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AN INVESTIGATION OF THE INFLUENCE OF HIGH-VELOCITY FLOW ON THE TRANSIENT PRESSURE BEHAVIOR OF LIQUID-DOMINATED WELLS

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ABSTRACT

The present study on the influence of high-velocity effects on the flow of hot-water through porous media was undertaken based upon the analysis of tests taken in the Cerro Prieto and East Mesa fields. These fields produce form a sedimentary formation of the "homogeneous" (non-fractured) type. The study is based on a numerical solution to the radial flow (isothermal) problem of hot-water considering high-velocity flow. An expression for the rate dependent pseudo-skin effect term is derived. It is demonstrated through an integration of the Forchheimer flow equation and the simulation of drawdown tests that consider no skin damage that this pseudo-skin is essentially equal to the product Dw, where D is the turbulent term coefficient defined as $\beta k/2\pi r_w h\mu$ It is also shown that the semilogarithmic slope of 1.1513 characteristic of radial flow is obtained once a stabilized high-velocity condition is reached. The start of this straight line was found to be dependent on the intensity of high-velocity flow effects. For practical producing conditions found in the field, it was found that the start of the semi-log straight line can be predicted by the correlation of Ramey et al.; provided that the apparent skin effect s' is used instead of the skin factor s. This study also considers the influence of high velocity flow on pressure buildup tests. The effects of a finite formation skin and isothermic wellbore storage are also included in this work.

INTRODUCTION

The subject of high-velocity flow through porous media was first discussed by Forchheimer (1901). After this work a number of studies have addressed this subject, particularly oriented toward the laboratory verification of this phenomenon (Fancher et al., 1933; Johnson and Taliaferro, 1938; Green and Duwez, 1951; Cornell and Katz, 1953; Firoozabadi and Katz, 1979).

The influence of high-velocity flow in the transient pressure behavior of gas well tests has been thoroughly reported in the literature (Ramey, 1965; Wattenbarger and Ramey, 1968; Energy Resources Conservation Board, 1975). This effect has also been considered in two phase flow of oil and gas (Kadi, 1980). With regard to the flow through perforations, it has also been studied for gas flow (Tarik, 1984) and for two phase flow of oil and gas (Perez and Kelkar, 1988).

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Due to the high production rates commonly encountered in geothermal liquid-dominated wells, we suspected that conditions were proper for high-velocity effects to affect the transient pressure behavior of well tests. With this idea in mind, we analyzed testing conditions for the Cerro Prieto and East Mesa fields and found that this effect was present. These fields produce from a sedimentary formation of the "homogeneous" (non-fractured) type.

The purpose of this study is to present an analysis of the influence of high-velocity flow on the transient pressure behavior of liquid-dominated wells. Pressure drawdown and buildup tests are considered. The effects of skin damage and wellbore storage affecting the test simultaneously with high-velocity flow are also studied.

MATHEMATICAL DEVELOPMENT

Due to the fact that single-phase (steam or hot water) flow in geothermal reservoirs is essentially isothermal (Whiting and Ramey, 1969), transient pressure analysis techniques are ussually based on a strict analogy with the single-phase isothermal flow tecniques developed by petroleum engineers and hydrogeologists. The analysis techniques are based on solutions to the difussivity equation (Muskat, 1937; Matthews and Russell, 1967; Earlougher, 1977) which consider the following assumptions: a) flow of a constant compressibility fluid in a radial, horizontal, isotropic reservoir, b) applicability of Darcy's law, c) small pressure gradients, and d) rock and fluid properties are independent of pressure. For convenience, the solution to this reservoir fluid flow problem is ussually expressed in dimensionless form. The following groups have been defined by Ramey (1975) and

Ramey and Gringarten (1975), where α_w and β_t are unit constants:

Dimensionless pressure for hot-water reservoir flow (p_D)

$$p_D(r_D,t_D)=\frac{kh(p_i-p(r,t))}{\alpha_w \nu_{sc} w B \mu} \quad (1)$$

Dimensionless time (t_D)

$$t_D=\frac{\beta_t kt}{\phi \mu c_t r_w^2} \quad (2)$$

Dimensionless radial distance (r_D)

$$r_D=\frac{r}{r_w} \quad (3)$$

If a consistent set of units is used, then the constants will have a value equal to one. Table 1 (Samaniego and Cinco, 1982) shows some of the most used unit systems and the corresponding values for α_w and β_t.

Using the definitions of the dimensionless groups given by Eqs. 1-3, the equation that describes the flow of hot-water, considering the effect of high-velocity flow is given by Eq. 4:

$$\frac{1}{r_D}\frac{\partial}{\partial r_D}\left(r_D \delta \frac{\partial p_D}{\partial r_D}\right) = \frac{\partial p_D}{\partial t_D} \quad (4)$$

where δ is the L.I.T. (laminar, inertial and turbulence) correction factor. In the derivation of this equation and in all remaining equations of this section, a consistent set of units is assumed, resulting in values of the parameters α_w and β_t equal to $\frac{1}{2}\pi$ and unity, respectively. This is just for easiness in the derivations, but for field applications of the results of this study these unit conversion constants are very convenient.

The inner boundary condition considered in this study is of constant mass rate at the well, including the effects of skin damage and isothermic wellbore storage:

$$-\left(\delta \frac{\partial p_D}{\partial r_D}\right)_{r_D=1} = \frac{k}{k_s} - C_D \frac{k}{k_s}\left(\frac{\partial p_D}{\partial t_D}\right)_{r_D=1} \quad (5)$$

The external boundary condition is that of an infinite reservoir:

$$\lim_{r_D \to \infty} p_D(r_D,t_D)=0 \quad (6)$$

The initial condition is of uniform pressure at the reference time $t_D=0$:

$$\lim_{t_D \to 0} p_D(r_D,t_D)=0 \ , \ 1 \le r_D < \infty \quad (7)$$

This completes the mathematical model solved numerically in this study.

Next we present some additional mathematical aspects related to the high-velocity flow effects. First, we will comment on the way we handled Forchheimer's equation given by Eq. 8:

$$-\frac{dp}{dr} = \frac{\mu}{k} v_r + \beta \delta v_r^2 \quad (8)$$

where β is the velocity coefficient. This equation can be written in dimensionless form by means of the parameters defined by Eqs. 1-3:

$$\frac{dp_D}{dr_D} = v_{rD} + \beta_D v_{rD}^2 \quad (9)$$

where v_{rD} and β_D are a dimensionless velocity and a dimensionless velocity coefficient defined by Eqs. 10 and 11, respectively:

$$v_{rD} = \frac{2\pi h r_w}{\nu_{sc} w} v_r \quad (10)$$

$$\beta_D = \beta \frac{k}{\mu} \cdot \frac{w}{2\pi r_w h} \quad (11)$$

Eq. 9 is valid for flow in the formation outside the damaged region near the wellbore. Thus, for flow in the damaged region, Eq. 9 can be written:

$$\frac{dp_D}{dr_D} = \frac{1}{k_{sD}} v_{rD} + \beta_{sD} v_{rD}^2 \quad (12)$$

where β_{sD} is the dimensionless velocity coefficient for the damaged region, and k_{sD} is the permeability ratio given by Eq. 13:

$$k_{sD} = \frac{k_s}{k} \quad (13)$$

Last, we will present an expression for the extra pressure drop caused by high-velocity effects. This, in other words, is the rate dependent pseudo-skin due to high-velocity effects. From Eq. 9, the pressure gradient caused by high-velocity flow $(dp_D/dr_D)_{hv}$, is given as follows:

$$\left(\frac{dp_D}{dr_D}\right)_{hv} = \beta_D v_{rD}^2 \quad (14)$$

It can be demonstrated that for radial flow, the dimensionless velocity v_{rD} can be expressed as follows:

$$v_{rD} = \frac{1}{r_D} \quad (15)$$

Then, Eq. 14 can be written as:

$$\left(\frac{dp_D}{dr_D}\right)_{hv} = \frac{\beta_D}{r_D^2} \quad (16)$$

Integrating this equation:

$$(p_D)_{hv} = (1-\frac{1}{r_{hvD}})\beta_D \qquad (17)$$

If we want to express Eq. 17 in the conventional way used for gas flow (Ramey, 1965); Wattenbarger and Ramey, 1968), we can get:

$$(p_D)_{hv} = Dw \qquad (18)$$

where D is the turbulent term coefficient defined as:

$$D = \frac{\beta k}{2\pi r_w h\mu}(1-\frac{1}{r_{hvD}}) \qquad (19)$$

If a damaged region near the wellbore is considered, Eq. 17 can be written as follows:

$$(p_D)_{hv}=\beta_D\ [\frac{\beta_s}{\beta}\ (1-\frac{1}{r_{sD}}) + (\frac{1}{r_{sD}}-\frac{1}{r_{hvD}})] \qquad (20)$$

where r_{sD} is the dimensionless outer radius of the damaged region.

In the simulation of transient pressure tests to be discussed later in this paper, the velocity coefficient was evaluated by means of the correlation of Firoozabadi and Katz (1979).

FIELD EVIDENCE OF HIGH-VELOCITY FLOW

It has been shown that the extra dimensionless pressure drop caused by high-velocity effects, in the absence of formation damage, is given by Eq. 17. The results of our numerical simulations, to be discussed in the next section, indicate that the high-velocity radius r_{hvD} ranges between 33 and 110 for β_D values of 0.3 and 1, respectively; consequently for practical purposes the $1/r_{hvD}$ term may be neglected in the estimation of the rate dependent pseudo-skin due to high-velocity effects. Thus, in light of the foregoing conclusion we can write:

$$(p_D)_{hv}=\beta_D= Dw \qquad (21)$$

where D is the turbulent term coefficient defined as:

$$D = \frac{\beta k}{2\pi r_w h\mu} \qquad (22)$$

Next we present estimations of the rate dependent pseudo-skin Dw for wells of Cerro Prieto and East Mesa fields. As mentioned, these fields produce from a sedimentary formation of the "homogeneous" (non-fractured) type (Grant et al., 1984; Lyons and van de Kamps, 1974; Witherspoon et al., 1978).

For units of the hybrid system (Table 1), the parameter β_D(=Dw) given by Eq. 21 can be expressed as follows:

$$Dw= 1.54084\times10^{-12}\ \frac{\beta kw}{r_w h\mu} \qquad (23)$$

First we evaluate this parameter for the data of well M-21A of Cerro Prieto taken from Rivera and Ramey (1977). The values of the parameters that enter into Eq. 23 are presented in Table 2. Evaluating Dw we obtain:

Dw = 0.405

Next calculations are shown for well M-109 of Cerro Prieto. This well was chosen because its characteristic curve shown by Iglesias et al. (1983) (their Fig. 5.6) shows a nonlinear relationship of mass flow rate (w) vs bottom-hole pressure (p_{wf}), indicating that high-velocity effects may be influencing the performance of the well. The values of the parameters that enter into Eq. 23 are presented in Table 2. We obtain the following value for Dw:

Dw = 0.25

Last we show calculations for a well of the East Mesa field (Witherspoon et al., 1978). Again, the values of the parameters that enter into Eq. 22 are shown in Table 2. Evaluating the pseudo-skin Dw we get:

Dw = 0.14

The motivation for this last calculation came from reviewing the results of Morris et at. (1987) (their Fig. 9) for well E.M. 87-6, regarding a graph of pressure drawdown vs flow rate which shows slight curvature and Reynolds numbers (their Table 7) that are higher than unity, which is the ussually agreed upon upper limit for the validity of Darcy's law (Muskat, 1937).

Based on the above shown calculations and discussion, we felt that high-velocity flow may influence the transient pressure behavior of liquid-dominated wells and started the research reported in this paper.

VALIDATION OF THE NUMERICAL MODEL

Basically we checked our numerical model by considering Darcy flow (δ=1) conditions for which an analytical or a numerical solution are already available in the literature. A sensitivity analysis of results to different time and space discretizations was first undartaken. For cases of no skin damage and no wellbore storage, the numerical solution of this study were compared to that of van Everdingen and Hurst (1949), and a difference of less than 0.2% was obtained. For cases that included the skin damage and wellbore storage, the comparison was with the numerical solutions presented by Wattenbarger and Ramey (1970), and essentially we obtained identical results. The above mentioned comparison with available results in the literature was acquired with a 40 nodes space discretization for $r_{eD}=2x10^4$; this reservoir external radius was large enough to have infinite acting behavior during the test time. With regard to the time discretization, 45 time steps per log cycle of time were needed to obtain this comparison. For more details of the numerical model the reader is referred to the report of Villalobos (1989).

DISCUSSION OF RESULTS

Based upon our discussion of the mathematical development section, it was found that high-velocity flow effects are strictly related to the dimensionless velocity coefficient β_D (Eqs. 9 and 11). The evaluation of this parameter for maximum producing conditions of a well gives an upper limit for β_D of one.

We first simulated drawdown tests for different values of the dimensionless velocity coefficient β_D. The results for values of β_D of 0.3, 0.6 and 1 are shown in the semilogarithmic graph of p_{wD} vs t_D of Fig. 1. We observe from these results that after the high-velocity flow region is stabilized, a straight line is reached of slope equal to the conventional value of liquid flow of 1.1513. This means, as already mentioned, that after stabilization occurs, the pressure drop due to high-velocity can be expressed as a rate-dependent pseudo-skin Dw. Thus, the dimensionless pressure drop may be expressed as follows:

$$p_{wD} = \tfrac{1}{2}(\ln t_D+0.80907)+Dw \qquad (23)$$

From the above discussion, it can be concluded that the formation conductivity kh can be accurately estimated even if the test is under the influence of high-velocity flow.

Next we consider the combined effects of formation damage and high-velocity flow. Constant flow rate cases were run for values of β_D of 1 that corresponds to maximum conditions and values of the skin factor s of -2, 0, 5, 10 and 20. Fig. 2 shows the results of these simulations. These data indicate that high-velocity flow in a composite reservoir does not affect the transient behavior more than in a homogeneous reservoir. The early transient flow is dominated by the region of altered permeability near the well. After a transition period, a straight line occurs whose slope is equal to the conventional value of liquid flow of 1.1513. This second straight line is parallel to $p_D(\beta_D=0)$ solution of van Everdingen and Hurst (1949), but is displaced by an amount equal to the apparent skin effect s'(Ramey, 1965) defined by

$$s' = s + Dw \qquad (24)$$

We checked the results of our simulations with regard to the rate dependent pseudo-skin factor Dw that resulted from the computer runs and that calculated from Eq. 20 and found an excellent agreement.

The factor that the straight line portion of the drawdown curve is parallel to $p_D(\beta_D=0)$ is important. This means that the conductivity kh of the outer portion of the formation can be determined accurately from a drawdown test. Thus, Eq. 23 can be extended to

$$p_{wD}= \tfrac{1}{2} (\ln t_D+0.80907)+s+Dw \qquad (25)$$

To calculate the skin factor s and the turbulent term coefficient D, the method of Ramey (1965) can be used.

To complete the study we included in our simulations the effect of isothermic wellbore storage. Constant flow rate cases were run at values of β_D of 1 and of c_D of 10, 10^2, 10^3 and 10^4. Fig. 3 shows a semilog graph of p_{wD} vs t_D. We observe from these results that the hot-water solutions that consider high-velocity flow essentially follow a parallel behavior with the liquid solution $p_D(\beta_D=0)$.

The wellbore storage effect was found to behave like liquid case solutions (van Everdingen and Hurst, 1949; Wattenbarger and Ramey, 1970). Wellbore storage has only a short-time effect on the transient pressure behavior and has no effect on the ultimate slope of the semilogarithmic drawdown curve.

The last case considered with regard to drawdown tests was one that includes simultaneously the effects of high-velocity flow, formation damage and wellbore storage. Constant flow rate cases were run for values of s=5 and $C_D=10^2$, and values of β_D of 0.3 0.6 and 1. Fig. 4 shows the results of these simulations. The conclusions reached from these results are essentially those already made for the cases of high-velocity flow affected either by formation damage (Fig. 2) or wellbore storage (Fig. 3). In short, the formation conductivity can be estimated from the drawdown test. In addition the skin factor s and the turbulent term coefficient D can be estimated by means of the method of Ramey (1965).

We also investigated what effects high-velocity flow would have on an analysis using the derivative type curve of Bourdet et al. (1983). We found that as the intensity of high-velocity flow increases, the error in the estimation of the formation parameters from the match point data also increases. As expected, the maximum error is found in the estimation of the skin factor, in some cases off by 200 per cent. A similar finding for real gas flow has been reported by Berumen et al.(1989). Fig. 5 shows an example of derivative type curves for the case of $C_D=100$, s=5 and different values of β_D. Thus, in cases where high-velocity flow affects a test, results of type curve analysis are to be taken with caution.

We looked carefully to the effects of high-velocity flow on the beginning of the semi-log straight line. As expected, it was found that it was affected by the intensity of high-velocity flow represented by the parameter β_D. For practical producing conditions found in the field, it was found that the start of the semi-log straight line can be predicted by the correlation of Ramey et al. (1973), provided that the apparent skin effect s' is used instead of the skin factor s. This time for the start of the semi-log straight line is:

$$t_{Dbsl} = C_D(60+3.5s') \qquad (26.a)$$

or in term of real variables (Table 1):

$$t_{bsl} = \frac{\varepsilon}{\beta} \cdot \frac{CB\,\nu_{sc}}{kh}(60+3.5\ s') \qquad (26.b)$$

This study also considered the simulation of buildup tests under the influence of high-velocity flow. Fig. 6 presents a semi-logarithmic graph of simulated buildup curves for values of the parameter β_D of 0.3, 0.6 and 1. We see from these results that after the high-velocity flow effects vanish in a short time, the buildup curve joins the buildup solution for β_D=0. The shut-in time required to reach the straight line portion is approximately $\Delta t_D = 10^2$. For practical purposes, the determination of the formation conductivity kh from buildup test under the influence of high-velocity flow appears to be very accurate.

After having checked the influence of high-velocity flow on buildup tests, simulations then were made to investigate the effect of formation damage and wellbore storage on buildup tests under the influence of high-velocity flow. The main aim was to determine whether any of these two effects or both, in combination with high-velocity flow alter the straight line portion of the semilog buildup curve.

Results of simulated buildup curves under the influence of combined effects of high-velocity flow and formation damage are shown in Fig. 7. The values of the β_D and s parameters were the same as those of the corresponding drawdown tests already discussed (Fig. 2). It is concluded from these graphical results that after a period of influence from the formation damage, the buildup solutions become straight lines with the proper slope. Thus, the formation conductivity kh can be determined accurately from a buildup curve. As previously discussed for drawdown tests, the method of Ramey (1965) can be used to calculated the skin factor s and the turbulent term coefficient D.

Results of simulated buildup curves under the influence of combined effects of high-velocity flow and isothermic wellbore storage are shown in Fig. 8. The values of the β_D and C_D parameters were the same as those of the corresponding drawdown tests already discussed (Fig. 3). The family of curves of this figure is similar to buildup curves that consider β_D=0. After the effect of wellbore storage dies out, the buildup solutions joins the solution for C_D=0. Thus, the slope of the straight line portion is accurate provided the correct straight line portion is chosen.

Finally, the last case considered with regard to buildup tests is one that includes simultaneously the effects of high-velocity flow, formation damage and wellbore storage. The values of the β_D, s and C_D parameters were the same as those of the corresponding drawdown tests already discussed (Fig. 4). Fig. 9 shows results of these tests. The conclusions reached from these results are essentially those already made for the cases of high-velocity flow affected either by formation damage (Fig. 7) or wellbore storage (Fig. 8). In short, the formation conductivity can be estimated from the buildup test. The skin factor s and the turbulent term coefficient D can be estimated from results of buildup analysis by means of the method of Ramey (1965).

CONCLUSIONS

The main purpose of this work was to present a systematic study of transient pressure analysis of liquid dominated wells producing at constant mass rate under the influence of high-velocity flow. The motivation for the research subject of this study came from the analysis of testing conditions for the Cerro Prieto and East Mesa fields, that indicated the presence of this effect.

Based on the material presented in this paper, the following conclusions are pertinent:

1. The formation conductivity can be determined accurately from the analysis of pressure drawdown or buildup tests under the influence of high-velocity flow and the effects of formation damage and wellbore storage.

2. An easy to use expression is presented for approximate determination of the rate dependent pseudo-skin Dw.

3. The method of Ramey (1965) can be used for an accurate determination of the skin factor s and the turbulent term coefficient D.

4. If high-velocity flow affects a test, results of type curve analysis by means of the derivative type curves of Bourdet et al. (1983) are to be taken with caution.

5. It was found that the start of the semi-log straight line can be predicted by the correlation of Ramey et al.(1973), provided that the apparent skin effect s' is used instead of the skin factor s.

NOMENCLATURE

B= formation volume factor
c_t= system total compressibility
C^t= wellbore storage constant for hot water
C_D= Dimensionless wellbore storage constant $= \frac{\epsilon C B \nu_{sc}}{\phi h r_w^2 c_t}$
h= thickness
k= permeability
p= pressure
r= radial distance
s= van Everdingen and Hurst skin factor
s'= apparent skin factor, Eq. 24
t= time
v_r= radial velocity
w= mass flow rate
β= velocity coefficient
δ= L.I.T. (laminar, inertial, and turbulent) correction factor
ϕ= porosity
μ= viscosity
ρ= density

Subscripts

D= dimensionless
hv= high-velocity
s= damaged region
t= total or time
sc= standard conditions
w= wellbore

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TABLE I.- ABSOLUTE AND HYBRID SYSTEM OF UNITS USED IN GEOTHERMAL RESERVOIR ENGINEERING (After Samaniego and Cinco-Ley, 1982).

Variable	SI system*	Hybrid-system
k	$metre^2$	md
h	m	m
p	$Newton/metre^2$=pascal	kg_f/cm^2
w	kg/sec	ton/hr
ν_{sc}	$metre^3/kg$	cm^3/gm
B	$metre^3_{rc}/metre^3_{sc}$**	$metre^3_{rc}/metre^3_{sc}$
μ	kg/metre.sec	cp
t	sec	hours
φ	fraction	fraction
c_t	$(Newton/metre^2)^{-1}$	$(kg_f/cm^2)^{-1}$
r	metre	metre
B_t	1	0.000348
α	1/2π	456.7869
ε^{ω}	1/2π	1/2π

*SI is the abbreviation for International System of Units
**rc stands for reservoir conditions and sc for standard conditions

TABLE 2.- DATA ON TWO WELLS OF CERRO PRIETO AND A WELL OF EAST MESA FOR CALCULATION OF THE PARAMETER Dw

	Well M-21A (Cerro Prieto)	Well M-109 (Cerro Prieto)	Well 6-2 (East Mesa)
k(md)	36	36[2]	46
h(ft)	177.3	984[3]	500
w(ton/hr)	111	380	-
q(STB/D)	-	-	30000
B(STB/RB)	-	-	1.13[4]
μ(cp)	0.1017	0.1017	0.18
r_w(ft)	0.27	0.27	0.27[4]
β[1](ft^{-1})	$3.2x10^8$	$3.2x10^8$	$2.5x10^8$

(1) Estimated from Firoozabadi and Katz's correlation (1979)
(2) Assumed value equal to the permeability of the Cerro Prieto I area
(3) Assumed value similar to the thickness of nearby well M-117 (Fig. 5.A of Halfman et al., 1985)
(4) Assumed values because they are not shown in the paper of Witherspoon et al. (1978)

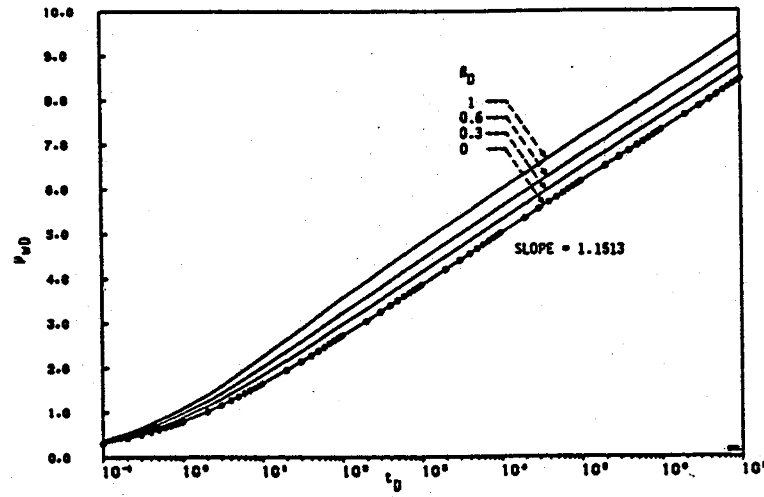

Fig. 1 Drawdown tests in a radial reservoir considering the effect of high-velocity Flow.

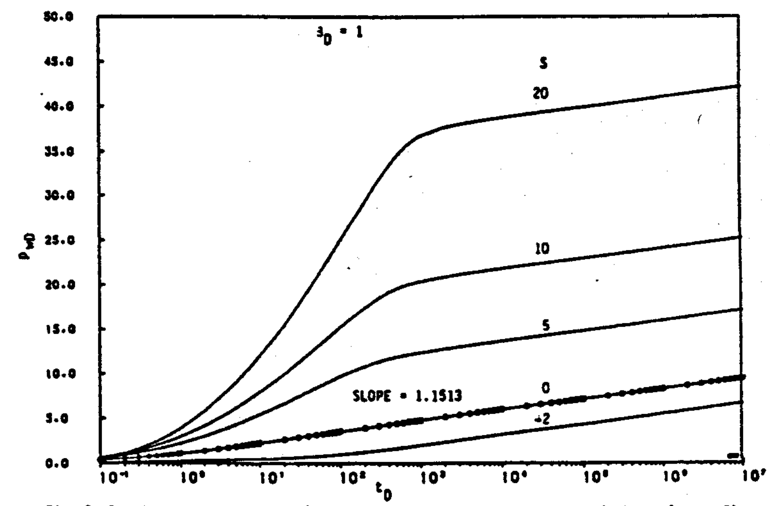

Fig. 2 Drawdown tests in a radial reservoir considering the effects of high velocity Flow and formation damage

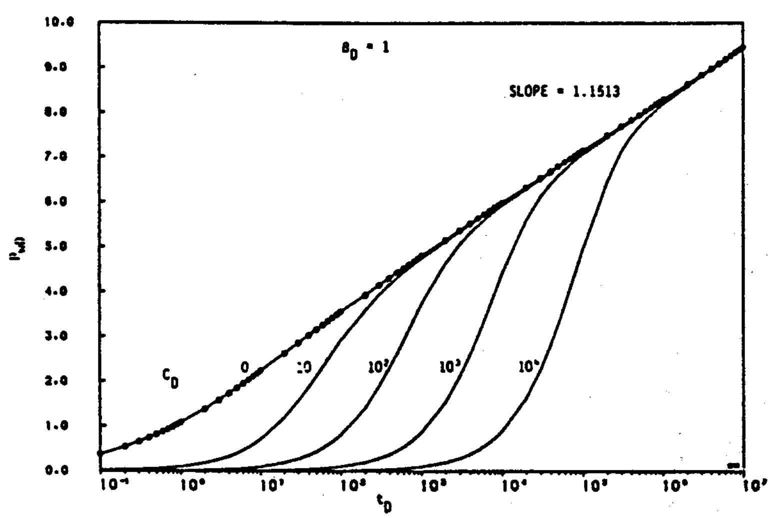

Fig. 3 Drawdown tests in a radial reservoir considering the effects of high-velocity flow and wellbore storage

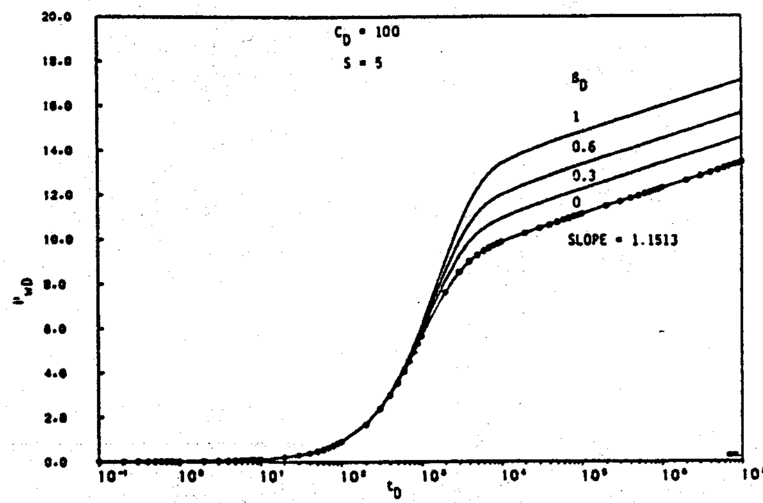

Fig.4 Drawdown tests in a radial reservoir considering the effects of high-velocity flow, formation damage and welltore storage

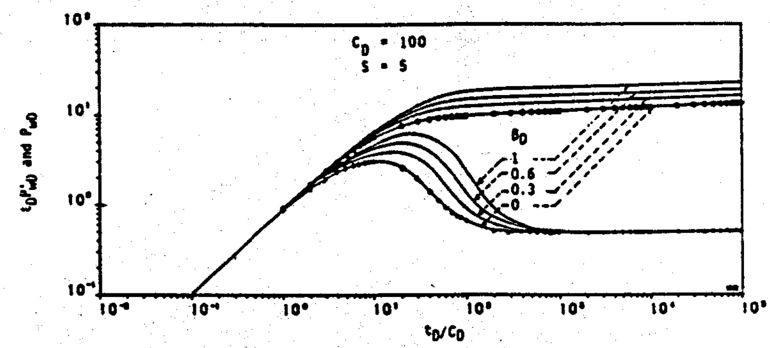

Fig. 5 Pressure derivative type curve results for a drawdown test in a radial reservoir, considering the effects of high-velocity flow, formation damage and wellbore storage

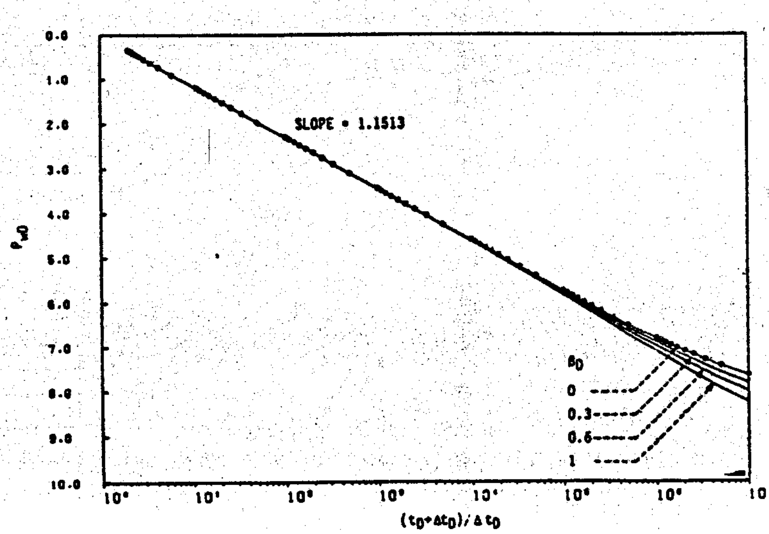

Fig. 6 Buildup tests in a radial reservoir considering the effect of high-velocity flow.

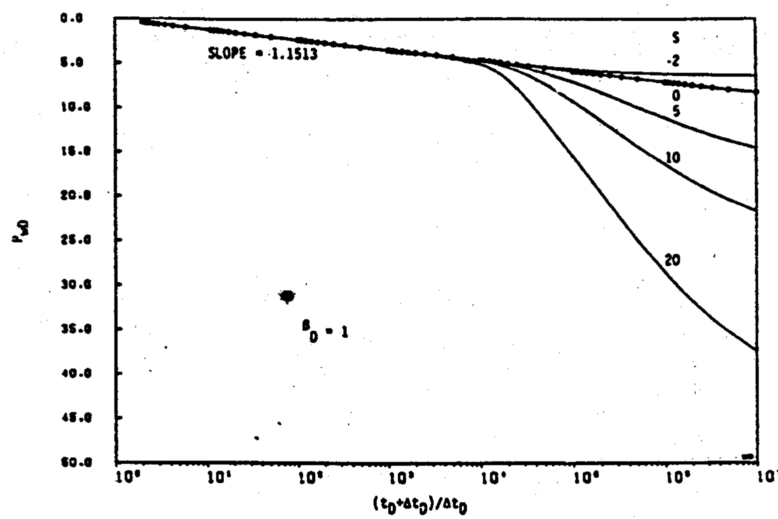

Fig. 7 Buildup tests in a radial reservoir considering the effects of high-velocity flow and formation damage.

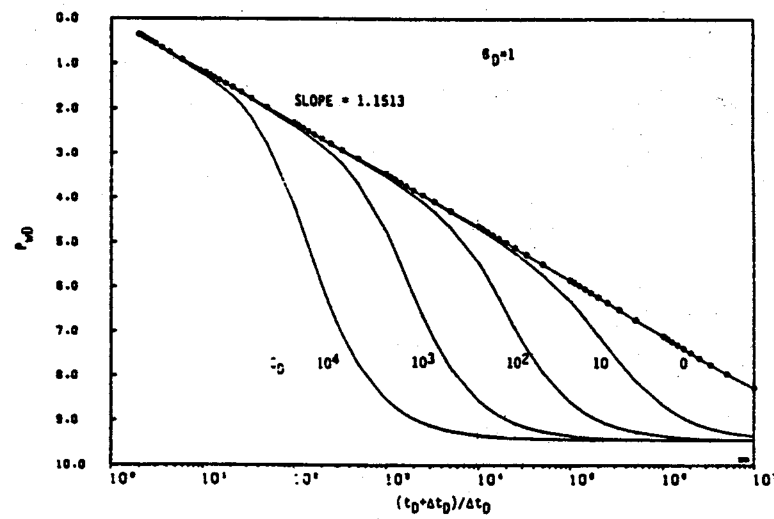

Fig. 8 Buildup tests in a radial reservoir considering the efects of high-velocity flow and wellbore storage.

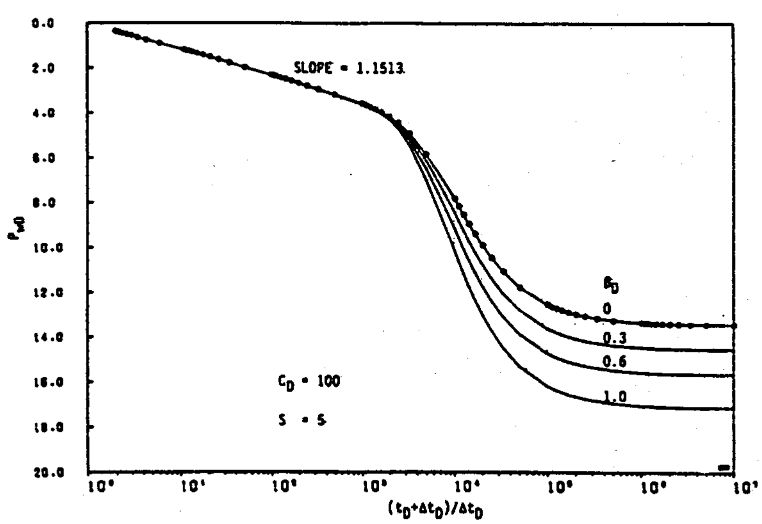

Fig. 9 Buildup test in a radial reservoir considering the effects of high-velocity flow, formation damage and wellbore storage.