SPE-169770-MS

Scale Removal with Ultrasonic Waves

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This paper was prepared for presentation at the SPE International Oilfield Scale Conference and Exhibition held in Aberdeen, Scotland, UK, 14–15 May 2014.

Abstract

Today, ultrasound is a widely used technology for a number of industrial applications, from processing liquids and slurries, cleaning of optical lenses and jewellery, purification of water, enhancement of mechanical and physical properties of metals, welding, dispersing, humidifiers, to material testing. In the oil and gas industry the ultrasonic technology is typically used for measurement applications. This paper describes first test and research results using ultrasonic waves to remove scaling in the borehole. So far most standard scaling treatments involve the use of chemicals. With ultrasonic treatment, it may be possible to reduce or even substitute the chemical applications. This transgression from a chemical to a physical cleaning process would most likely save costs and reduce the environmental impact. Scaling from calcium carbonate, gypsum/anhydrite or barium/strontium sulfate is considered a major issue with oil and gas production, causing the industry enormous efforts on prevention and removal. To assess the usability of ultrasound for scaling removal, a series of laboratory experiments were conducted, starting with gypsum due to its easy handling and continuing with the more critical calcium carbonate scaling. The cleaning effects could be proven and the main factors influencing the ultrasonic cleaning efficiency could be identified in the laboratory. This paper will present and discuss the findings so far and will give an outlook on future research issues with ultrasonic scale removal.

Introduction

Scale is a common problem during production operations and can lead to significant production decline. Typical scales found in the field are the carbonate and sulfate salts of calcium, barium and strontium. The formulation of carbonate scales is mainly caused by changes in temperature and pressure, whereby sulfate scales come for the most part from mixing incompatible waters. A lot of different scaling prevention and removal methods are found in the literature. Most commonly used in the industry are chemical solutions like scale inhibitors. If these are not sufficient to hinder the scale to formulate, a scale dissolver can be used(Sanchez, et al., 2009). Furthermore mechanical methods for scale removal are available, even if they are not used that often. In this paper ultrasonic waves are presented as a new method for scale removal. The main driving parameters for scale removal by ultrasonic waves are tested in the laboratory, to identify their impact on the purification. Artificially generated gypsum scaling was used for the laboratory tests due to its easier fabrication and handling.

Working principle of ultrasonic cleaning

Ultrasound is used for a wide variety of processes in chemical and related industries. It has to be distinguished between “high frequency ultrasound” and so called “power ultrasound”. High frequency ultrasound ranging between 2 to 10 MHz is typically used for measurement applications. Power ultrasound lies between 20 and 100 kHz and is used for cleaning, plastic welding and also for sonochemistry. In this paper the focus is put on the cleaning applications.(Mason & Lorimer, Applied Sonochemistry, 2002)

Cavitation is supposed to be the most forceful physical reason for ultrasonic cleaning. Due to the ultrasonic waves pressure nodes and low-pressure zones are created in a fluid. Within the low-pressure zones small bubbles can be formed. These bubbles are filled with gas or steam and grow until they reach a critical diameter. When this critical diameter is reached the bubbles implode. The critical diameter of a bubble in water at a frequency of 20 kHz is about 170 m. If a bubble implodes near a surface, the implosion is asymmetric and a fluid jet in direction of the surface is created. These jets can have velocities up to 400 km/s and can act abrasive. Also shock waves are generated due to the bubble implosions which propagate in the surrounding media.(Lerch, Sessler, & Wolf, 2009)In the literature are also found applications were cleaning occurred and no cavitation was measured. In principle hydrostatic pressure has an inhibitory effect on cavitation. While hydrostatic pressure is rising the cavitation decreases until it disappears completely. As a precondition to this statement the sound intensity has to be constant during the pressure rise. In water wells cavitation was measured down to a depth of about 20 meters, deeper it was not detectable any more. Nevertheless, cleaning effects due to ultrasound can be observed in deep wells, too. (Bott, Wiacek, & Wilken, 2003)

Due to the high complex proceedings in the profoundly non-linear cavitation fields and the fact that the relation between cavitation and its cleaning effect is still not understood completely, most ultrasonic systems are designed empirically nowadays. It is presumed that the local distribution of cavitation is not constant. For example there are some pressure nodes due to standing ultrasonic waves in an ultrasonic cleaning bath. So the cleaning effect correlates with the pressure distribution of the standing wave. This means some zones get cleaned very well, while others, particularly at the pressure nodes show almost no cleaning at all. In ultrasound baths it is possible to vary the field of the standing wave and thereby increase the cleaning efficiency.(Lerch, Sessler, & Wolf, 2009)

The cleaning devices used in our laboratory operate at a working frequency of about 20 kHz; the samples are fixed during the ultrasonic treatment.

Preparation of Samples

To ascertain that the samples used for the laboratory tests comprise a defined and reproducible quality a setup was designed to generate the gypsum samples artificially. A low grade steel half pipe formed the basis of the sample. Half pipes were taken because of their geometric properties. The pipes with an inner diameter of 28 mm were cut into 70 mm long pieces and then along their longitudinal axis into half pipes. For the gypsum sample commercially available gypsum (GI 70 Murexin) was used. The gypsum powder was mixed with water and the half pipe pieces were dipped into the gypsum slurry. The samples were dried on air in the laboratory. The laboratory is a very controlled environment, if one considers temperature and pressure conditions and the samples could be prepared in a very short time compared to the time it would take in the field, until scaling occurs.

Equipment and Settings

The treatment with ultrasonic waves also called “sonification” of the artificially generated gypsum samples was done with an ultrasonic device (DG 2000) from the Swiss company Telsonic AG. The device is operated with a working frequency of about 20 kHz and its maximum power is 2 kW. The generation

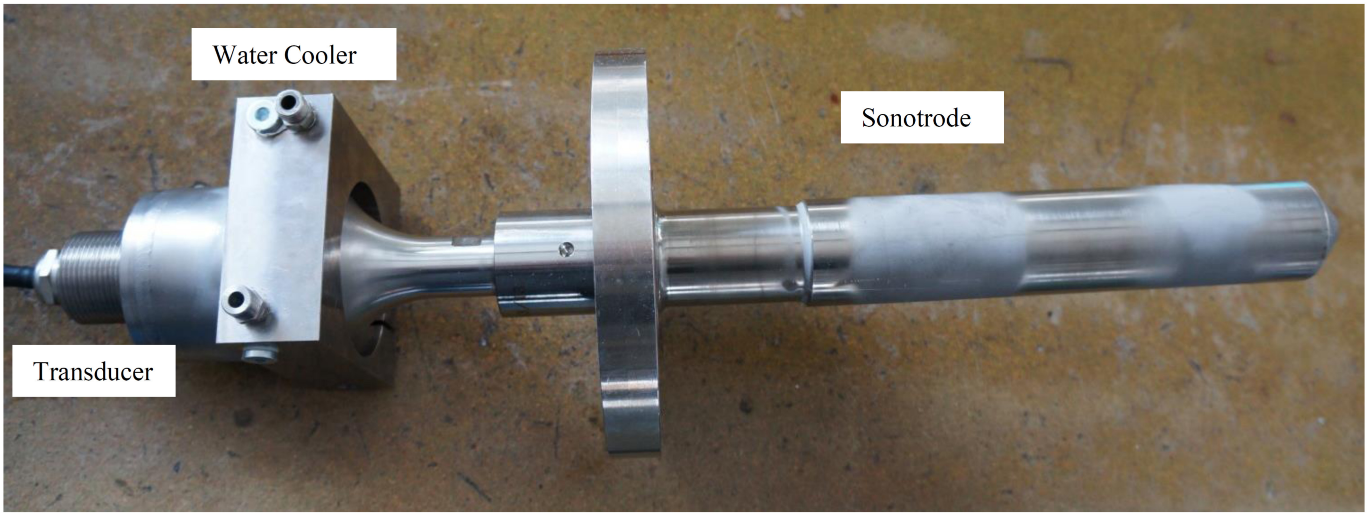

Figure 1—Sonotrode with Transducer and Water Cooler

of the ultrasonic waves is based on the reverse piezoelectric effect and therefore the working frequency cannot be adjusted, because it is given by the piezoelectric material used in the transducer. The amplitude of the ultrasonic waves can be adjusted between 50 and 100 %, while the maximum amplitude on the end face of the sonotrode is about 100 μm. The regulation of the power is possible between 400 and 2000 W. A limiting factor is that either the amplitude or the power can be set on a certain value, but not both on the same time, because they are interdependent. If one parameter it set to a constant value the other is regulated automatically by the generator. It was decided to set the amplitude on a fixed value for the experiments and record the corresponding power every minute of the treatments duration. It is assumed that a larger amplitude results in a better purification. There is also a timer function available on the generator. It was used for all experiments to set the exact required duration of the sonification. A longer duration of the sonification is expected to lead to a better purification effect.

The vibrating horn is called “sonotrode” and is responsible for the transportation of the vibration from the transducer to the liquid. The transducer converts the electrical power to mechanical vibrations. The sonotrode itself and the transducer are seen in Figure 1 with a simple water cooler attached to avoid overheating of the piezoelectric material in the transducer higher than about 90 °C.

The complete equipment is displayed in Figure 2 where the sonotrode is put into a steel cylinder. The cylinder has to be filled with liquid, in our case tap water, because the ultrasonic device best operates in liquids. Between the inner wall of the cylinder and the sonotrode there is a gap of some centimeters where the sample was positioned. The sample was fixed by a special construction of polystyrene on the bottom of the cylinder, 1 cm away from the sonotrode. The test setup displayed in Figure 2 shows an experiment with flow. The water is pumped through the cylinder by a small rotary pump with a flow rate of 5.5 l/min. It streams through the blue flexible tube to the lower end of the cylinder, passes by the sample, leaves the cylinder on the upper end and flows back into the water reservoir. The flow rate of this water is considered an important parameter for the cleaning success.

Experimental Procedure

For each experiment the same procedure was run. At first the settings on the generator were adjusted. This means the duration and the amplitude were set, according to the experimental design. The settings for all experiments are seen in Table 1. Before the experiments were started the samples were weighted and pictures of each sample from front and back side were taken. Distinction has to be made between the experimental procedure with and without water flowing.

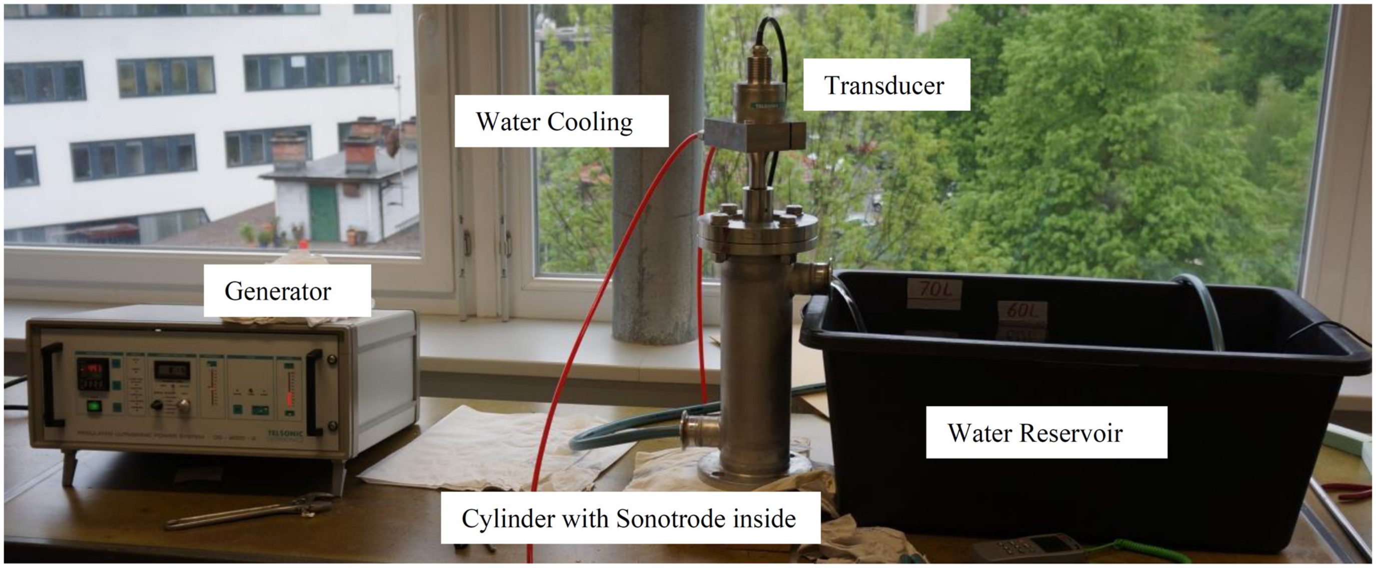

Figure 2—Ultrasonic Equipment for Experiments with Flow

Table 1—Experimental Design

Nr.	Experiment Nr.	Amplitude	Duration	Flow
-	-	[%]	[min]	5.5 [l/min]
1	V37	100	5	No
2	V38	50	5	Yes
3	V39	50	10	No
4	V40	50	5	Yes
5	V41	100	10	Yes
6	V42	50	10	No
7	V43	50	10	No
8	V44	50	5	Yes
9	V45	100	10	Yes
10	V46	100	10	Yes
11	V47	100	5	No
12	V48	100	5	No
13	V49	50	5	No
14	V50	100	5	Yes
15	V51	50	10	Yes
16	V52	50	10	Yes
17	V53	100	10	No
18	V54	100	5	Yes
19	V55	50	10	Yes
20	V56	100	10	No
21	V57	100	10	No
22	V58	50	5	No
23	V59	50	5	No
24	V60	100	5	Yes

Without water flowing In all tests without flow the cylinder was filled with 2.2 liters of water and after this the sonotrode was screwed on the cylinder. Next the temperature of the cylinders outer surface was measured and the water cooling of the sonotrode was switched on. Then the ultrasonic device was switched on. After the sonification the temperature of the outer surface of the cylinder was measured again. Accordingly the sonotrode was unscrewed and water was emptied from the cylinder. Then the sample was taken out and put into the desiccator to dry.

Figure 3—Sample before Treatment V38

With water flowing In all tests with flow the sonotrode was screwed on the cylinder after the samples were fixed on the cylinders bottom. The pump was connected and switched on. Therefore 60 liters of ordinary tap water were filled into a tank called “water reservoir”and circulated. A flow of 5.5 l/min was provided by the pump. This lead to a flow velocity in the flexible tube of about 0.8 m/s and in the cylinder of about 0.007 m/s which is far below the critical value of 1 m/s. At the flow velocity higher than 1 m/s the ultrasonic effects are hindered due to turbulence.(Mason & Lorimer, Applied Sonochemistry, 2002)

As soon as the cylinder was filled and the flow was given, the temperature of the cylinder was measured. Then the ultrasonic device was switched on. Immediately after the sonification the temperature of the cylinder was measured again and the pump was switched off. The sonotrode was screwed off, the water was poured out of the cylinder and the sample was put into the desiccator to dry.

The dried samples were weighted again. During all tests the power displayed on the ultrasonic generator was recorded.

Experimental Design

To identify the influence of amplitude, duration and flow on the cleaning effect a statistical analysis was done. Due to that a high and a low value for each parameter were determined. The amplitude was set on 50 or 100 percent. The duration of the sonification was given with 5 or 10 minutes. In the case of the flow the high value “yes” means a flow with 5.5 l/min and the low value “no” means no flow at all. The different settings were tested in a full factorial design of experiments, where each combination of the parameters was tested three times. This leaded to 24 experiments. The experimental settings and their order are listed in Table 1. The experimental order was done randomly, to minimize the possibility of systematic failures during the experiments.

Results and Interpretation

In the following pictures the cleaning performance is displayed for a weak and a strong cleaning success. The example for a weak cleaning success is given by experiment V38 and a successful cleaning is shown in experiment V58. For the experiment V38 the amplitude was set to 50 %. The sonification lasted for 5 minutes at a flow rate of 5.5 l/min. A clear difference between Figure 3 which shows the untreated sample and Figure 4 where the treated sample is displayed can be noticed. There is also seen some rust on the surface of the sample after the treatment. As mentioned above, low grade steel was used for these experiments and as the sample got in contact with water and air it is no surprise that corrosion occurs on its surface. The half pipes were cleaned with a wire brush before they were used again to avoid any effects due to corrosion. Generally corrosion and scaling effects cannot be separated very strictly because in most cases they occur both at the same time. (Becker, 1998) The sample weighted 88.17 grams before the treatment and 87.49 grams after the sonification. The original weight of the half pipe without gypsum was 85.18 grams. This means originally we had 2.98 grams gypsum adhered on the samples surface and due to the treatment 0.67 grams gypsum were removed. This means a removal of about 22.5 % in mass. The rust on the samples surface was neglected. During all experiments every minute the actually displayed power was noted. For experiment V38 an average power of 246 Watts was seen. There was no temperature rise during this experiment.

Figure 4—Sample after Treatment V38

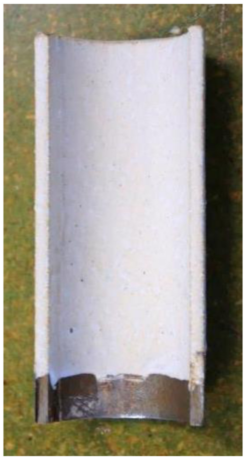

Figure 5—Sample before Treatment V57

Figure 6—Sample after Treatment V57

The experiment V58 was very successful in terms of gypsum cleaning. The amplitude was set to 100%. The experiment lasted for 10 minutes without flow. Therefore a strong temperature rise of 31.7°C was recognised. The average power used during the experiment was 750.9 Watts. The weight of the half pipe sample without gypsum was 84.66 grams and the gypsum on the sample's surface weighted 1.69 grams. Gravimetrically 100% of cleaning took place. The cleaning results can be seen by comparing Figure 5 with Figure 6.

Each experiment was analysed gravimetrically. During all of them the power used and the temperature rise during the experiment were noted. All results were calculated as described in the two examples above and are displayed in the following table. In Table 2 the number of each experiment is displayed on the left, and the samples are sorted from the weakest to the best gravimetrical cleaning effect (second row). In the following column the power usage in average during each experiment is seen. The last column displays the temperature rise during each experiment.

Figure 7 shows the average power usage during each experiment plotted against the purification in mass percent. Two groups of experiments are clearly seen in this plot. The first group was operated with power consumptions between 250 and 320 Watts. In the second group an average power between 750 and 810 Watts was used during the sonification. These groups correlate with the set amplitude. Group one tests were done with amplitudes of 50% and group two experiments with amplitudes of 100%. Furthermore it can be said that higher power consumption indicates a better purification effect.

In Figure 8 the temperature rise due to the sonification is plotted against the purification of the gypsum samples. As one can see a strong temperature rise does not mean automatically an increase in purification of the gypsum samples.

In Figure 9 the three parameters of interest amplitude, duration and flow and their main effects on the purification are shown. Therefore the mean values of all experiments done were used. The statistical analysis itself was done with the help of the computer program Minitab. In the diagram an own graph is shown for each parameter. In the graphs the low and the high values are seen on the abscissa. On the ordinate the mean purification of the samples surface is displayed in mass percent of removed gypsum.

Table 2—Results

Nr. Experiment	Gravimetric Cleaning Effect	Power	Temperature Rise
-	[%]	[W]	[°C]
V40	18,90	279,00	0,20
V38	22,50	246,00	0,00
V44	25,60	242,00	0,70
V43	46,90	307,00	12,70
V42	47,50	297,00	13,00
V59	49,30	322,00	7,10
V58	51,40	314,00	6,40
V52	52,50	244,00	0,70
V39	53,90	593,00	12,60
V49	59,20	317,00	6,60
V54	60,70	787,00	0,00
V37	66,00	799,00	16,40
V55	71,70	286,00	1,60
V60	72,70	782,00	1,30
V51	74,30	260,00	0,70
V47	74,60	795,00	16,60
V45	76,40	781,00	2,60
V46	82,50	810,00	3,00
V50	84,20	777,00	1,90
V48	87,50	775,00	16,70
V53	92,20	768,00	30,20
V41	96,10	801,00	2,80
V56	100,00	766,00	30,70
V57	100,00	751,00	31,70

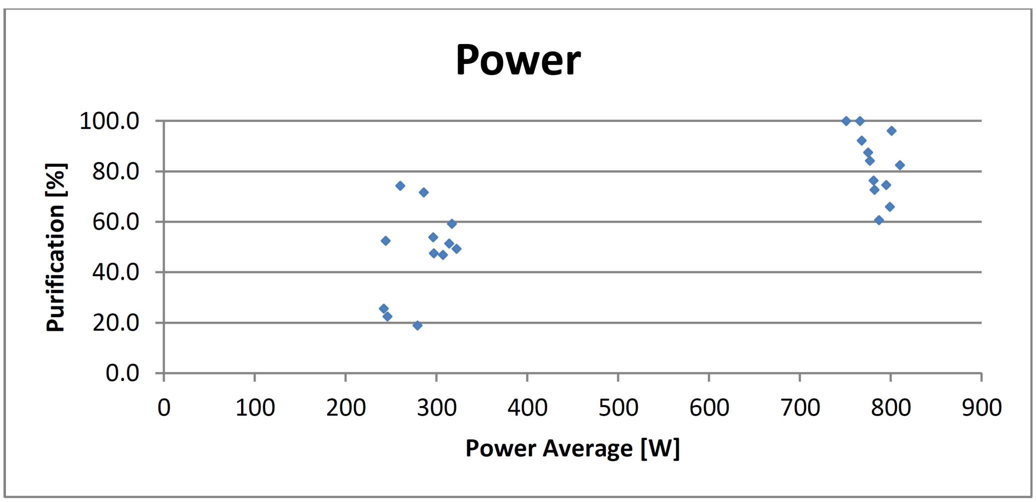

Figure 7—Power Plot

The benefit of this illustration is that one can see by one view if there is a difference in purification by changing the value of a parameter from low to high, how strong this difference is and which parameter has the strongest influence compared to the other parameters.

It can easily be seen that the amplitude had the biggest impact on the purification in the realised experiments. For the experiments with 50% amplitude the average purification in mass percentage was about 48%, but for the experiments done with amplitudes of 100% the average purification rises up to 82 mass percent. It can be said that the higher the amplitude the better the cleaning works.

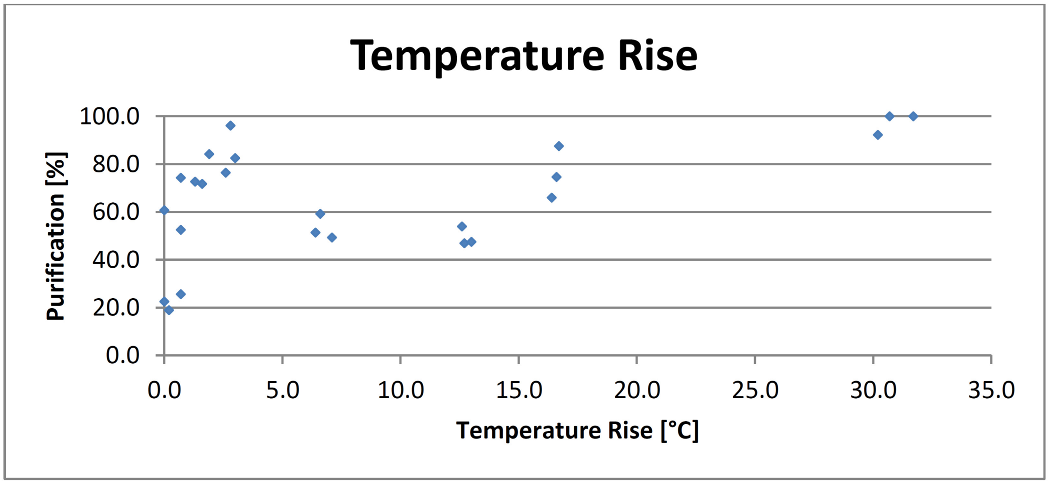

Figure 8—Temperature Plot

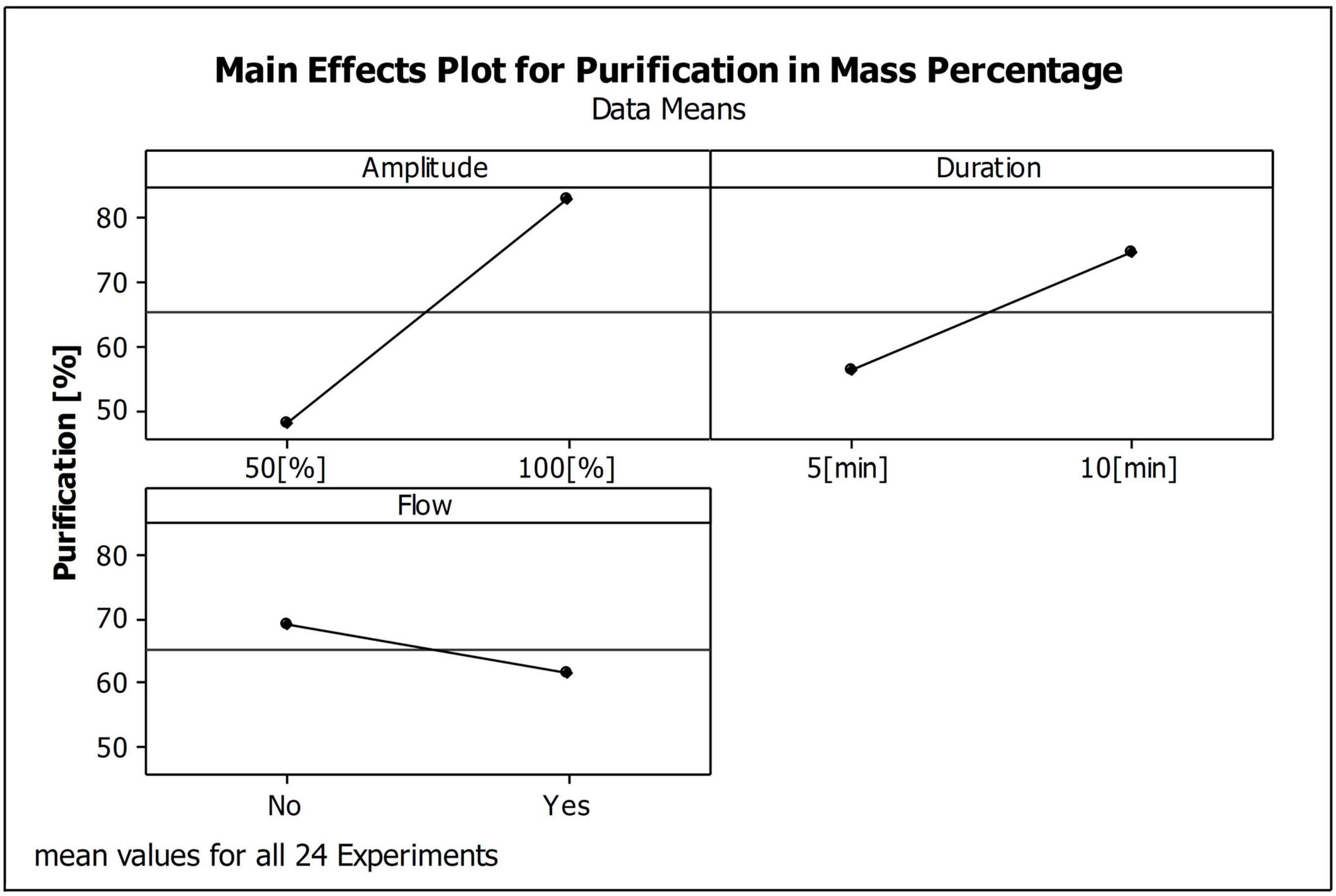

Figure 9—Main Effects Plot

While a longer duration also leads to a big increase in cleaning effect, the flow had a negative impact on the cleaning efficiency. The purification effect rose from 56 up to about 74mass percent if the duration of the sonification was increased from 5 to 10 minutes.

As expected the flow has a negative impact on the purification. Experiments operated without flow had an average purification effect of about 69 mass percent while with flow the cleaning effect went down to

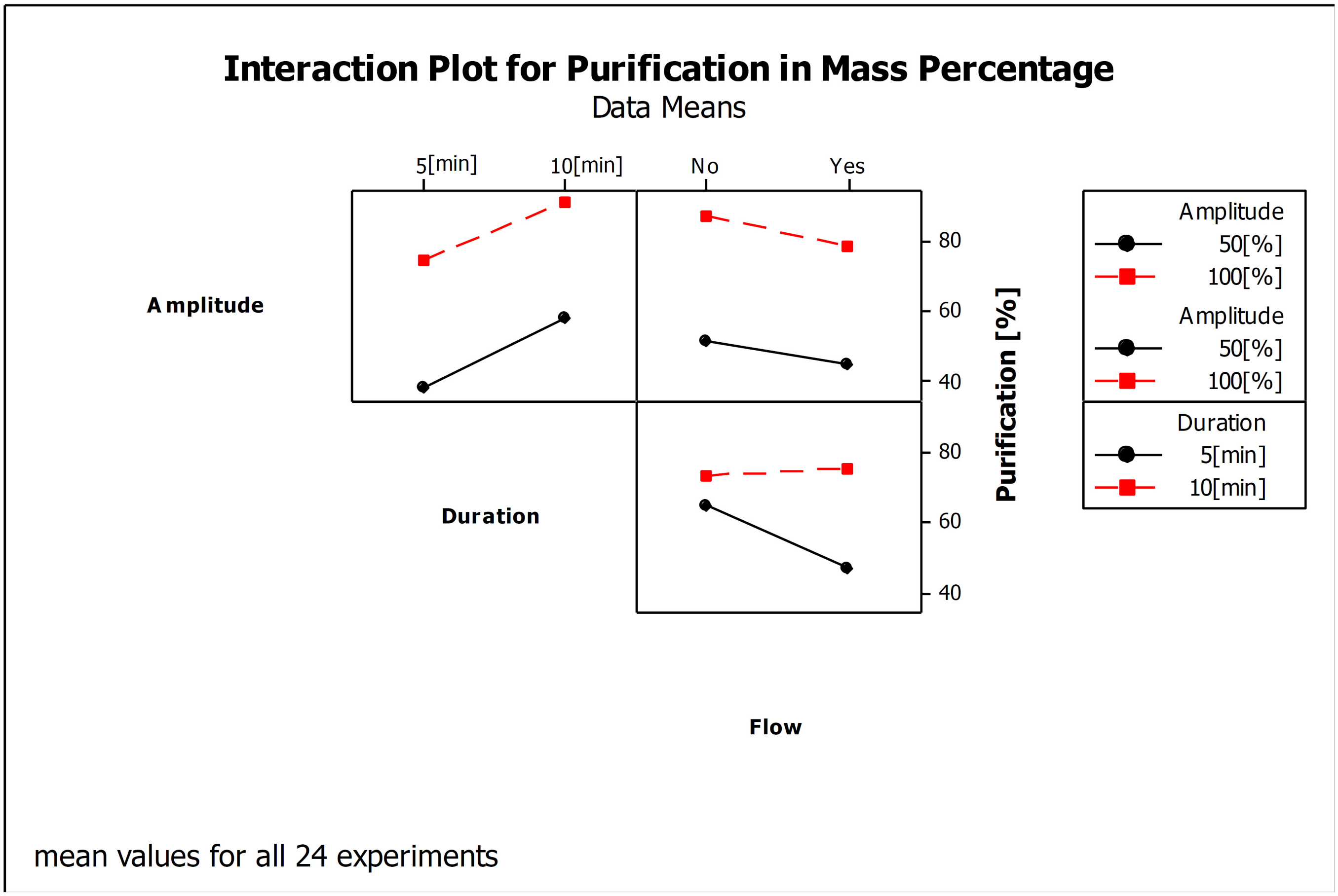

Figure 10—Interaction Plot

about 61 mass percent of removed gypsum. For these experiments the flow had a minor impact on the cleaning, compared to the other parameters.

In the interaction plot (Figure 10) the influences of the parameters on each other are shown. One can see if the purification effect of one parameter was intensified or mitigated by another parameter.

The upper left graph shows that a longer duration had the same improvement on the cleaning effect for 50% amplitude and 100% amplitude.

The upper right graph displays that the flow had a slightly higher negative influence on the purification at 100% compared to 50% amplitude, but the difference was not very high, there is only a very slight change in inclination seen.

Really interesting is the lower right graph were the impact of the duration on the flow is plotted. It clearly indicates that the negative effect of the flow on the purification was compensated by a longer duration. During short sonification the flow had a very big negative impact on the cleaning effect, while in the longer run this negative influence was not seen any more.

Conclusions & Recommendations

The experiments done in this paper clearly demonstrate that gypsum precipitation can be removed by ultrasonic waves. In every single test purification due to ultrasonic treatment took place. The main influence parameters during these experiments were identified as the amplitude of the vibrations, the duration of the sonification and if a flow is given or not. There may be other influences not accounted for in this paper like surrounding pressure and temperature in the field and also the time in which the precipitations are formed. The amplitude had the biggest positive effect on the purification. This also correlates with average power consumption, because amplitude and power are interdependent. Another very big positive effect is longer treatment duration. A flow during sonification had a negative impact on the cleaning, but with the used flow rate it had the smallest influence on the purification, compared to the other two tested parameters. Thought ahead that means that sonification in a borehole for example could take place in free flowing wells during production as long as the flow rates respectively the velocities at the point of sonification are not too high. With a higher flow rate the negative influence of the flow rate will most likely increase. The temperature rise during an experiment did not automatically lead to a better cleaning effect.

Further research is required; particularly on other even more critical scaling types like $CaCO_3$, $BaSO_4$ and $SrSO_4$. Especially calcium carbonate ($CaCO_3$) is a big problem in daily production operations. The hardness of the scaling and also the thickness of the scaling layers will have to be investigated in relation to effective ultrasonic treatments. Therefore further investigations are done on the Chair of Petroleum and Geothermal Energy Recovery. Ultrasonic waves could be an environmentally friendly addition to already established wellbore cleaning tools.

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