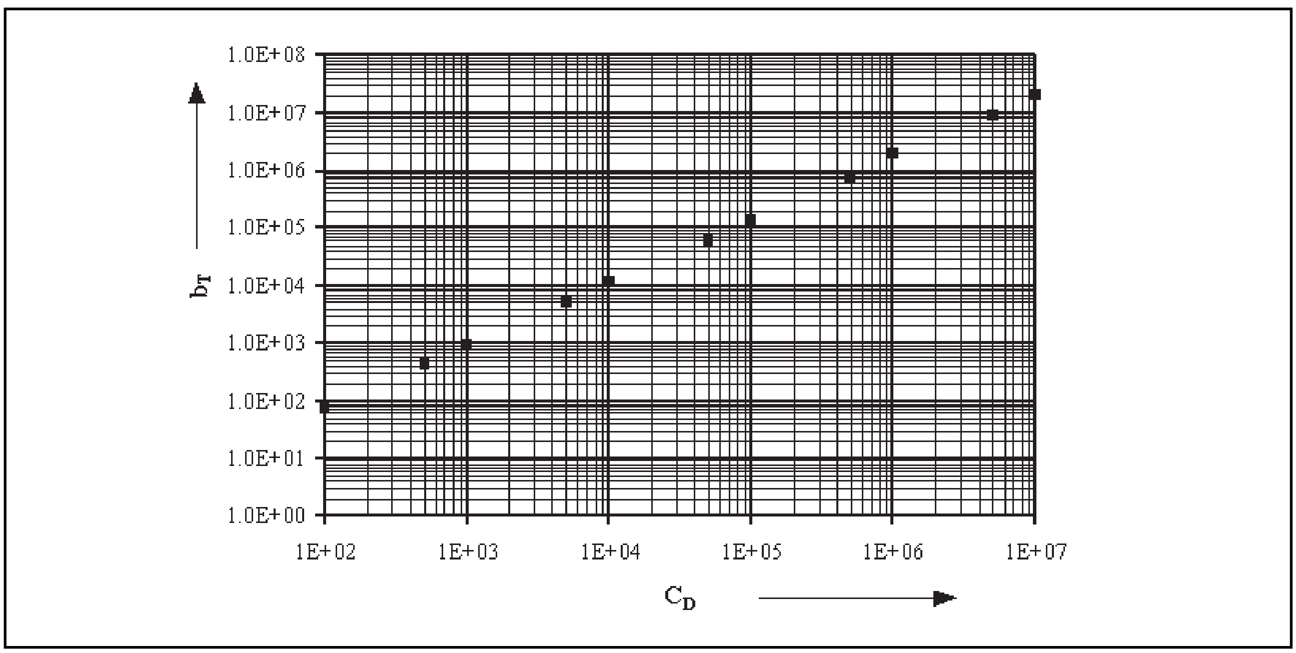

Figure 5. Graph of coefficient log b_T vs. log C_D.

$$a_{2T} = \frac{n\sum_{i=l}^{n}\left[(\log C_D)_i\right]^2 \sum_{i=l}^{n}(\log a_T)_i - \sum_{i=l}^{n}(\log C_D)_i \sum_{i=l}^{n}(\log C_D)_i (\log a_T)_i}{n\sum_{i=l}^{n}\left[(\log C_D)_i W_i\right]^2 - \left(\sum_{i=l}^{n}(\log C_D)_i\right)^2} \tag{10b}$$

By means of (10a) and (10b), a_{1T} and a_{2T} were evaluated:

a_{1T} = 1.0036

a_{2T} = -0.7553

By substituting a_{1T} and a_{2T} into (9a) and rearranging, we obtain

$$a_T = 10^{1.0036\log C_D - 0.7552} \tag{11}$$

Coefficients b_{1T} and b_{2T} were obtained from equations similar to (8a) and (8b)

b_{1T} = 1.0852

b_{2T} = -0.2821

Similarly we obtain:

$$b_T = 10^{1.0852\log C_D - 0.2821} \tag{12}$$

By combining (11) and (12) with (7) we obtain the dimensionless intersection time, $t_D^{'}$:

$$t_D^{'} = \left(10^{1.0036\log C_D - 0.7553}\right)W + 10^{1.0852\log C_D - 0.2821} \tag{13}$$

From Equation (13) the skin factor, W is given by:

$$W = \left[t_D^{'} - 10^{1.0852\log C_D - 0.2821}\right] / \left[\left(10^{1.0036\log C_D - 0.7553}\right)\right] \tag{14}$$

CONCLUSIONS

In this paper a correlation of the dimensionless intersection time, t_D' , as a function of the dimensionless wellbore storage, C_D , and skin factor, W , has been derived (Equation 13).

The derivation was done with utilization of an approximate solution of the general partial differential equation for the problem of radial flow in an extensive confined aquifer of uniform thickness to a single fully penetrating well pumped at a steady rate of flow. The solution was obtained by applying the Laplace transform and the Agarwal (1970) method, in conjunction with the algorithm 368 of Stehfest (Stehfest , 1970) approximate method of inversion.

Skin factor, W , is estimated from short-time transient test data by means of Equation (14).

To apply this method, it is necessary that formation transmissivity, storativity, and wellbore radius be known or evaluated. The test must must be conducted at a known constant flow rate.

ACKNOWLEDGMENTS

The author would like to thank Prof. Ing. Vladimir Havlik, Ph.D., Czech Technical University, Prague, for his review of this paper.

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