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Title: ULTRASONIC REMOVAL OF ORGANIC DEPOSITS AND POLYMER INDUCED FORMATION DAMAGE

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Los Alamos
NATIONAL LABORATORY

Ultrasonic Removal of Organic Deposits and Polymer Induced Formation Damage

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Abstract

Experiments were conducted that evaluate the feasibility of using high intensity acoustic sources to remove near wellbore formation damage caused by organic deposits (paraffins and asphaltenes) and polymers (HEC). It is shown that mechanical agitation provided by the acoustic waves effectively re-suspends the paraffin and restores the effective permeability of the core to oil to its undamaged condition in a relatively short period of time. The depth of treatment is approximately 12-15 cm. This suggests that an acoustic source with or without solvents may provide an effective method of removing paraffins from the wellbore and the near wellbore region.

Acoustics was not found to be as effective at restoring the permeability of cores damaged by polymers (HEC). Only small (factor of 1.5) increases in permeability were obtained for both poorly mixed and well mixed HEC.

Experiments conducted over a range of frequencies and acoustic intensities allow us to specify the design requirements for a field deployable transducer. Eight such transducers have been incorporated into a through tubing tool that has recently been built and is now available for field testing.

Our results demonstrate that acoustic cleaning may be a viable method for cleaning both the wellbore and near wellbore region when paraffin precipitation is a problem. The method would be particularly effective at treating long sections of pay (horizontal wells) where chemical methods may be too expensive. Acoustic cleaning is much less effective for treating polymer damage problems.

Introduction

This paper is a follow-up to work presented previously, where ultrasonic treatment was used to reduce damage caused by drilling mud infiltration and in-situ fines migration in sandstone core samples[1]. Some background on wellbore and near wellbore formation damage, and a brief review of research on acoustic cleaning is also given in that paper. In addition, Ref. 2 contains a comprehensive review of historical work on acoustic and elastic wave methods for improving oil production. In the present paper, experimental investigations are presented on applying the previously developed ultrasonic techniques to the cleaning of damage created in sandstone cores by paraffin precipitation and polymer infiltration.

The physical and chemical characteristics of many crude oils are such that small changes in temperature and pressure can result in the deposition of waxy material (paraffins), or in some instances, asphaltenes. These precipitates can occur at the bottom of the wellbore adjacent to the producing formation, in the tubing or flow line, or in the formation itself[3]. Methods used to remove wax accumulations can be classified as mechanical, thermal and chemical. Mechanical methods utilize such instruments as scrapers, knives, hooks, etc., to remove the deposits from the tubulars. Chemical methods involve the use of solvents to remove the deposits. Such treatments are usually expensive, due to chemical costs and the extensive safety precautions required in handling toxic chemicals with low flash points. Thermal methods consist of using hot oil or steam to raise the temperature of the oil and the tubulars above the paraffin cloud point. However, these methods can harm the formation if the hot oil containing the dissolved paraffin gets squeezed into the formation.

The use of ultrasonics as a method for the effective removal of paraffin from the wellbore was attempted before[4]. This work was based on the ability of ultrasound to produce heat which in turn causes paraffin to be re-dissolved. However, this is an inefficient, dissipative process, and is considered undesirable. In our study, the removal of paraffin is induced by mechanical agitation caused by acoustic cavitation and micro-streaming[5]. This agitation re-suspends paraffin crystals so that they can flow more easily to the surface with the oil. These mechanisms were not accounted for in the previous study[4].

Polymers are widely used in the oil industry as viscosifiers in completion and fracturing fluids. Studies have shown that the adsorption of polymer molecules to the formation grains results in a local buildup of polymer concentration at pore throats, which in turn causes a reduction in the permeability[6]. It is usually difficult to remove polymer induced formation damage. Much of the work in this field has concentrated on the prevention of such damage in the field through the use of biodegradable or acid-degradable polymers.

In the following, we present strong evidence for the potential effectiveness of ultrasonics for removing paraffin damage and, to a much lesser degree, polymer infiltration. We summarize results for all types of damage investigated to date, and provide quantitative measurements of the wavefield intensity required to achieve effective cleaning. Specifications for a field-deployable ultrasonic transducer are also discussed.

Experimental Apparatus

The experimental apparatus used in this study is described in detail in an earlier publication[1]. Figure 1 shows a schematic of the apparatus and configuration used for the polymer damage

experiments, and Figure 2 shows the same apparatus reconfigured for the paraffin experiments. Berea sandstone core samples, 2.54 cm in diameter and 20.32 cm long, are held in a Hassler dynamic filtration cell, that allows fluid to flow through the sample in either axial direction. Cores are held at 6.2 MPa (900 psi) radial confining pressure, applied to a rubber holding sleeve by a hydraulic oil hand pump. The design includes a flow slot perpendicular to the core axis, that allows fluid to be circulated across the exposed core face. The Hassler cell was modified at the flow-slot end to allow various ultrasonic sources to be attached and coupled acoustically to the core face. Pressure taps along the length of the core holder allow permeability changes to be monitored continuously across three adjacent core sections, labeled "1", "2" and "3" in Figs. 1 and 2, with lengths of 6.35, 5.08 and 7.62 cm, respectively. An accelerometer was used for measuring the intensity of the acoustic field at the core face furthest from the ultrasonic source. A hydrophone (not shown) was used to measure the acoustic intensity in the fluid at the core face closest to the source.

The same two ultrasonic sources described in the previous paper[1] were used in the polymer and paraffin experiments. The first is a cylindrical piezo-electric transducer, 2.54 cm in diameter, that is driven by a sine-wave generator through a power amplifier. Although this device produces measurable signals when operated at frequencies between 10 to 100 kHz, its peak acoustic output power is achieved when driven by a 200-Volt P-P sine wave at the transducer's peak resonance frequency of 36 kHz. With these operating parameters, the low-power source will deliver approximately 0.4 Watts rms acoustic power to the core face. The other source used is a high-power metal acoustic horn that operates at a fixed frequency of 20 kHz and can output up to 250 W of acoustic power into the fluid in which the horn tip is immersed. At this maximum power setting, however, only about 2.9 W of acoustic power (1.2%) is actually delivered to the core face. Most of the power is wasted by generating cavitation in the fluid near the horn's tip and, thus, does not reach the core.

Experimental Procedures

Polymer Damage. These experiments were performed with the experimental configuration shown in Figure 1. The procedure is identical to that used for the mud damage removal experiments reported previously[1]. The fluid circulation system was used to flow hydroxyethylcellulose (HEC) polymer mixtures across the exposed face of the core. Two separate experiments were performed. In the first experiment, damage was induced with a well-mixed polymer solution, prepared by following the API recommended mixing procedure. Because polymer solutions mixed in the field are often not up to API standards, a second experiment was performed with a poorly-mixed solution, prepared simply by agitating the mixture for a shorter period of time.

The remaining steps are identical for both the well-mixed and poorly-mixed solutions. The core sample is first evacuated, and then saturated with a 3% brine solution. Next, the initial permeabilities for core sections 1, 2 and 3 are measured. This is done by measuring the pressure drop across each section while pumping brine through the core at a constant flow rate. To damage the sample, the polymer solution is circulated across the face of the core at a constant pressure differential of 413 kPa (60 psi) for 10 hours. The post-damage permeability changes are measured periodically during the rest of the experiment while backflowing the core with brine. After the permeabilities re-stabilize during initial backflow, the core is sonicated with the two different ultrasonic sources at various power levels, while continuously monitoring permeabilities during the cleaning process. A flow rate of 3.2 cc/min. was used for backflowing brine during all cleaning stages of the polymer experiments.

Paraffin Damage. The apparatus used for these experiments, (Figure 2), is similar to the polymer-damage configuration, except that an oven was used to keep the core holder and flow lines at a particular temperature. At ambient temperature, decane+paraffin mixtures were pumped through the core with the same constant-flow pump apparatus as before. At elevated temperatures, solutions were injected by holding the mixture in a Plexiglas transfer vessel inside the oven and pushing the solution through the core with air pressure at approximately 150 kPa (22 psi).

Paraffin-decane mixtures were prepared with 4 different paraffin concentrations: 5, 10, 15 and 20%. The viscosity of each mixture was determined at different temperatures, using a viscometer. The cloud point temperature of the mixtures was also determined by letting the samples cool down and noting the temperature at which paraffin begins precipitating out of solution. This information was used to select two paraffin concentrations to be used for damaging the core and for subsequent backflow during ultrasonic treatment, respectively. Pure decane could not be used during backflow because it completely dissolves all precipitated wax in the core at ambient temperature. Instead, a decane+paraffin mixture with a cloud point just below ambient temperature was used for backflow. The following summarizes the procedure.

The core is first evacuated and saturated with 3% brine. Pure decane is then injected until irreducible water saturation is achieved. The apparatus is then placed in the oven and the core is damaged with a 20% paraffin mixture by injecting the mixture at 65^{0}C and then cooling the core down to 28^{0}C to precipitate the paraffin. After cooling, the apparatus is removed from the oven and the core is backflowed with a 10% paraffin solution at 28^{0}C, which is close enough to the cloud point that only a fraction of the paraffin is re-dissolved. Backflow is continued until stable permeabilities are obtained for all 3 core sections. A flow rate of 3.0 cc/min. was used for backflowing the 10% solution during all stages of the paraffin cleaning experiments.

Sonication of the core was carried out in the same manner as in the polymer-damage experiments, except that particular care was taken in monitoring the temperature of the sample to ensure that observed permeability changes were caused solely by ultrasonic agitation.

Acoustic Measurements. Measurements of acoustic intensity and power used during ultrasonic treatment were obtained at or near the two opposite ends of the core to determine the input power requirements for cleaning and to estimate the power loss in the rock/coreholder system. Ref. 7

discusses the appropriate acoustics theories and formulae used here. At the far end of the core, a calibrated accelerometer was glued directly onto the core face and the rms acoustic particle acceleration of the rock was measured using a charge amplifier and a digital oscilloscope. The rms acoustic intensity, I_{out}, is then calculated using the following formula:

$$I_{out} = \rho_c v_c a_c^2/(2\pi f)^2, \quad (1)$$

where f is the frequency of the acoustic signal, a_c is the measured rms acoustic particle acceleration at the output core face, ρ_c is the density of the saturated sandstone sample, and v_c is the acoustic propagation velocity of the sample, which was measured separately using pulse transmission delay techniques. The accelerometer measurements, then, provide continuous real-time estimates of intensity during treatment after the signal has propagated through 20 cm of core. Power losses due to cavitation in the fluid, inefficient coupling to the core and anelastic attenuation in the rock will all contribute to the accelerometer measurements.

It was impossible to obtain real-time measurements of source input power because the space between the source end of the core and the ultrasonic transducer was too small to fit a calibrated sensor during treatments. Instead, estimates of intensity at the source input end of the core were obtained separately as follows. The core is removed from the Hassler cell and replaced with a calibrated hydrophone mounted in a cylindrical adapter. The hydrophone tip is positioned where the core face would normally be located. The ultrasonic source is then inserted as in the core cleaning tests and the cavity between the source and the hydrophone is filled with water. The source is operated at various power levels, and the hydrophone is used to measure rms acoustic pressure, p_w, in the water, which is converted to input intensity, I_{in}, using:

$$I_{in} = p_w^2/\rho_w v_w, \quad (2)$$

where ρ_w and v_w are now the density and acoustic velocity of the water. This indirect procedure provides reasonable estimates of the input acoustic intensity used to achieve effective cleaning during treatment experiments. Applied and transmitted acoustic power, P_{in} and P_{out}, respectively, and total acoustic energy, E, delivered to the sample, are calculated from:

$$P = I\pi r_c^2, \quad (3)$$

and:

$$E = Pt, \quad (4)$$

where r_c is the radius of the core faces, and t is the cumulative treatment time that ultrasonic power was applied to the core.

Results and Discussion

Paraffin Damage Removal. Permeability data for the paraffin experiments are given for each core section as the ratio of the values measured at various cleaning stages after damage is induced, k_d, divided by the initial value, k_i, before damage was induced. Detailed experimental results are shown for two separate cleaning experiments in Figs. 3–6. Based on the cloud point measurements, two decane+paraffin solutions were chosen, one for damaging the core and another for backflowing, as described earlier.

Fig. 3 shows plots of the permeability ratio, k_d/k_i, for all three core sections, plotted against total backflowed pore volumes of the 10% mixture, after damaging the core. Backflow in the absence of ultrasound produced stable permeability ratios, just prior to sonication, of 0.4, 0.35 and 0.33, for sections 1, 2 and 3, respectively.

The core was first sonicated with the low-power, piezo-electric source at two different frequencies, 20 and 30 kHz. Although the same drive amplitude was used in both cases, the peak transmitted acoustic intensity and power were a factor of 4 lower at 20 kHz than at 30 kHz because the transducer's resonant frequency, at which maximum power output is achieved, is 36 kHz. Fig. 4 shows permeability changes observed during the low-power treatment. No improvement was observed in any core section during the 20 kHz treatment, but at 30 kHz section 1 is restored to its initial undamaged state in approximately 6 pore volumes. The cleaning effectiveness is probably due more to the increase in the input acoustic intensity, I_{in} = 100 W/m^2 at 20 kHz vs. I_{in} = 400 W/m^2 at 30 kHz, than to other frequency-dependent effects. This is supported by previous work[1], as well as by the following results.

Fig. 5 shows the effects of additional sonication with the high-power acoustic horn on the same sample. The horn operates at a fixed frequency of 20 kHz. For this experiment, the horn produced an input acoustic intensity of I_{in} = 1800 W/m^2. Integrated over the face of the core, this gives an equivalent input acoustic power of P_{in} = 0.91 W. Power was delivered in pulses of 3 minutes duration, once every 1.5 pore volumes. Immediately after the first horn pulse, the permeability ratio in section 1 jumped to k_d/k_i = 1.2 and remained there. Section 2 increased from 0.4 to 0.85 in approximately 12 pore volumes. Acoustic power was applied for a total of 24 minutes (8 pulses @ 3 minutes each). Total cumulative acoustic energy input to the core was E = 1.3 kJ.

A second experiment was performed with a newly damaged core sample. The goals were to first determine the minimum power input threshold above which noticeable cleaning occurs, and second, to repeat the previous experiment with the acoustic horn used to clean both sections 1 and 2. After damage and initial backflow, as before, the permeability ratios in sections 1 and 2 were 0.40 and 0.30, respectively. Ultrasound was applied with the low-power transducer at 36 kHz. The power output of the source was raised slowly from 0.0 W until the permeability in section 1 began to change. This point occurred at an input intensity of I_{in} = 300 W/m^2, which explains why no cleaning was observed in the first stage of sonication for the first paraffin experiment (Fig. 5), until the effective intensity was raised from 100 to 400 W/m^2. Thus, this threshold intensity places a lower bound on required acoustic power for significant paraffin cleaning at P_{in} = 0.15 W. The power threshold tests improved the permeability ratio for

section 1 slightly to $k_d/k_i = 0.45$. The acoustic horn was then used to perform the remaining cleaning for sections 1 and 2. The results are shown in Fig. 6. The horn, operating at the same power input level as before, achieves cleaning in both sections similar to the previous combined experiment. Approximately 9 pore volumes and 18 minutes total sonication time were required. Total cumulative acoustic input energy used was $E = 0.9–1.0$ kJ.

Combining the input acoustic energy estimates from both paraffin experiments provides the following guidelines for ultrasonic cleaning of paraffin damage. Approximately 0.9–1.3 kJ of acoustic energy was sufficient to completely restore section 1 (6.35 cm) to its initial undamaged permeability and to increase the permeability ratio in section 2 (5.08 cm) by approximately 100% relative to the pre-sonication value. No significant improvement was observed in core section 3. The maximum penetration depth for effective ultrasonic cleaning of paraffin, then, is approximately 12 cm. Total ultrasonic treatment duration required at input powers of 1.0 W is on the order of 20 minutes. Required treatment duration should be inversely proportional to applied input intensity, except below the lower threshold of 300 W/m^2, where no cleaning was observed regardless of the duration. To achieve this intensity uniformly at the wall of a 10-cm (4-in.) diameter wellbore, a minimum power input level of 2–3 W is required for every 2.54 cm (1 in.) of wellbore length treated. This combination of parameters can be achieved in a downhole acoustic cleaning tool, and thus, ultrasonics could become an economically viable technique for treatment of paraffin problems downhole.

In both paraffin experiments, the final permeability in section 1 after cleaning appears to be higher than the initial pre-damage value. We are reasonably certain, given the observed repeatability, that this is caused by removal of formation fines in section 1. Increases in permeability due to fines removal were observed and reported in Ref. 1. Further experiments need to be conducted to prove this conjecture.

Throughout both paraffin experiments, the temperature of the fluid near the face of the core was monitored continuously. Ultrasonic pulse durations were sufficiently short that no significant temperature changes were induced by the high-intensity excitation. Thus, the observed cleaning must be due to either re-suspension or increased solubility of paraffin crystals caused by mechanical agitation or mixing. The most likely mechanism producing this agitation is acoustic microstreaming[5] in the pore space, which can occur at relatively low acoustic intensity.

Although acoustic cavitation[5] is another possible mechanism that could actually cause chemical breakdown of paraffins, the intensity measurements, I_{out}, at the output end of the core showed that the total power loss, P_{out}/P_{in}, of the core system was approximately 1/30. This loss is due mainly to acoustic coupling inefficiency between the fluid and core face, and to natural anelastic attenuation in the rock. There was no practical technique found for measuring the actual energy distribution in the core samples during sonication, but given the strong losses observed over 20 cm of core, and the modest input power levels applied, it is unlikely that acoustic pressure levels in the rock at depths greater than 1–2 cm were sufficient to generate acoustic cavitation in the pore space. In fact, the experimental evidence suggests that it is desirable to suppress cavitation in the coupling fluid because this consumes large amounts of acoustic energy that would otherwise be transmitted to the rock. With the acoustic horn delivering 1.0 W to the core face, the device was operating at 80 W acoustic output into the coupling fluid. Thus, almost 2 orders of magnitude in potential cleaning power are lost primarily to wasted cavitation. Any potential downhole ultrasonic source should be designed to transmit power more uniformly than an acoustic horn does, to avoid generating localized regions of high acoustic intensity near the face of the transducer. As an added benefit, the high fluid pressures typically encountered in wellbores will suppress cavitation and allow more acoustic energy to be delivered to the wellbore wall.

Polymer Damage Reduction. The results for ultrasonic cleaning of well-mixed and poorly-mixed polymer damage were similar in both cases, and we only present detailed experimental data for the well-mixed polymer experiment here. Permeability data are given as ratios, k_d/k_i, for each core section as before. After flowing the polymer solution across the core for 10 hours at 413 kPa (60 psi) differential fluid pressure, the permeability ratios for the first two core sections were both approximately 0.05. Due to equipment malfunction, the permeability for section 3 could not be measured for the well-mixed polymer experiment. However, the results for section 3 with poorly-mixed polymer, as well as for all previous experiments[1], show that ultrasonic cleaning is not effective at depths greater than approximately 12-15 cm.

Fig. 7 shows plots of the permeability ratio, k_d/k_i, for sections 1 and 2, plotted against total pore volumes of brine solution pumped through the core during the initial backflow phase of the experiment. Backflow, in the absence of ultrasound improves the ratio to approximately 0.22 and 0.53 in sections 1 and 2 respectively. No additional improvement was observed with further backflow alone.

The core was then sonicated with both the low-power transducer and the high-power acoustic horn. Fig. 8 shows the observed permeability changes versus pore volumes of brine backflowed during ultrasonic treatment. The low-power source was used first, operating continuously at resonance (36 kHz), with estimated input acoustic intensity of $I_{in} = 800$ W/m^2. Although the permeability in section 2 fluctuated, there was no permanent improvement in either section. Next the core was treated with the acoustic horn, operating at $I_{in} = 5700$ W/m^2, for 5 minutes every 1-2 pore volumes.

As shown in Fig. 8, the horn increased the permeability ratio in both sections by approximately 50-70% relative to the values at the beginning of ultrasonic treatment. Acoustic power input was $P_{in} = 2.9$ W. Cumulative ultrasonic energy, applied for approximately 70-80 minutes, was $E = 12.0$-14.0 kJ. The total energy required to clean polymer damage is an order of magnitude larger than that required to treat paraffin damage. This indicates that the cleaning mechanism for polymer damage is not dominated by re-suspension or increased solubility due to mechanical agitation, as in the case of paraffin damage. Apparently much more work is required to loosen the accumulations of long-chain polymer molecules that clog the pore throats. Ultrasonics alone does not appear to

be a viable technique for treating polymer damage. It could, perhaps, be combined with chemical treatments to accelerate the breakdown of polymer and enhance the removal of byproducts. This approach still needs to be investigated.

Summary

The previous paper[1] did not report input acoustic power used in the mud-damage and fines-migration cleaning experiments because the hydrophone measurements were taken after those results had already been reported. To compare cleaning effectiveness and energy requirements for all four types of damage investigated to date, the most significant results from all experiments performed are summarized in TABLE 1. For each type of damage treated, the table lists, in order by column, the permeability ratios measured before and after ultrasonic treatment for core sections 1 and 2, followed by the ranges of acoustic intensity and power applied, and finally, the typical cumulative input acoustic energy delivered to the core during each type of experiment.

Clearly, the energy cost to achieve a given net permeability recovery is lowest for treating paraffin problems, and highest for polymer damage. Although the acoustic energy used for treating mud and fines damage was similar to that for paraffin, and the percentage increase in permeability ratios was larger, cleaning was effective only in core section 1.

The paraffin experiments reported here and the main discussion above focused on the ability of acoustic energy to clean paraffin deposits precipitated within the rock pore-space matrix. This is a much more challenging task than the treatment of paraffin accumulations on the wellbore wall or in tubulars. Direct exposure of these deposits to acoustic radiation allows them to be removed much more easily than from the formation. Visual experiments conducted with an ultrasonic source immersed in paraffin+decane solutions in glass and metal containers show that paraffin deposits are removed from the walls and re-suspended within several seconds after applying modest power levels of acoustic energy.

Conclusions

Experiments were performed to investigate the effectiveness of using ultrasonic energy to reduce formation damage caused by paraffin precipitation and HEC polymer infiltration in Berea sandstone cores. Previously reported work indicated that ultrasonics is capable of significantly reducing damage induced by drilling mud infiltration and in-situ fines migration. Similarly, positive cleaning results were obtained for paraffin and polymer damage. Approximately 1.4 kJ of acoustic energy at 20 kHz removed all precipitated paraffin from the first 6.35-cm core section and increased the permeability in the second 5.08-cm section by 100%. An order of magnitude more energy was required to significantly clean damage caused by polymer infiltration, and the net permeability increases were only about 50% in both core sections. Ultrasonic cleaning appears to be a viable technique for treating paraffin problems, especially if combined with solvent soaks. The dominant physical mechanisms appear to be increased re-suspension and solubility of paraffin due to mechanical agitation. Polymer infiltration is much harder to remove acoustically than any other type of damage investigated. The viability of using ultrasonics to remove polymer damage in the absence of complimentary chemical treatments is questionable at best. Acoustic power requirements measured during cleaning experiments provide working specifications for possible ultrasonic sources that could be used in downhole applications. Transducers with these specifications have recently been developed and a prototype downhole cleaning tool has been built. This tool will be field tested in the near future.

Nomenclature

a = acoustic particle acceleration, L/t^2, m/s^2
E = acoustic energy or work, mL^2/t^2, J
f = acoustic frequency, 1/t, Hz
I = acoustic intensity, m/t^3, W/m^2
k = permeability of core samples, L^2, md
p = acoustic pressure, m/Lt^2, Pa
P = acoustic power, mL^2/t^3, W
r = radius, L, m
t = time duration of applied acoustic power, t, s
v = acoustic wave propagation velocity, L/t, m/s
ρ = density, m/L^3, kg/m^3

Subscripts

c = core
d = damaged state for permeability
i = initial undamaged state for permeability
in = input acoustic parameters at 0 cm core depth
out = output acoustic parameters at 20 cm core depth
w = water

Acknowledgments

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TABLE 1–SUMMARY OF ULTRASONIC CLEANING RESULTS AND PARAMETERS

Type of Damage	Core Section 1 (6.35 cm)		Core Section 2 (5.08 cm)		Input RMS Intensity (W/m^2)	Input RMS Power (W)	Total Input Energy (kJ)
	K_d/K_i before sonication	K_d/K_i after sonication	K_d/K_i before sonication	K_d/K_i after sonication			
Mud	0.07	0.32	1.0	1.0	1500–4500	0.76–2.28	1.3
Fines	0.03	0.18	0.03	0.03	1200–3000	0.61–1.51	0.7–1.4
Paraffin	0.40	1.20	0.40	0.85	300–1800	0.15–0.91	0.9–1.4
Polymer	0.22	0.37	0.53	0.78	5700	2.89	12.0–14.0

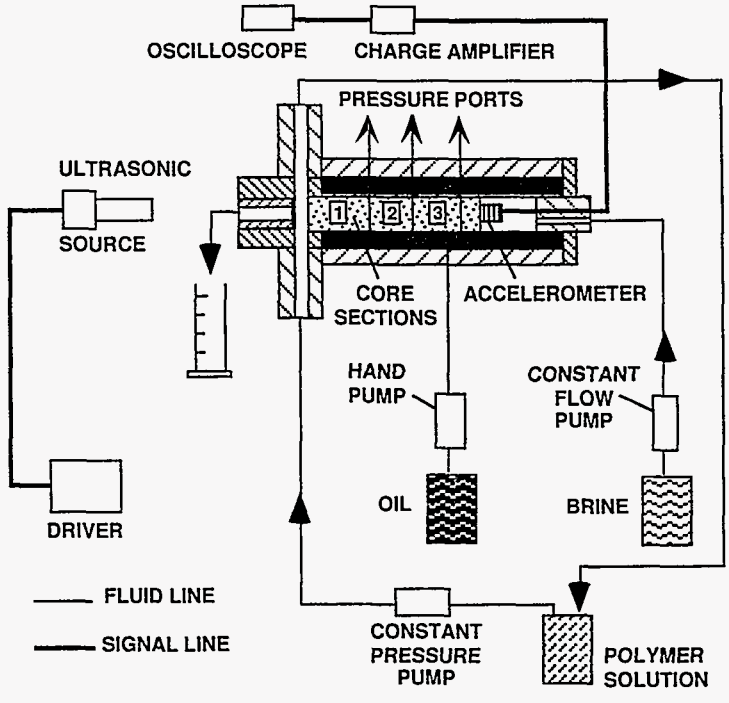

Fig. 1–Apparatus and configuration used for the polymer damage experiments.

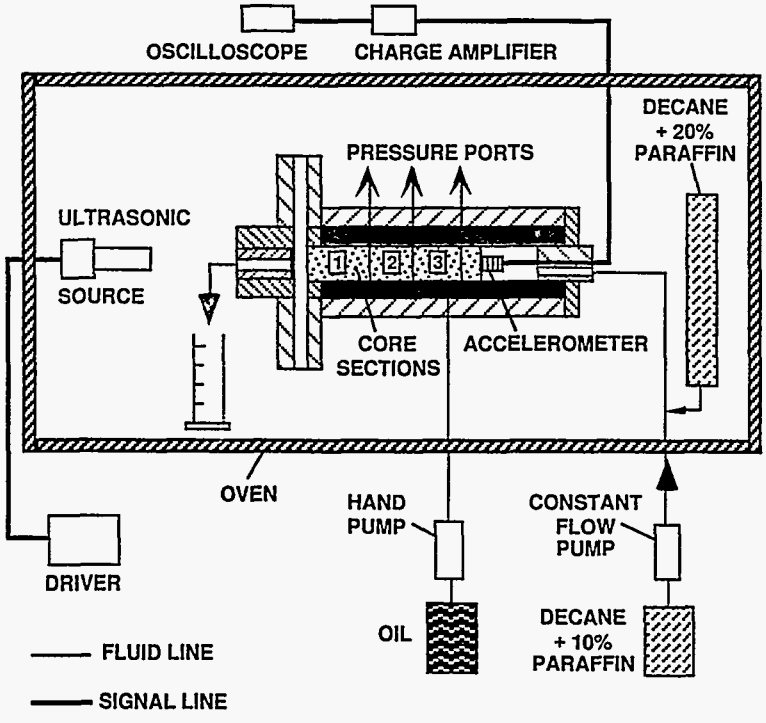

Fig. 2–Apparatus and configuration used for the paraffin damage experiments.

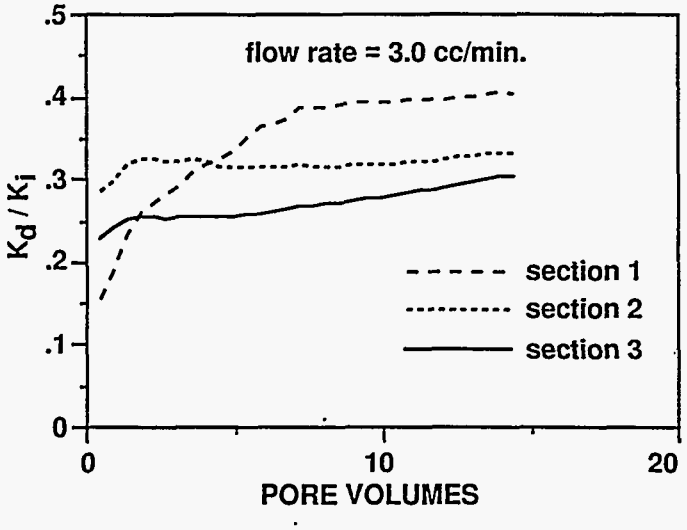

Fig. 3–Permeability ratios during backflow alone for 3 paraffin-damaged core sections plotted vs. total backflowed pore volumes of a mixture of decane plus 10% paraffin. Backflow commenced after damage was induced (see text). Ultrasonic treatment began only when no further changes were observed during backflow alone.

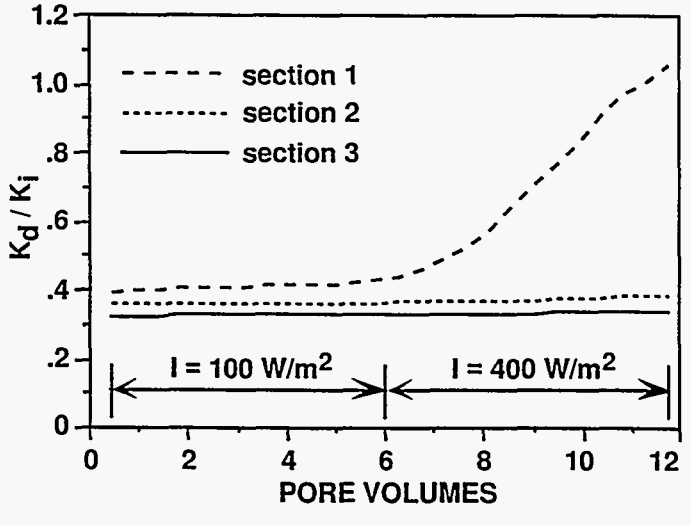

Fig. 4–Permeability changes observed during ultrasonic treatment at 2 different power outputs, using the low-power source. Treatment began after the permeabilities stabilized during the previous backflow phase (Fig. 3). The source was running continuously during this intial cleaning phase of the experiment.

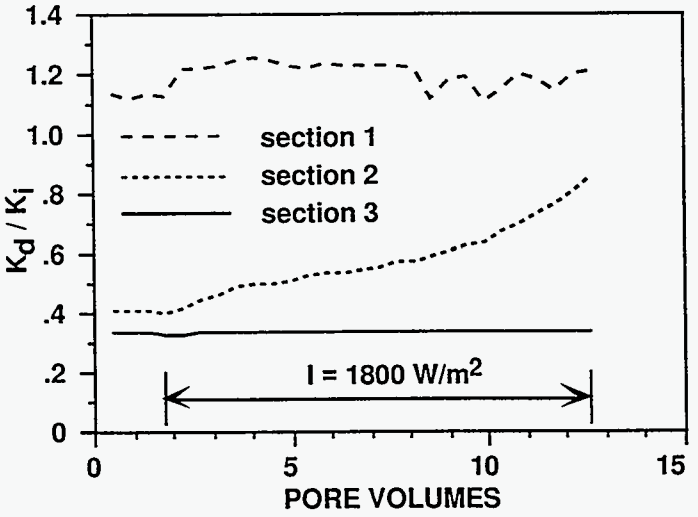

Fig. 5–Additional permeability change observed during ultrasonic treatment with the high-power acoustic horn after the previous low-power treatment (Fig. 4). The horn was turned on for 3 minutes once every 1.5 pore volumes pumped. Cumulative treatment duration was 24 minutes.

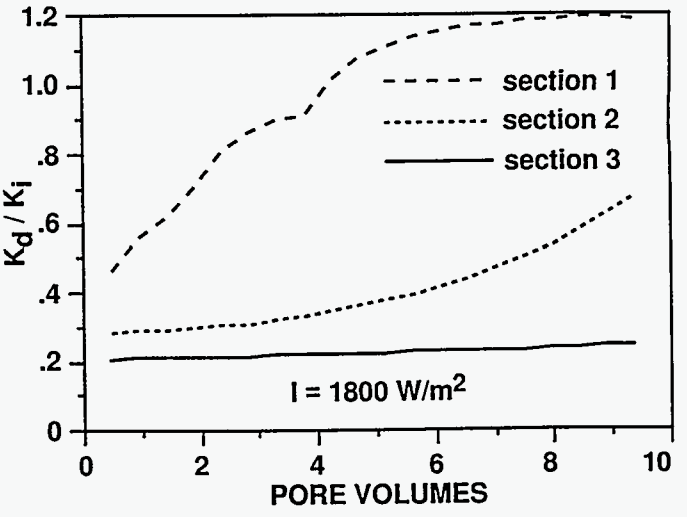

Fig. 6–Paraffin damage removal using only the acoustic horn. Treatment began after initial damage, backflow, and cleaning-threshold power tests (see text). Ultrasound was applied for 3 minutes every 1.5 pore volumes, as before (Fig. 5). Cleaning was stopped when section 1 stabilized.

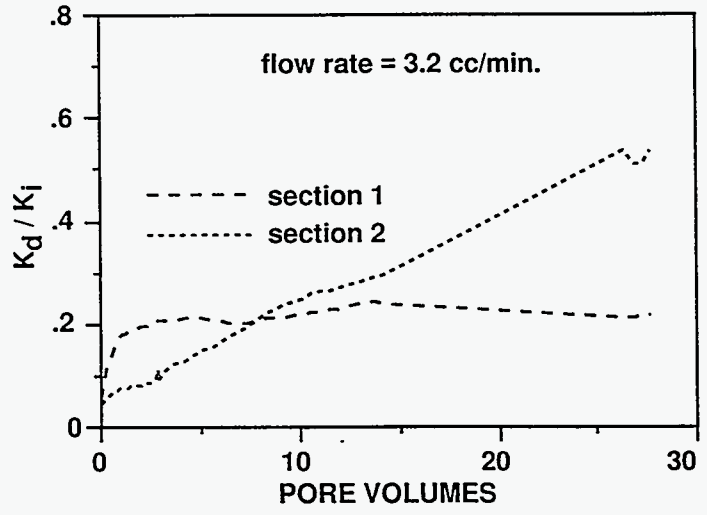

Fig. 7–Permeability ratios during backflow alone for first 2 polymer-damaged core sections plotted vs. total backflowed pore volumes of brine solution. Backflow commenced after polymer damage was induced. Ultrasonic treatment began only when no further changes were observed during backflow alone.

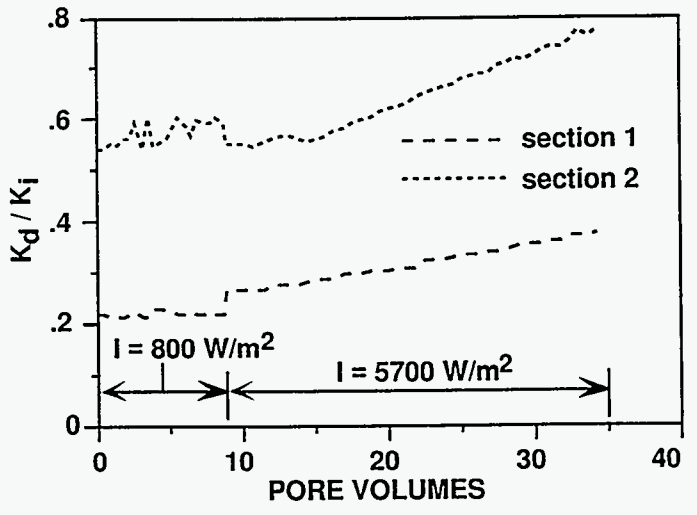

Fig. 8–Permeability changes observed for the polymer-damaged core during ultrasonic treatment with 2 different sources. Low-power treatment began after stable permeabilities were obtained during backflow (Fig. 7). High-power treatment with the acoustic horn began after 9 pore volumes were pumped.