USE OF A NON-DESTRUCTIVE METHOD TO ESTIMATE DRILLING FLUID INVASION DEPTH IN CORES, APPLICATION TO FORMATION DAMAGE

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ABSTRACT

Formation damage results each year in substantial losses for the oil industry. Most of the damage is due to drilling and completion operations during well construction. This is particularly true when the drilling fluids used are not chosen meticulously. It has been proven that well impairment is due to drilling fluids invasion in the formation, which in turn induces a permeability reduction in the vicinity of the well. One of the main characteristics of a drilling fluid is its bridging ability, which depends on the size of the particles present in the mud. A rule of thumb in order to minimize invasion of the formation is that the average diameter of the solid particles present in the mud, should be no smaller than the third of the median pore throat diameter. Since the source of the solid particles is diverse; weighting agents, cuttings etc, an efficient solid control mechanism is needed. In fact, a compromise solution between an adequate bridging and an efficient solid transport and removal is sought. Laboratory measurements are conducted in order to determine the optimum conditions for a minimum invasion depth and consequently limited damaging effects of drilling fluids.

In this paper a non-destructive method for investigating drilling fluids invasion in cores is suggested. This method is based on the propagation of ultrasonic waves to estimate invasion depth in cores. This method has been validated using Berea sandstone cores saturated with oil at irreducible water saturation. To illustrate its applicability, drilling fluids with different solid particles size distribution have been used to study the impact of the average diameter of the solid particles on formation damage.

The results showed an invasion depth ranging from one to three folds depending on the particle diameter and the contact time investigated. The return permeability varied from 40 to 60%. In-as-much as a too large average diameter of the particles remaining in the mud affects the solid transport and removal ability of a drilling fluid, a too small average diameter results not only in larger invasion depth but also in smaller return permeability. Depending on the best and worst conditions investigated, the skin varies from one to seven folds in the optimum case.

INTRODUCTION

Most field operations are a potential source of formation damage [1]. In particular, the drilling phase can result in serious well impairment if the problem of formation damage is not addressed properly. The detrimental effect of formation damage could only be demonstrated by the amount of research devoted to this topic and the number of scientific conferences organized each year.

The primary causes of formation damage during well construction and especially during work-over operations are related to drilling fluids. Unfortunately there is no safe drilling fluid. An unpublished study by a major oil company [2] has shown that even slight formation damage in a well can result in significant loss of revenue. For instance, for a mild formation damage with a skin of approximately 1, the loss of production rate is in the range of 8 to 10% while severe formation damage with a skin of 20, could result in the loss of more than 80% of the production rate [2]. Similar results have been reported in another study published recently [3].

Another reason why research on formation damage is given such importance is the new trend of the oil industry for horizontal and multilateral drilling. Numerous studies have shown that horizontal wells are more susceptible to formation damage than vertical ones. This is due to the following reasons [4-6].

1. Long duration of the drilling phase and therefore prolonged exposure of the reservoir to drilling fluids.
2. Open hole drilling.
3. Poor cleaning in the case of horizontal wells.
4. Great risk of shale exposure
5. Great risk of overbalance exposure

The objective of this study is to investigate the effect of the average solid particle diameters in the drilling fluid on formation damage. A method based on ultrasonic wave propagation [7] is used to estimate drilling fluid invasion in cores. Since this problem is quite complex due to the large number of parameters involved, it was decided to limit the number of these parameters by using a constant composition drilling fluid in the present study. Berea sandstone cores were utilized in all experiments. In this paper, the formation damage mechanisms are briefly reviewed first then, the experimental set-up and procedures including the ultrasonic method of investigation are described. Finally, the results are presented and discussed.

Formation damage falls into four broad categories depending on the mechanisms of damage involved, namely: Mechanically-, chemically-, biologically-, and thermally induced formation damage [8,9]. The present study concerns the mechanically induced formation damage. More specifically, it addresses the effect of average diameter of the particles on formation damage [10,11].

EXPERIMENTAL SET-UP AND PROCEDURE

Leak-off Experiment

The leak-off experimental set-up is designed to simulate the drilling fluid circulation process in the well bore at the sand face level under bottom hole conditions. A Hassler type core holder is used for this purpose. It is a stainless steel core holder that can accommodate up to 30.48-cm and 5.08-cm diameter cores. The core itself is mounted inside a rubber sleeve and subjected to a confining pressure (overburden pressure). One end piece of the core holder, the injection end, has two ports to circulate the drilling fluid across the face and also to saturate the core with oil or brine. The other end piece, the production end, is used to collect the filtrate/oil/brine, pumped from the injection end.

The set-up described in Figure 1 is designed to simulate in the laboratory the process that leads to formation damage as it occurs in the field. After contamination by the drilling fluids, a method based on ultrasonic wave propagation across the contaminated core is used to determine the length of the damaged zone. Other characteristics of the damaged zone such as the permeability are determined using routine measurement methods.

Ultrasonic Experiment

The experimental set-up for the ultrasonic investigation of the damaged zone consists of a Panametric pulser-receiver model 5072 and two Panametric transducers model V403, one to launch the ultrasonic pulses from one side and the other to receive them from the other side (Figure 2). A Panametric pre-amplifier is used to amplify the transmitted signals and a 500 MHz digital oscilloscope HP 54615B is used to record the results, which are subsequently transmitted to a PC for further processing and analysis. The investigations were conducted in three steps as explained below.

First Step

Initially, the core samples were completely dry and consequently the pores were filled with air. This gave a reference velocity of the ultrasonic waves for the particular sample under dry conditions at different locations along the length.

Second Step

In the second step, the same dry samples were completely saturated with brine and then saturated with oil at irreducible water saturation. The mean velocity in this case was expected to be higher than the case of the dry sample and indeed that has been observed actually (Figure 3).

Third Step

Finally, the oil saturated core samples were exposed to the circulating drilling fluid to simulate the reservoir contamination by mud during the drilling phase. The invading particles will travel a certain distance in the porous medium. This distance is an important parameter to characterize formation damage and therefore to evaluate the skin. The velocity of the ultrasonic waves in the presence of these particles is expected to differ from the velocity in the zones of the porous media where there is only oil and/or water without drilling fluid particles.

VALIDATION OF THE METHOD

The effectiveness of this method is demonstrated in an experiment where a oil saturated core sample was cut into two halves. One half was kept virgin while the other has been exposed to mud contamination in a leak-off laboratory experiment as described previously. The measured velocity profile along the length of the core indeed displays two regions. One region corresponding to the virgin half of the core where the velocity is equal to the base velocity in the oil saturated sample at irreducible water saturation and another region corresponding to the contaminated half where the velocity is higher due to the presence of the drilling fluid particles in the sample. This experiment shows a significant difference between the velocity in the non-damaged sample and the velocity in the damaged sample (Figure 4). It is clear that this jump in velocity can be used to estimate the invasion depth in a sample that has been actually damaged.

The actual experiments used single piece cores but the regions of particles invasion were clearly mapped by this method. A typical result is presented in Figure 5 where the change in the magnitude of the velocity in the mud contaminated zone and the rest of the core indicates clearly the difference between the two regions giving therefore the length of the damaged zone or the invasion depth. Similar experiments have been performed to estimate the invasion depth under different conditions of overbalance pressure, contact time between drilling fluids and cores, and for different average diameters of the solid particles in the drilling fluid. These invasion depth results are combined with the measurement of the permeability in the damaged zone to characterize formation damage under the conditions described before and to estimate the skin using Hawkins relation [12].

CHARACTERIZATION OF FORMATION DAMAGE

Four different types of drilling fluid were used in the present study. The compositions and the characteristics are shown in Table 1. Note that the only parameter that has been changed is the average particle diameter, which were 8, 12, 24 and 41 microns respectively. In fact, the distributions of particle size in the four different drilling fluids used have been determined and are reported respectively from Figures 6 to 9.

The characteristics of the Berea sandstone cores samples used are reported in Table 2. Figure 10 shows the pore size distribution in a typical Berea sandstone core sample. All the experiments have been conducted at 150F temperature and 100 psi overbalance pressure. The confining and pore pressure were 2500 psia and 1000 psia respectively.

Several authors [12-14] have reported that two of the most important parameters that characterize formation damage are the permeability of the damaged zone and the extent of the damaged zone or more specifically the radius of the damaged zone. The most representative relation between these two parameters and the formation damage is given by Hawkin's relation [12]:

$$S = (k/k_d - 1) \ln (r_d/r_w) \tag{1}$$

RESULTS & DISCUSSION

In this section, the effect of particle size on both the invasion depth and the return permeability will be examined. Finally, the effect on the skin will be presented.

Effect of Average Particle Diameter on Invasion Depth

Three sets of experiments were performed using different particle diameters under the conditions described above and for different contact times between drilling fluids and rock sample. Figure 11 shows the invasion depth measured using the Ultrasonic wave propagation method, as a function of the average particle diameter present in the drilling fluid. It is noted that the invasion depth decreases when the average particle diameter increases. This can be explained by the improvement of the effectiveness of the bridging process when the average particle diameter increases. The same trend has been observed for all the experiments performed using different constant contact times between drilling fluids and rock samples. Figure 12 presents the results in the form of invasion depth as a function of total flooding time for different average particle diameter. Concerning the relation invasion depth versus the average particles diameter, it should be observed that:

1. For small contact times (4 hrs), the variation of invasion depth versus the average particles diameter is less pronounced than for longer contact times, (30 hrs). For instance, for the 4 hrs experiment, the decrease in invasion depth from an 8 micron average diameter to a 21 micron is about 10 % only while for a contact time of 30 hrs, the same decrease is in the order of 30% as shown in figure 11.

2. The variation of invasion depth as a function of the total contact time is essentially similar for different average particle diameter studied.

Effect of Average Particle Diameter on Return Permeability

For each one of the experiments reported, the oil permeability of the core sample before and after damage has been measured. The return permeability, which is the ratio of the permeability of the core sample after damage over the permeability of the core sample before damage, has been estimated. Figure 13 where the results of the experiments for the different contact times have been reported, shows that the return permeability increases with the average particle diameter. For instance, for a contact time of 4 hrs, Figure 13 shows that this increase continues until a plateau is reached at an average particle diameter of 15 microns approximately. Beyond this value, the increase in return permeability is negligible. The increasing trend of return permeability with average particle diameter for the 4 hrs constant contact time is also observed for larger contact times. Figure 14 presents the return permeability as a function of contact times.

Effect of Average Particle Diameter on the Skin

Utilizing the return permeability and invasion depth results, the skin has been estimated for all the experiments performed using Hawkin's relation, Eq.1. The results for the 4 hrs contact time are presented in figure 15. It can be seen from this figure that, as expected, the skin decreases when the average particle diameter in the drilling fluid increases. This means, the larger the average particle diameter, the lower the formation damage level. This result is a confirmation of the fact that a more effective bridging process takes place for larger average particle diameter. Again, the improvement is less significant beyond a certain value of average particle diameter. A summary of the results obtained for the different contact times used is presented in figure 16 also. This figure shows that longer contact times result in more formation damage.

CONCLUSION

In summary, the following conclusions can be drawn:

1. A non-destructive method of investigation of drilling fluid invasion depths in porous media is presented.
2. This study shows that in order to minimize formation damage by drilling fluids, an efficient solid control mechanism needs to be implemented.
3. The longer the contact with drilling fluids, the more damage is done to the formation. This means, drilling horizontal wells can result in more severe formation damage and special precaution should be taken in this case.
4. The effect of average particle diameter on formation damage is at least as important as the effect of total contact time between drilling fluids and formation.

ACKNOWLEDGMENTS

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NOMENCLATURE

ΔP = Overbalance Pressure, psi.
k = Permeability in the virgin zone, md.
k_d = Permeability in the damaged zone, md .
r_d = Radius of damaged zone, cm.
S = Skin
r_w = Well bore radius, cm.

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Table 1. Properties and composition of the XC-Polymeric water based mud

	WBM-1	WBM-2	WBM-3	WBM-4
Component	**Composition**			
Fresh water, cc	500	500	500	500
KCl, gm	66.5	66.5	66.5	66.5
XC-Polymer, gm	2.5	2.5	2.5	2.5
Drispac, gm	0.85	0.85	0.85	0.85
Dextrid, gm	10	10	10	10
KOH, gm	0.5	0.5	0.5	0.5
$CaCO_3$(Fine), gm	8.4	8.4	8.4	8.4
$CaCO_3$(Medium),gm	5.7	5.7	5.7	5.7
Average particle diameter, micron	**8**	**12**	**21**	**41**
Properties				
Density, lb/cu. Ft	66.9	67	67	67
Rheology @ 150^{O}F & 600RPM 300RPM 3RPM	43 28 4	43 27 3	43 27 3	43 27 3
10 Sec. gel, lb/100 sq. ft	4	3	3	3
10min gel. lb/100 sq. ft	6	4	5	4
PLASTIC VISCOSITY, cp	15	16	16	16
Yield point,lb/100sq ft	13	11	11	11
PH	10.81	10.80	10.82	10.80
Filtrate API,ml/30min	4.6	4.4	4.6	4.0
Cake API, 32^{ND}/inch	1	1	1	1
Final volume, mls	563	565	565	565

Table 2. Leak-off test results

Sample #	**Particle size(μ)**	**Absolute, Kabs (md)**	**Effective before damage, Keff1 (md)**	**Effective after damage, Keff2 (md)**	**Return Permeability, RP(%)**
FLOODING TIME=4Hrs					
A-17	**8**	**373.4**	**170**	**74.8**	**44**
A-20	**12**	**204.6**	**165**	**98.1**	**59.5**
A-23	**21**	**197**	**126**	**76.6**	**60.8**
A-22	**41**	**155**	**82**	**49.5**	**60.4**
TIME=12Hrs.					
A-26	**8**	**368.6**	**141.7**	**78.6**	**55.5**
A-25	**12**	**408**	**159.6**	**76.91**	**48.2**
A-24	**21**	**309**	**131.5**	**75.5**	**57.4**
TIME =30Hrs.					
A-28	**8**	**528**	**247**	**85.1**	**34.45**
A-19	**12**	**406**	**312.5**	**125**	**39.93**
A-29	**21**	**309.2**	**163.7**	**88.9**	**54.3**

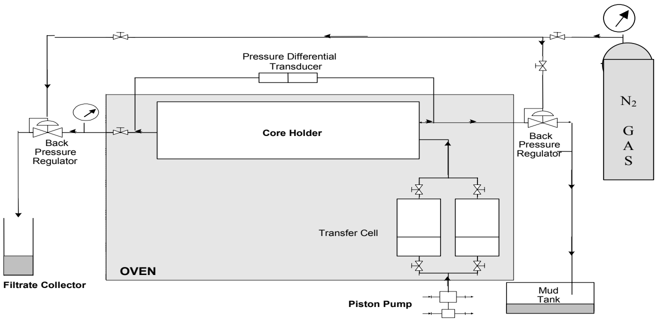

Figure 1. Schematic of dynamic leak-off apparatus

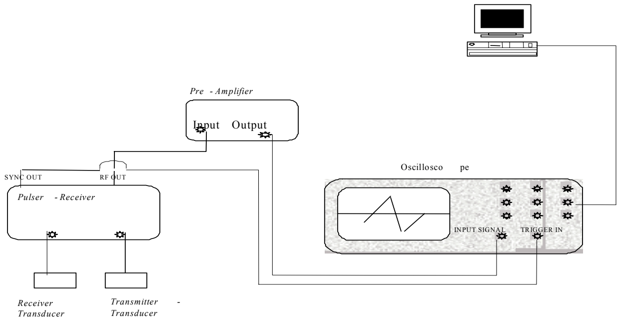

Figure 2. Schematic of Ultrasonic Apparatus

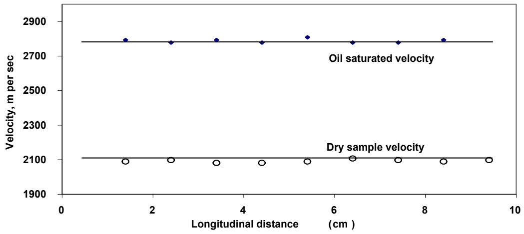

Figure 3. Comparison of the velocity profile of dry and saturated sample, A-17

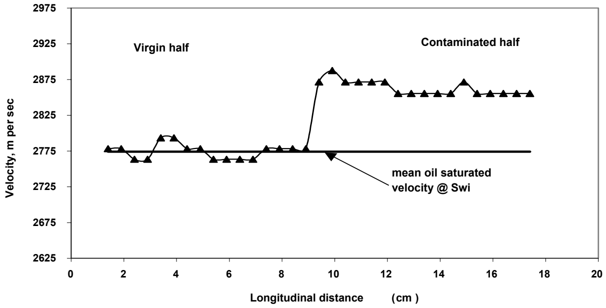

Figure 4. Velocity profiles for contaminated and virgin zones of sample, A-18

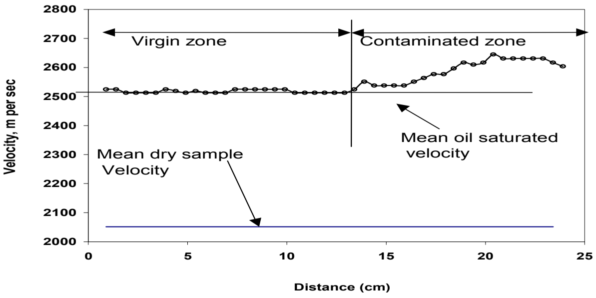

Figure 5. Velocity profiles for dry, contaminated and virgin zones of sample J-16

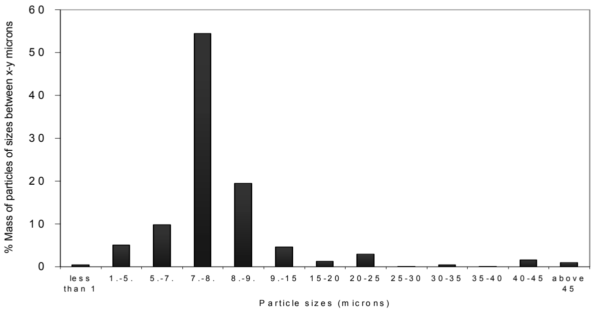

Figure 6. Particle size distribution of sample WBM-1

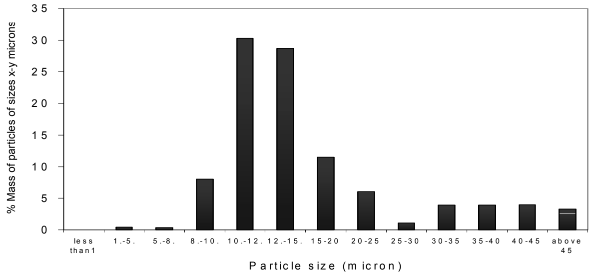

Figure 7. Particle size distribution of sample WBM-2

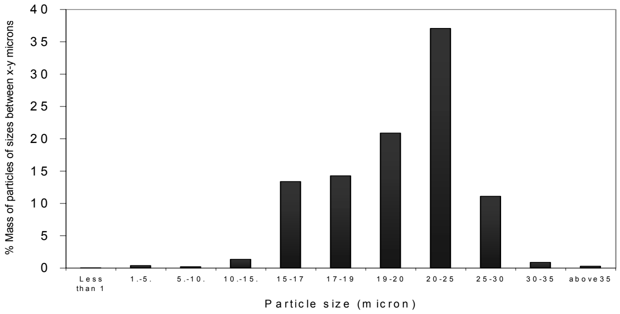

Figure 8. Particle size distribution of sample WBM-3

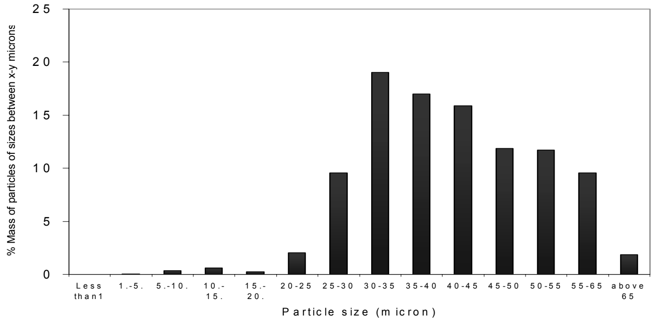

Figure 9. Particle size distribution of sample WBM-4

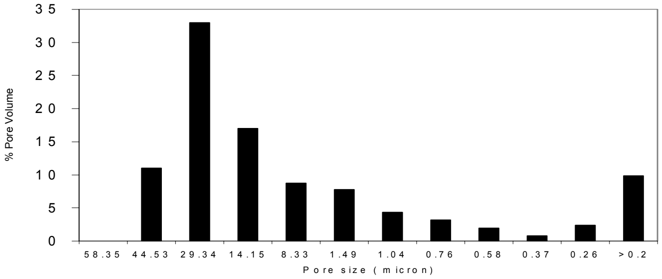

Figure 10. Pore size distribution for a typical Berea core sample

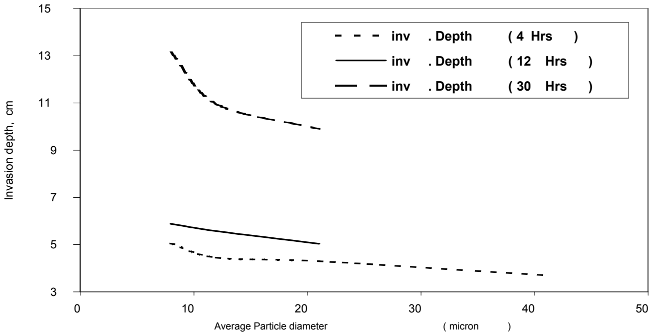

Figure 11. Effect of average particle diameter on the invasion depth

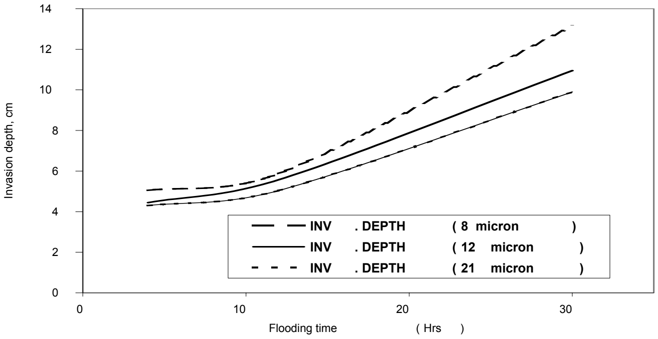

Figure 12. Effect of flooding time on the invasion depth

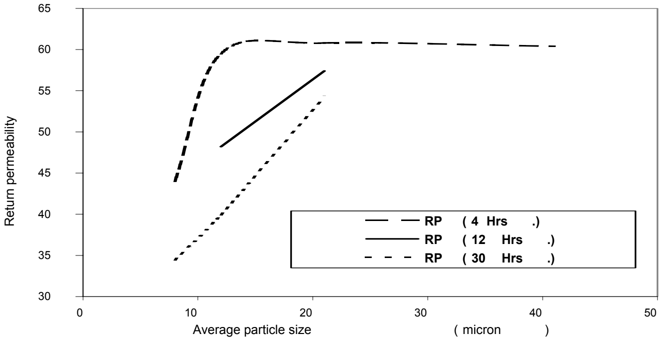

Figure 13. Return permeability as function of average particle diameter

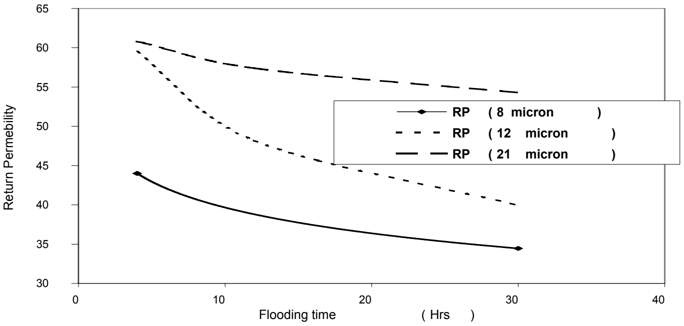

Figure 14. Return permeability as function of flooding time

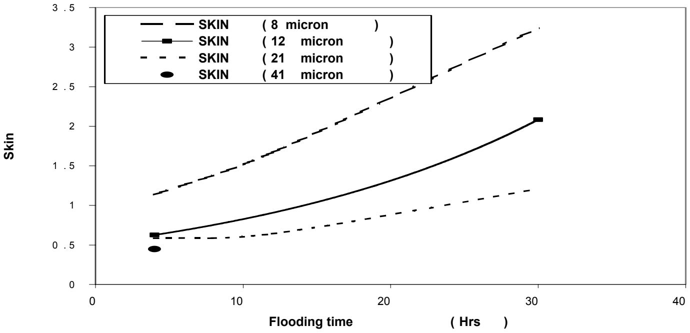

Figure 15. Effect of average particle diameter on the skin

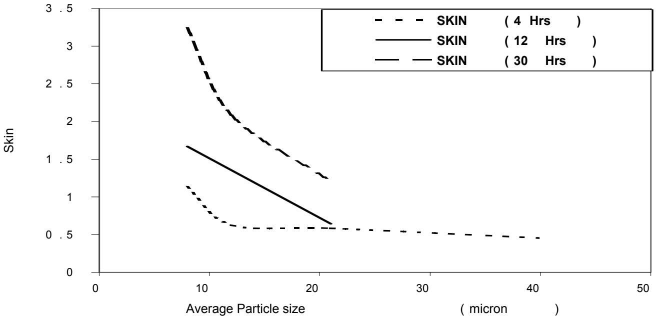

Figure 16. Effect of flooding time on the skin factor