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Effect of Formation Damage, Length and Reservoir Thickness on the Inflow Performance of Horizontal Wells

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Abstract

Horizontal wells offer many advantages, compared to vertical ones. However up to now, their performance did not always live up to expectation especially in the Middle East where vertical wells are commonly naturally prolific. This has been attributed in general to near well bore formation damage. Because of their large contact area of reservoir rock, horizontal wells are more susceptible to drilling and work-over induced formation damage than vertical ones. The effect of skin damage on horizontal wells has been abundantly discussed in the literature; however, the method of handling the calculations varies from one author to the other. In most cases, the authors did not take into consideration friction, the variation of skin along the horizontal section of the well and the perforation distribution. It is common now to drill very long horizontal wells where the skin may vary along the well. Therefore, it is important to estimate the real contribution of the different sections of the horizontal well to the total production of the well and the role of formation damage and friction in the overall performance of the well.

The present paper addresses the case of highly permeable reservoirs displaying variable skin along the horizontal section of the well. Friction losses as well as perforation distribution are taken into account. A literature survey is conducted in order to understand the role of formation damage and friction. A semi analytical approach is used to study the simultaneous effect of perforation distribution, near well bore formation damage and friction losses on the production of horizontal wells. The results show the effect of various well parameters such as well length, anisotropy ratio, skin and perforation distribution on the inflow performance of the horizontal well. The study shows particularly that:

1. For short horizontal wells, formation damage does not significantly penalize horizontal wells. This is particularly true for thin reservoirs.

2. For medium horizontal wells:

    . For thin reservoirs, formation damage moderately affects the production of horizontal wells. For example, for the case studied, where the skin S=10, the production loss is only about 20% while for S=30, the production loss is 45%.

    . For thick reservoirs, the situation is not the same. For example, the production loss of a damaged well with a skin of 10 is about 70% and the production loss of a damaged well with S=30 is almost 95%.

3. For long horizontal wells:

    . For thin reservoirs, the production loss due to formation damage is still not excessive. It is only 35% for S=10 and about half when the skin reaches 24.

    . For thick reservoirs however, horizontal wells become very sensitive to formation damage. Even for a skin of 10, the production loss may exceed 95%. The larger the fraction of the well open to production, the more severe is the impairment.

Introduction

Horizontal drilling which started less than ten years ago in the Middle East is becoming a major factor in reserve improvement and recovery acceleration. In fact, drilling horizontal wells is now more of a default option than an unconventional way of developing oil fields. As stated in a recent study[1], major operating companies will ultimately utilize horizontal and multilateral technology. The only question is when. The reason for this trend resides in the advantages horizontal wells offer[2]. These are:

- Higher production rates
- Cost reduction
- Reserves increase
- Less water and gas coning
- Less sand control problems
- New reservoir evaluation possibilities

The primary objective is to develop the reservoir with horizontal wells and multilaterals to increase drainage and optimize the production rate. In the Middle East where the total production accounts for only few thousand wells, approximately one thousand horizontal wells[3] have been drilled from 1990 to date, among which about 200 are multilaterals. These horizontal wells are expected to have a major impact. In Saudi Arabia alone, horizontal and multilateral wells are expected to result in up to 10% improvement in recovery. However, not all horizontal wells are successful. For instance, in one important reservoir in the Middle East, eight horizontal wells have been drilled between 1995 and 1996 to target a thin oil column in the north of the structure and an oil pocket beneath a gas cap in the south. The majority of these wells never produced any oil at all mainly because of formation damage. Recent literature survey raises a serious debate about whether formation damage is more detrimental for vertical wells or for horizontal ones. It remains a fact that in both cases, the production loss due to formation damage is significant. In the next section, formation damage and its implication on oil recovery will be discussed. A review of the literature and the statement of the problem will follow. Finally, a method of solution will be suggested and some results will be presented.

Objective of the Study

The concept of skin as introduced by Van Everdingen[5] and Hurst[6] for vertical wells quantifies the severity of formation damage. The relation between skin, permeability of the damaged zone and the radius of the damaged zone is given by Hawkins relation[7].

$$S = (k/k_d - 1)\ln(r_d/r_w) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

The larger the skin, the larger the production loss due to formation damage will be. For instance, for a damaged vertical well with $r_d = 2$ ft, $r_w = 0.3$ ft and $k/k_d = 10$, S is in the order of 17. Typically, for the data given in Table 1, a vertical well producing 4000 STB/d looses more than half of its production for this value of the skin. The production loss could be much higher for a horizontal well. This shows how formation damage can affect the production rate. This also explains why solving formation damage problems is equivalent to mobilizing additional oil reserves and increasing recovery, at least from an economic standpoint.

The objective of this study is directed specifically towards, assessing the effect of actual formation damage on the well performance by taking into account friction in the well bore. The effect of other reservoir characteristics such as anisotropy ratio and geometry will be also examined.

Literature Review

Most of the research related to horizontal wells concerns pressure transient analysis and productivity index estimation. Little has been done on the quantitative effect of formation damage on well performances. Among the parameters that play an important role in the determination of horizontal well performances, formation damage and friction in the well bore are the most important. In the case of vertical wells, productivity index estimation is fairly simple. For horizontal wells, performance prediction is less straightforward. The problem is complicated by the effect of boundary conditions on the type of drainage that results from the influx towards the well. Merkulov[8] and later Borisov[9] presented analytical expressions for horizontal wells producing under ideal conditions of isotropic reservoirs with no formation damage and no friction. Joshi[10] studied the same problem extended to three dimensional steady state flow with relatively short horizontal wells compared to the drainage area which is assumed to be elliptical. Giger[11] generalized the results to a rectangular area to account for longer horizontal wells using the potential flow theory. Other investigators like Economides[12,13] and Renard and Dupuy[14] did more work to take into account the anisotropy ratio and contributed in developing the theoretical expression of the productivity index as it is now accepted as reported by Economides[13] .

Still this expression is true for an open hole only. For a well partially completed, Goode and Wilkinson[15] developed an expression for the inflow performance based on the consideration that the different sections open to flow can be assimilated to a series of vertical fractures. The pressure drop is assumed to be the sum of two parts: A two-D fracture contribution and a three-D well contribution due to the convergence of flow near the horizontal well.

In all the theoretical expressions of inflow performance presented in the literature, formation damage effect on the productivity index is taken care of by assuming that a constant skin applies along the whole length of the horizontal section of the well. Consequently, a constant skin S is added to the denominator of the productivity index the same way it is done for vertical wells. Recent literature shows that this is not accurate. Many investigators[16,22] demonstrated that formation damage varies in fact from the heel to the toe in a horizontal well, especially if it is a long well as it is often the case now. Economides[18], Yan et al[19], Engler et al[20] Toulekima[21] and others, all showed that the skin decreases along the horizontal section of the well from heel to toe. The reason is that formation damage is proportional to the exposure time of the reservoir during drilling and completion operations. Economides[13] for example, using a numerical model showed that the distribution of damage along the horizontal well and around it is not uniform. Particularly, because of permeability anisotropy, the invasion zone has the shape of an elliptical cone with the larger base near the vertical section of the well. Consequently, the skin profile decreases from heel to toe and therefore the constant skin assumption used in vertical wells is not valid.

The justification of this assumption is even more questionable when friction is taken into account. In fact many investigators[23,24] showed that friction which is neglected in vertical wells may be significant in long horizontal wells, especially if the wells are open hole and if there is a chance for debris to accumulate along the well bore. Menouar[25] et al studied the simultaneous effect of friction and skin on the well production. They showed that the profile of skin along the well affects significantly the horizontal well performance in the case of reservoirs with high permeability where the production rates are high and friction non negligible. They showed also that, assuming constant skin instead of the actual variable skin profile can lead to significant deviation from the real well performance. This deviation is larger when friction forces are more important such as in the case of open hole or cased well bores affected by debris. In another study[21] by Toulekima et al, one of the main conclusions was that productivity is more adversely affected by formation damage near the toe end of the well than near the heel. Toulekima et al also showed that incremental effect of formation damage on oil recovery is more significant for lower skin factors than for higher skin factors.

The experimental work published in this area concerns mostly the different types of skin and the mechanisms involved in formation damage, particularly the emphasis has been on the mechanical type of formation damage specifically the invasion by solids and fines. Few studies were based on the experimental determination of skin factors[19] or on the use of well bore models to simulate realistic radial flow conditions for horizontal wells[26] and evaluate the pre- and post-mud damage on the well productivity and injectivity.

In summary, this literature review shows that theoretical horizontal well performances are predicted in general assuming constant skin along the horizontal well and negligible friction despite the fact that formation damage along the well is variable in nature and friction is not negligible in many instances.

Statement of the Problem

As stated earlier, the theoretical expressions used for well performances in most of the studies are based on vertical well assumptions. The skin is assumed constant, meaning that the pressure drop due to formation damage is assumed constant along the well length which can be several thousand feet. Assuming a variable skin along the well and accordingly, a variable pressure drop from heel to toe, the flux from the reservoir to the well bore will not be uniform. The difference of flux from heel to toe depends on the difference of magnitude between the level of formation damage at the heel and at the toe. For negligible friction forces, this variable distribution of flux may have little effect on the overall well performance. It is not the case when friction forces are not negligible.

Since no analytical expression exists to take into account all the forces involved, a numerical method to estimate the flux from the reservoir to the well on one hand and the pressure drop at the level of each section along the horizontal well on the other hand is used. This method is iterative because there is no exact solution available. In the next section, the details about this method are given.

Method of Solution

The method of solution used is based on a computer program constituted of two parts. The first one evaluates the inflow performance into the horizontal well and the second estimates the outflow performance from the horizontal well.

The estimation of the inflow performance of the reservoir is conducted using Goode and Willkinson's[15] method to take into account partially completed wells. Given a certain scenario of completion, especially the distribution of the different sections open to flow, the program estimates the resulting productivity index and computes the specific productivity index used at the level of each perforated section of the horizontal well. The generated flux is taken into consideration in the estimation of the outflow performance of the well in the second part of the program. To do that, the pressure drop in the well bore resulting from the flow at the level of the given perforation set is computed. Next, the current pressure at the level of the following set of perforation is estimated using not only the pressure drop due to friction forces but also the appropriate pressure drop due to skin at this level. The whole procedure is conducted iteratively for better accuracy. Both open hole horizontal wells and partially completed wells can be used and any type of skin profile, constant or monotonically decreasing can be considered. The program can also incorporate any correlation that reflects the real relation between flow rate and friction forces in the well bore.

Results and Discussion

This computer program has been tested against a field example from the Middle East and gave fairly accurate results. In this section, the program has been used to generate a parametric study of the effect of skin, reservoir thickness, well length, percentage completed and anisotropy ratio on the production rate. The reservoir characteristics considered for this parametric study are typically from the Middle East and are presented in Table 1. Figure 1 shows the reservoir and well bore model. As discussed earlier, different skin profiles are assumed. Some of these profiles are shown in Figure 2. The well performances are evaluated for each profile, not only for isotropic reservoirs but also for non isotropic reservoirs with different anisotropy ratio.

Effect of Skin Profile along the Well

As discussed in the previous section, see also ref. 25, the horizontal well performance obtained for a constant skin profile along the well are significantly different from the case of non constant skin profile. In this particular case, all skin profiles considered are constant or monotonically decreasing. The performances obtained for a given skin average value are compared for different profiles and different anisotropy ratio. This study shows that the nature of the skin profile affects the well performances regardless of the average value of skin. The program has been used to obtain the production rate for each profile. Tables 2 and 3 report these results in dimensionless form by reference to the case of undamaged well without friction. For instance, the well performances obtained for cases 2 and 3 are significantly different as shown from the comparison of Tables 2 and 3 respectively. An example of calculation of the real flow rates for an average skin value of 36 and a dimensionless length L_D = 0.75 for both cases 2 and 3, and different anisotropy ratios is also reported in Table 4. As shown in these tables, the difference between the two profiles is important despite the fact that for both cases, the average value of the skin is the same. Figure 3 shows a plot of the deviation between cases 2 and 3 versus the dimensionless length L_D for an average skin value of 21. It can be seen in this figure that the error, which increases with L_D, can be as large as 40%

Effect of Reservoir Thickness

The method described above has been used to investigate the effect of some parameters such as the reservoir thickness, skin, well length and percentage of the length completed on the performance. The results are presented in figures 4 through 11. In these figures, horizontal wells with various dimensionless lengths, L_D have been used. The wells have been open to production assuming different percentages of length completed. Different average skin value are considered depending on the total length of the well. The results are presented in the form of relation between Q_D , the percentage of length completed and the average skin. Q_D is defined as:

Q_D = Q/ Q_{max}
Where
Q = Production rate for current skin and % completed
Q_{max} = Production rate for fully completed well and zero skin

Figures 4 to 6 show that for thin reservoirs, dimensionless height H_D = 0.005, the first 40 to 50% of the horizontal well length contribute the most to the performance of the horizontal well. Also, a skin of 7 penalizes a well fully completed by less than 20% of the production rate. Even for extensively damaged well, S=21, the penalization in a thin reservoir does not exceed 35%.

This is not the case for thick reservoirs. Figure 6 shows for example that for H_D = 0.025 and for a dimensionless length L_D of 0.25 as in the previous example, the contribution of the last 50% of the horizontal well length is more important than in the case of a thin reservoir. In this last example, a skin of 7 penalizes a well fully completed by more than 40%. If the well is more damaged, S=21, the penalization reaches 70%.

Similar results generated for reservoirs with H_D varying from 0.005 to 0.025 and longer horizontal wells, L_D = 0.5, are presented in figures 7 to 9. The same trend is confirmed. However, figure 9 shows for example that the last 50% of the well length contribute more than the first half contrary to the results presented in figure 4 where the reservoir is thin and the well is short. Also, figure 9 shows that a skin of 10 penalizes the well more than 75% while a more damaged well is penalized by almost 90%.

This trend is even more pronounced for longer horizontal well lengths. Figure 11 shows for example that for H_D = 0.01 and L_D = 0.75, the penalization due to skin is excessive.

For H_D = 0.025 and L_D = 0.75, this penalization is very high, more than 97% for large values of skin.

Effect of Anisotropy Ratio

The effect of Anisotropy ratio on the well performance has been examined using the same method. The results are presented in figures 12 to 18. In these figures, the dimensionless rate Q_D is defined as:

Q_D = Q/ Q_{max}
Where
Q = Rate for current skin and percentage completed
Q_{max} = rate for β = 1 and zero skin
β = $(k_h/k_v)^{1/2}$

The results for short horizontal wells presented in figures 12 to 14 show that both the anisotropy ratio β and the skin S have an effect on the well performance. The comparison of figures 12 to 14 shows that this effect is more dramatic for thicker reservoirs than for thinner ones. Figure 12 shows for example that for a thin reservoir, H_D = 0.005, and for a value of β = 3.16 equivalent to k_h/k_v = 10, the production loss due to anisotropy is less than 20% for an undamaged well.

For a damaged well with a skin of 21, the production loss due to the combined effect of anisotropy ratio, β = 3.16 and skin is 65% compared to almost 50% production loss due to the effect of the skin alone when the reservoir is isotropic.

For a thick reservoir, H_D = 0.025 and for a dimensionless length L_D = 0.25, the production loss due to skin alone is almost 70% when the reservoir is isotropic, see figure 14. The combined production loss due to skin and anisotropy ratio is around 90% from which, almost 50% is due to anisotropy alone. See also figure 14.

Longer Horizontal wells, L_D = 0.5, exhibit similar but more pronounced trend. The combined effect of skin and anisotropy ratio for a thin reservoir which is 70%, increases to more than 96% for a thick reservoir, H_D = 0.025, see figure 17.

For very long horizontal wells, L_D = 0.75, even for thin reservoirs, the production loss is excessive. See figure 18.

For thick reservoirs, H_D = 0.025, and long horizontal wells, the production loss due to anisotropy ratio and formation damage combined is above 98%.

Conclusion

The following conclusion can be drawn:

1. For short horizontal wells, the oil production is not significantly penalized by formation damage. This is particularly true for thin reservoirs.
2. For thick reservoirs, the production loss due to formation damage is more severe for long horizontal wells than for short ones both in relative and absolute terms.
3. For thin reservoirs, formation damage is equally detrimental for isotropic reservoirs and for non-isotropic reservoirs.
4. Thick isotropic reservoirs are much more sensitive to formation damage than thick non-isotropic reservoirs.

Nomenclature

D= well diameter, ft
H= Reservoir Thickness
h= height of the reservoir, ft
k= permeability, md
k_D*= damaged permeability*
L_w*= Well Length, ft*
L_x*= Reservoir Length, ft*
L_y*= Reservoir width, ft*
N_p*= No. of open intervals*
P= Pressure, psia
Q= Oil Rate, bbl/day
Q_D*= Dimentionless rate*
r_w*= Well Radius, ft*
RSo_i*= Initial GOR scf/res.bbl*
S= Skin factor
S_g*= Gas gravity*
T= Temperature, ^oF
STB/d = Stock Tank Barrel per day
b= Anisotropy ratio $b = (k_h/k_v)^{1/2}$

Subscript

d= damaged
g= gas
o= oil
R= reservoir
w= well
x= x-direction
y= y-direction
z= z-direction
h= Horizontal
v= Vertical
D= Dimensionless

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SI Metric Conversion Factors

ft × 3.048* E-01=m
ft^2 × 9.290 304* E-02=m^2
ft^3 × 2.831 685 E-02=m^3
in. × 2.54* E+00=cm
md × 9.869 233 E-04=μm^2
psi × 6.894 757 E+00=kPa

*Conversion factor is exact

TABLE-1 TYPICAL DATA USED IN THIS STUDY

$k_x = k_y$	2500 md
k_z	1000 md
β	1.58
L_x	4000 ft
L_y	2000 ft
h	80 ft
L_w	1000ft, 2000ft, 3000 ft
N_p	5
Open percentage of well	From 20 to 100 %
D	4.5 inches & 6 inches
P_R	2250 psia
T_R	160 °F
°API	30
S_g	0.90
RSo_i	400 scf/bbl

TABLE-2 DIMENSIONLESS RATE CASE-2 PROFILE

LD=0.25 ; HD=0.02 ; CASE-2

Kh/Kv	S=0	S=7	S=14	S=21
1	1	0.65	0.51	0.43
2	0.85	0.52	0.40	0.34
3	0.77	0.46	0.35	0.29
4	0.71	0.42	0.32	0.26
5	0.67	0.38	0.29	0.24
6	0.63	0.36	0.27	0.22
7	0.60	0.34	0.26	0.21
8	0.58	0.32	0.24	0.20
9	0.56	0.31	0.23	0.19
10	0.54	0.30	0.22	0.18

LD=0.50 ; HD=0.02 ; CASE-2

Kh/Kv	S=0	S=10	S=20	S=30
1	1	0.39	0.27	0.21
2	0.72	0.29	0.20	0.16
3	0.60	0.24	0.17	0.13
4	0.52	0.21	0.15	0.12
5	0.47	0.19	0.13	0.11
6	0.43	0.18	0.12	0.10
7	0.40	0.16	0.12	0.09
8	0.38	0.15	0.11	0.09
9	0.36	0.15	0.10	0.08
10	0.34	0.14	0.10	0.08

TABLE-3 DIMENSIONLESS RATE CASE-3 PROFILE

LD=0.25 ; HD=0.02 ; CASE-3				
Kh/Kv	S=0	S=7	S=14	S=21
1	1	0.60	0.44	0.36
2	0.85	0.48	0.34	0.27
3	0.77	0.41	0.30	0.23
4	0.71	0.37	0.26	0.21
5	0.67	0.34	0.24	0.19
6	0.63	0.32	0.22	0.18
7	0.60	0.30	0.21	0.17
8	0.58	0.29	0.20	0.16
9	0.56	0.27	0.19	0.15
10	0.54	0.26	0.18	0.14
LD=0.50 ; HD=0.02 ; CASE-3				
Kh/Kv	S=0	S=10	S=20	S=30
1	1	0.35	0.22	0.17
2	0.72	0.25	0.16	0.12
3	0.60	0.21	0.13	0.10
4	0.52	0.18	0.12	0.09
5	0.47	0.17	0.11	0.08
6	0.43	0.15	0.10	0.07
7	0.40	0.14	0.09	0.07
8	0.38	0.13	0.09	0.07
9	0.36	0.13	0.08	0.06
10	0.34	0.12	0.08	0.06

TABLE-4 ACHIEVALBLE PRODUCTION RATE, (bbl/d), For the data in Table 1

	CASE-3	CASE-2
Kh/Kv	S=36	S=36
1	17886	26575
2	11932	17408
3	9578	13902
4	8238	11938
5	7346	10643
6	6698	9706
7	6198	8989
8	5799	8416
9	5469	7945
10	5192	7548

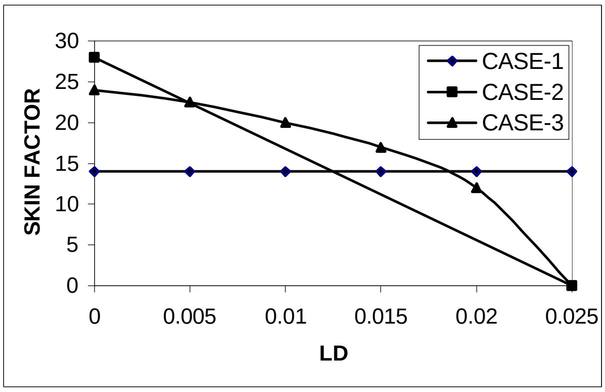

FIGURE 2: SELECTED SKIN PROFILES OF L_D=0.25

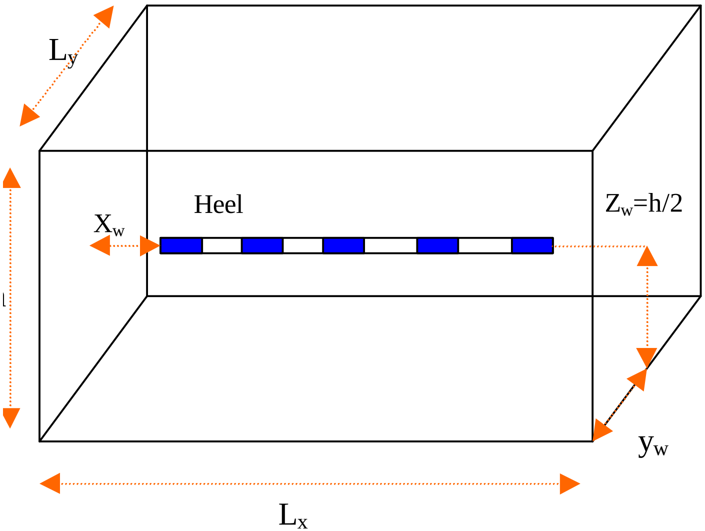

FIGURE 1: RESERVOIR AND WELLBORE MODEL.

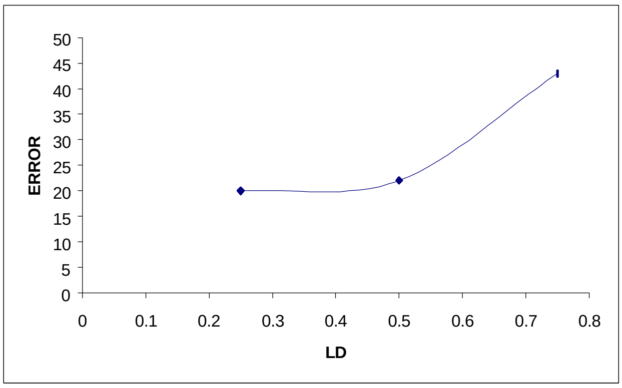

FIGURE 3: DEVIATION CASE2/CASE3 vs L_D

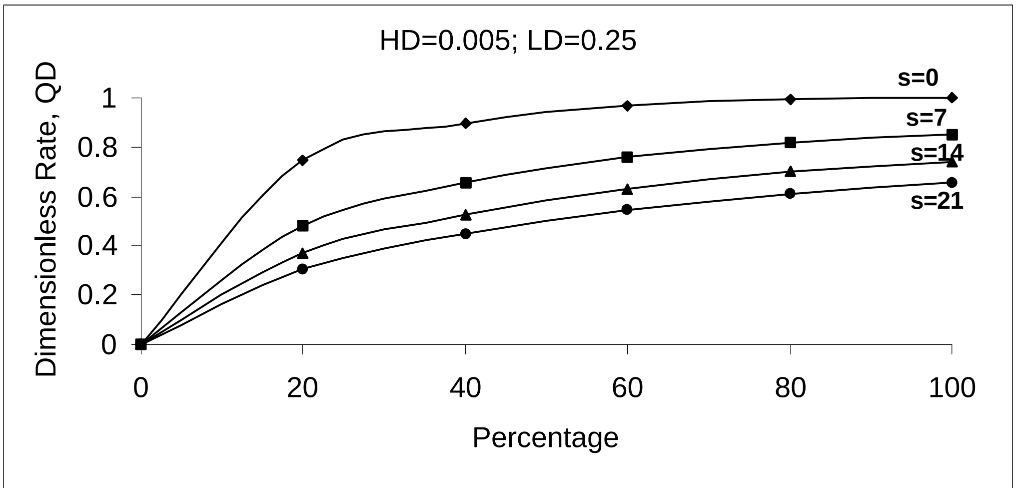

Figure # 4

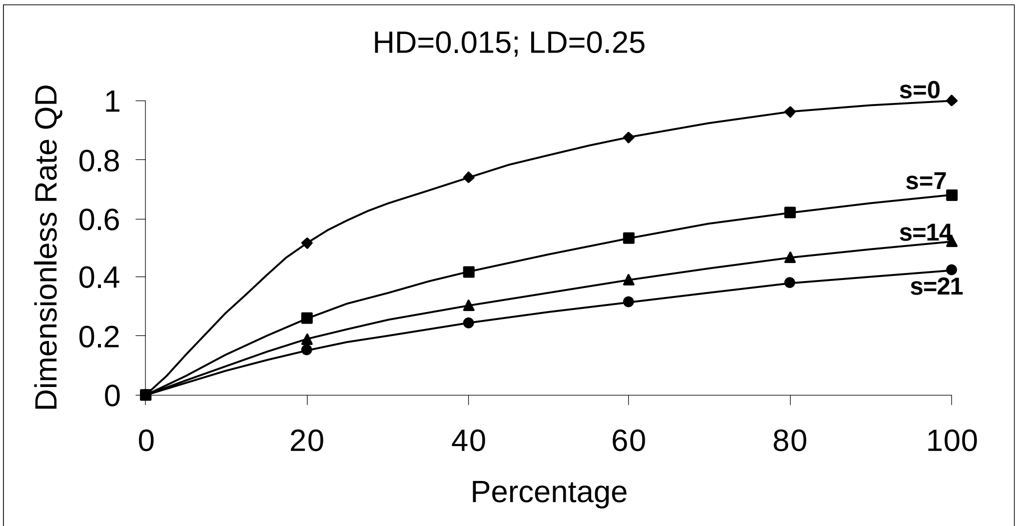

Figure # 5

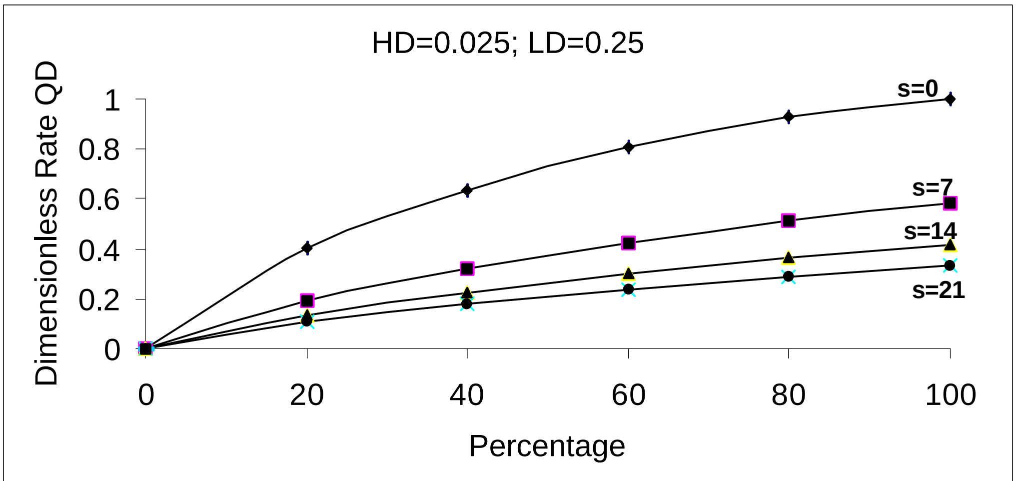

Figure # 6

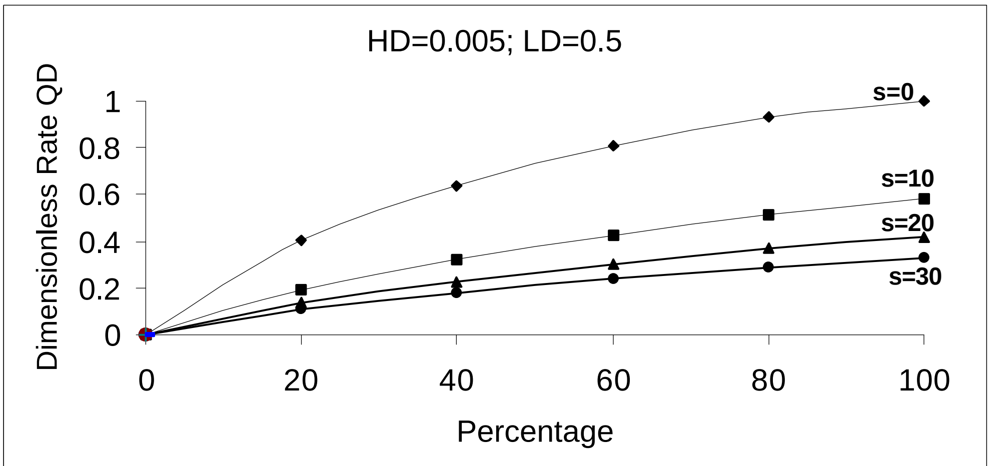

Figure # 7

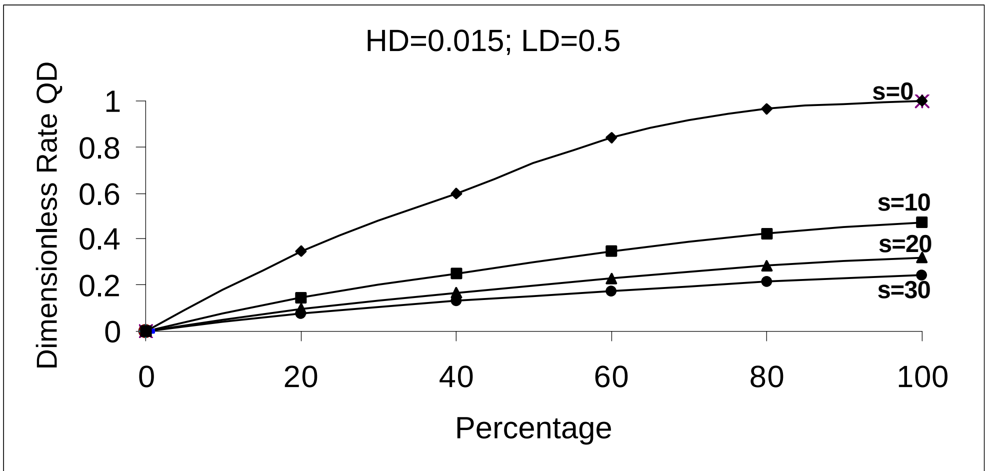

Figure # 8

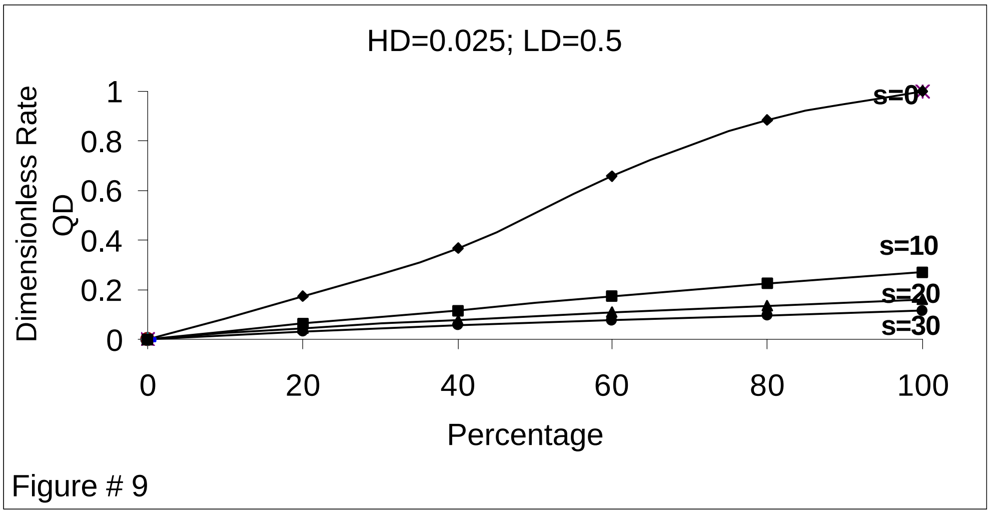

Figure # 9

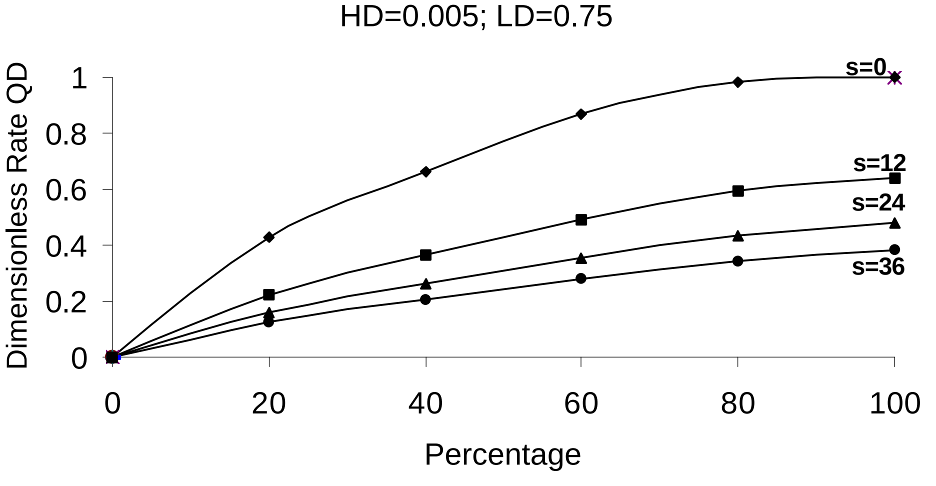

Figure # 10

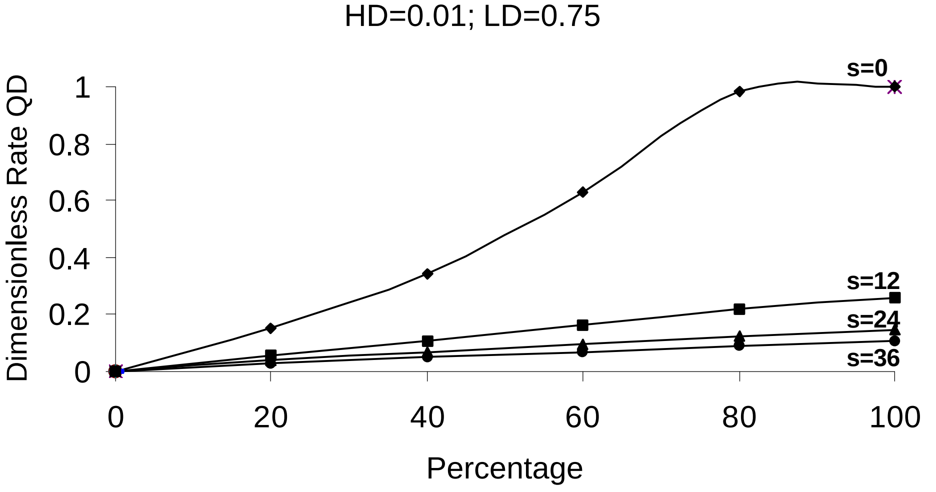

Figure # 11

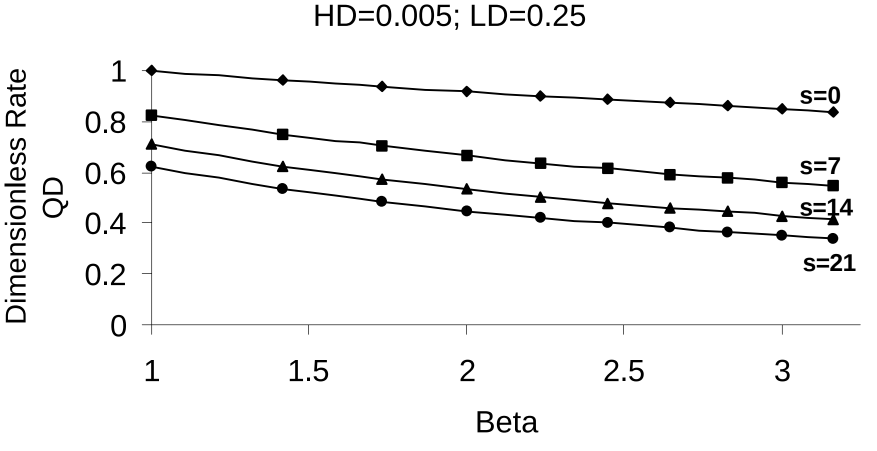

Figure # 12

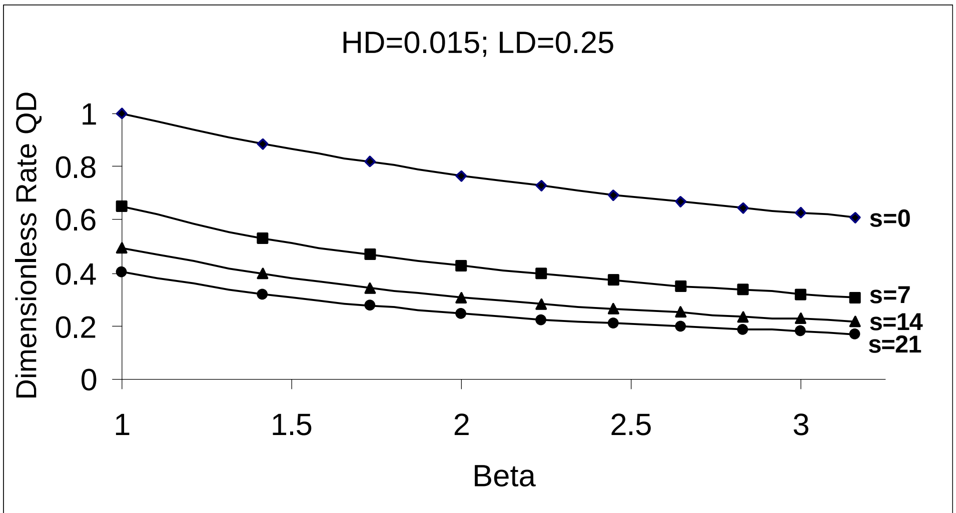

Figure # 13

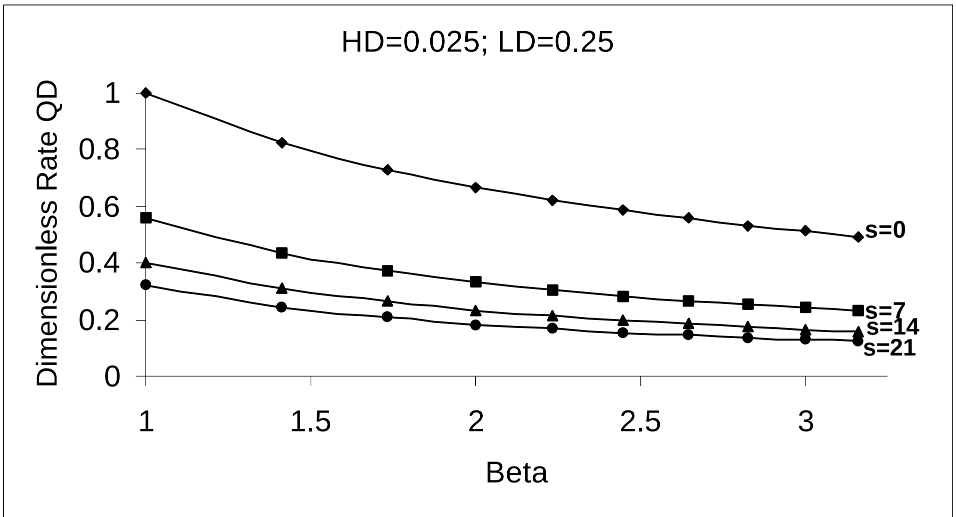

Figure # 14

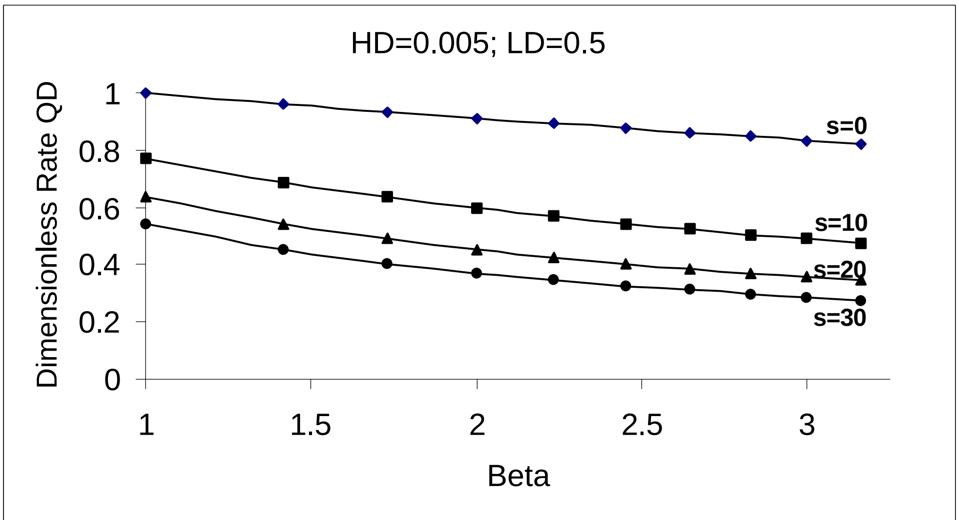

Figure # 15

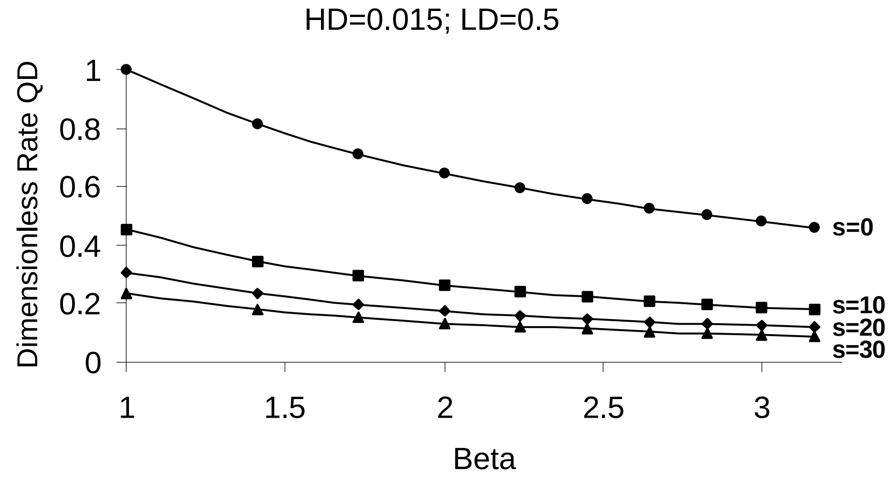

Figure # 16

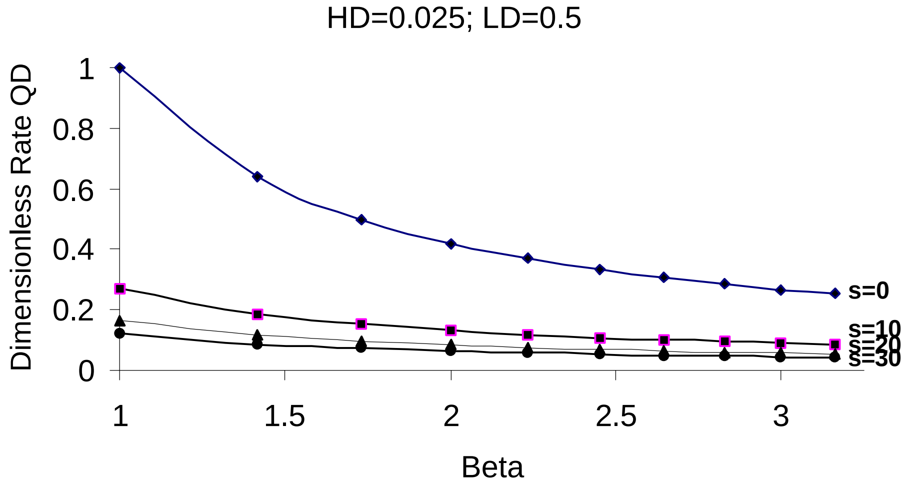

Figure # 17

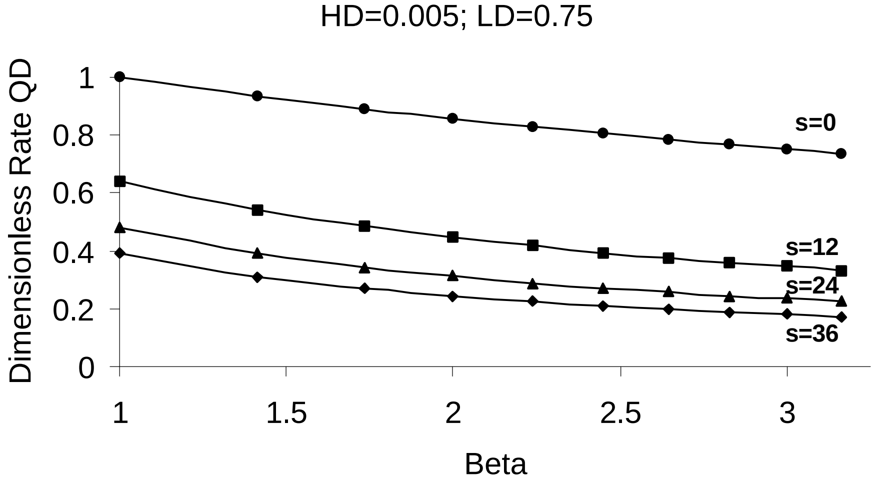

Figure # 18