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A method for water well regeneration based on shock waves and ultrasound

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ABSTRACT

The regeneration of water wells is an urgent problem nowadays, when drilling of new wells becomes more and more expensive. Formation damage leads to a reduction of the formation's permeability and/or pore volume which in turn inhibits the ability of the water to flow from the reservoir formation into the wellbore. A new technology that uses high-power ultrasound to remove formation damage of water wells has been developed. The effectiveness of regeneration of wells can be enhanced if ultrasound and shockwaves are used during the same treatment. It was shown by computer modelling, that the two methods have different depths of impact. Whereas the ultrasonic method has a strong impact on the area of the filter tube, the impact of the shock waves is focused on the gavel pack, the wall of the well and the adjacent aquifer. A shockwave treatment, which is normally more effective due to larger impact zone, needs to be followed by ultrasonic treatment in order to facilitate the removal of the detached deposits. These theoretical assumptions were confirmed by field tests on two wells. The use of the method leaded to an increase of the production by 40% and 109% respectively.

1. Introduction

The average age of drinking water wells in Germany and other European countries is growing steadily. This increases the importance of effective regeneration of drinking water wells. The construction of water wells on the one hand is very expensive, and on the other hand for legal and environmental reasons is becoming more and more difficult.

In typical water wells the filter tube is surrounded by a gravel pack [1]. There might be a single or multiple-layer gravel pack formed of gravel of different size. A scheme of a typical well is shown in Fig. 1.

The cause of well aging is basically the increasing constriction of the cross-sectional flow area of the inflowing groundwater wells, in which – depending on site conditions – different mechanisms may be involved. Most frequent reasons are ocherings by Fe and Mn ions, hydroxides, bacteria-induced mucilage (68%) [2] and siltation (14%) [3–5].

The narrowing of the cross-sectional flow area occurs at different locations depending on the particular cause of aging. However, there are three most likely colmatation zones [6–13]:

1. the filter slots;
2. the gravel directly behind the filter;
3. the formation near the sidewall of the well (directly behind the gravel pack).

Therefore, combinations of methods are often used for the regeneration of the drinking water wells [6,8,12,14–16]. Deposits, which protrude into the interior of the well are removed by a brush in the vertical and horizontal directions. Subsequently, the deposits from the filter slots are released by a gravel washer, high pressure water cleaner or plunger. These methods, however, can contribute to the removal of deposits, which are easily to remove, and which are located in the immediate vicinity of the filter tube. The deposits in the gravel filter (second colmatation zone) and at the borehole sidewall (third comlatation zone) must be removed by complex methods. The amount of methods, which can be used in water wells, is limited compared to the number of techniques for enhanced oil recovery. For example, such techniques like low frequency, inductive or microwave heating [17,18] cannot be used due to the nature of colmatation. Thus only chemical or dynamic regeneration methods can be considered.

In chemical regenerations acids or oxidizing agents are pumped to a chosen area between two packers [6]. This method, however, is harmful to the environment. In addition, the use of wrong concentrations can again lead to cross-sectional constrictions due

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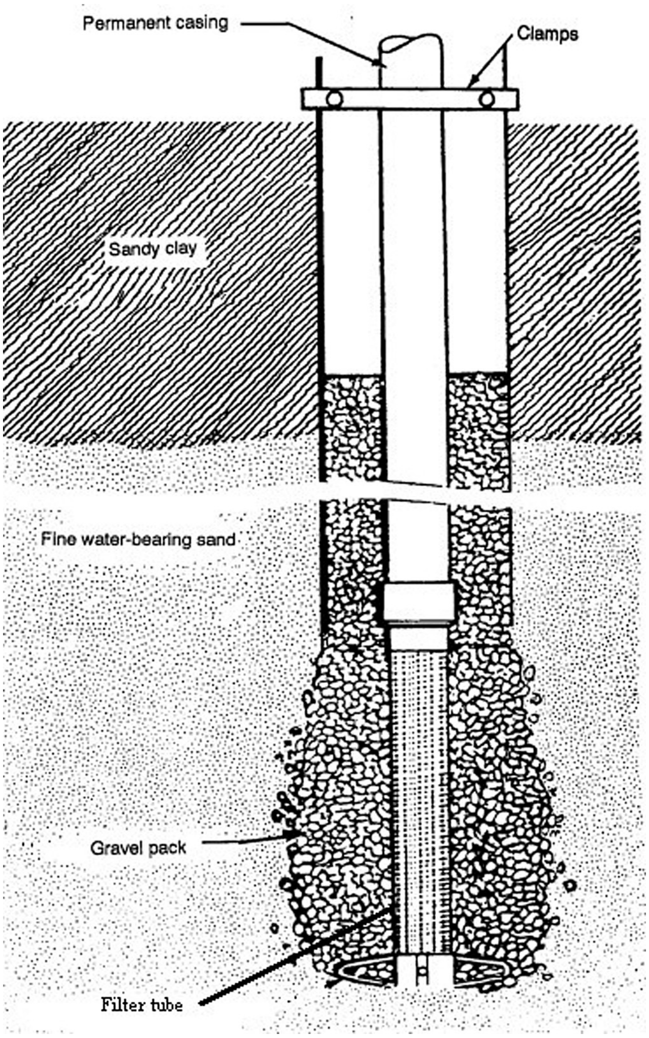

Fig. 1. Typical construction of a water well.

to various solid phases. The use of organic acids is often not possible for uncoated metal filters because there is a filter damage risk [19].

Dynamic regeneration processes are more environmentally friendly and less dependent on the material (only the ultimate strength of the material must not be exceeded). Traditional dynamic regeneration methods include ultrasonic pulses, detonating gas and detonating cord.

The effect of ultrasound is based on the following: deposits are destroyed by means of ultrasonic waves, which are generated by a resonance system in a well [20]. It is known that sound waves propagate in different media at different speeds. This leads to high accelerations and friction on the interfaces between the gravel filter and deposit products. Forces, which arise, and increased temperature cause the detachment of the deposit products. Ultrasound has been successfully applied in the oil industry [21], in particular for the increase of oil production [22–25]. However, the composition of the colmatants typical for oil wells is different from the composition of deposits, typical for water wells. Apart of that, in case of oil wells there is another important effect: oil viscosity reduction caused by ultrasound [26–28], which can be explained by temperature and pressure increase [26] and by destruction of the intermolecular connections in the long oil molecules [24]. This very important for oil wells effect is not relevant in case of water wells, since the mobility of water in well conditions is high enough to penetrate through tiny pores without any problems. These differences explain the necessity to use a combined approach in case of water production wells instead of the standard ultrasonic method.

The effectiveness of the cleaning power of the ultrasonic method is dependent on the ratio between the dimensions of the zone affected by the ultrasonic device and the well dimensions.

The diameter of drinking water wells is in many cases about 80 cm, the diameter of the filter tube is about 25–40 cm [29]. An ultrasonic device normally has a diameter of up to 10 cm. That is, the distance between the outer boundary of the ultrasonic device and the first and second colmatation zone (filter pipe) is 10–15 cm. The third colmatation zone is located at a distance of about 35 cm.

Detailed studies have shown [20] that the effect of an ultrasonic device can be detected at 35 cm from the surface of a powerful transducer. However, the maximum effect in a gravel pack is approximately 23–24 cm away from the device. This simple comparison suggests that the ultrasonic method should be suitable for effective cleaning in the first and second colmatation areas in particular. In order to confirm this assumption modelling should be carried out for particular ultrasonic devices. Based on such modelling the operation modes could be chosen in such a way, that most effective cleaning of the first and second colmatation zones could be achieved.

However, as mentioned above with ultrasound, the separation of hardened deposit products, typical for water wells, is limited. This is different for pulses caused by detonating gas and detonating cord.

In this case the deposits are removed by the generated shock waves. The shock waves affect a much bigger zone than those generated by ultrasonic tools. The shock waves cause vibrations of different frequencies in the gravel and near the borehole wall, although there is a risk that the filter tubes can be damaged [6]. These waves also reach and affect the second and third colmatation zone, and are capable to detach hardened deposits. After such a treatment ultrasonic treatment could be used during the removal of detached deposits to facilitate their movement towards the filter. The mechanism of this is based on the difference of static and sliding friction.

For this reason, it appears to be useful to combine the advantages of the ultrasonic method and the advantages of the pressure pulse technology. Such technique could be applied not only for water production wells, but also for water injection wells, used in the oil industry. However, in this case the compressive strength of the reservoir would need to be measured prior to the application. In case of unconsolidated sands the application of ultrasound alone could lead to sand production, causing in some cases equipment failure and blocking the pores [30]. The combined ultrasound-shockwave technique would cause sand migration even more easily, thus the applicability criteria in that case would be narrower. Such criteria for the application of the described method in the oil industry have to be studied further.

In this article, an attempt to develop a method, which combines the ultrasound and shock-waves techniques for water wells, is described. The article includes a theoretical analysis of the electrohydraulic controlled method for shock wave generation; an analysis of ultrasonic and shock waves propagation based on spectral calculations and modelling and a description of field tests of the technique.

2. Theoretical background

The techniques of ultrasonic oscillations generation in both water and oil wells are relatively well known and described in a number of publications [22–25,28,31]. The Equipment for this purpose has been developed for decades and nowadays is developed in such extend, that selective treatment of various sublayers of wells in different modes (for example, continuous, modulated or pulse mode) is possible. Thus, this article focuses on the theoretical background of shock wave generation. For the purpose of well regeneration the possibility to control the shock wave amplitude is critical, since collateral damage of the well itself should be avoided.

In order to achieve the generation of shock waves in the water well we have decided to look into the technique of generation using an electrical discharge between two electrodes. This technique has shown some promising results in oil wells [32], however is much more promising for water wells, since in oil wells it is critical to treat the sublayers selectively, while in case of the propagation of shockwaves, which are created via a discharge in a relatively small zone between two electrodes, the wave front has a spheroidal shape. Due to deep penetration of a shockwave, selective treatment of sublayers is relatively hard to achieve. In case of treatment of oil wells a treatment of the whole perforation zone, when both water and oil sublayers are subject of treatment, could lead to the increase of water cut and a consequent decrease of the well's efficiency. In case of water wells this is not the case, and the only limitation is the preservation of the well itself, which can be ensured, if the energy of the discharge is regulated.

In order to understand better the peculiarities of the method, it is worth to look into the physics of shockwave generation. In case of an electrical discharge between two electrodes in a liquid the duration of the current pulse is in the microsecond range, thus the instantaneous power of the current pulse can reach hundreds thousands of kW. The current amplitude in such a pulse can reach tens thousands A, if the voltage on the electrodes is in the range of tens kV. Since the steepness of the current pulse determines the velocity of the discharge channel expansion [32], such a discharge leads to a significant increase of pressure in the liquid.

Thus, the main effects caused by the electrical discharge are extremely high hydraulic pulse pressures, causing shock waves; significant pulse movements of liquids on the velocities of hundreds m/s; cavitation caused by the pulses and mechanical oscillations.

The liquid, accelerated by the increasing discharge channel is moved from the discharge zone, consequently a cavity is formed and the first hydraulic shockwave is caused. After that the cavity closes, causing the second hydraulic shockwave.

The shockwaves have a wide spectrum, which contains also low frequency signals, and consequently penetrate deeper into various media. The power of the shockwaves can be controlled by controlling the discharge energy.

3. Equipment and computer modelling of the oscillations

In order to demonstrate the effects of shock waves and verify the combined shockwave and ultrasonic method for water wells regeneration, special equipment was developed. The equipment included downhole and surface blocks. The downhole equipment consisted of a downhole tool with an electrohydraulic (shockwave) and an ultrasonic block and a pump. The blocks could be used as one single tool, or could be disassembled into two separate tools (ultrasonic and shockwave). Normally the ultrasonic block was attached above the shockwave block and connected to a geophysical cable with seven cores through a cable lug. If the ultrasonic block worked separately, its connection part was sealed with the protective cover. In case of separate operation of the shockwave block, it was connected directly to the cable lug. The downhole equipment included also a pump (Grundfos SQE7-40 1X200-240V 1.68 kW 1.5 M MOD.BB). The pump had a maximum flow of about 8–9 cubic meter per hour, it was put into the well on a separate cable and was used to create depression during or after the treatment. The downhole tool was connected to the surface equipment via the 7-cored geophysical cable (which was spooled on an automatic winch): the ultrasonic block to an ultrasonic generator and the shockwave block to a pulse generator. The pulse and ultrasonic generator were assembled in the same housing. A power station powered both generators and the pump. An operating scheme of the equipment is shown in Fig. 2.

The set of equipment had the following technical characteristics:

- Maximum well treatment depth, m 200
- Velocity of lowering the downhole tool into the well, m/s 1 ± 0.2
- Maximum power of the ultrasonic block, kW 3
- Frequency of the ultrasonic downhole block, kHz 23.5 ± 0.5
- Maximum energy of shockwave downhole block, J 200
- Electrical pulse duration, μs 5–10
- Size of the downhole tool, mm ∅ 102 × 2500

The ultrasonic block is described in detail in [28]. It was developed for operation in oil wells, however is also suitable for water wells. The verification of its characteristics was carried out during field tests, described in [28].

To verify the effect of the electrical discharge the electrohydraulic block of the downhole tool was checked in a transparent tank in laboratory conditions (under normal pressure and temperature). The block contained a multiplier scheme and pulse capacitors, which enabled us to create an electrical pulse between the two electrodes. The duration of the pulse was between 5 and 10 μs. The energy was enough to achieve a discharge between the two electrodes. A discharge with the maximum energy was created and photographs were made in order to verify the process of shockwave creation. The photographs of the discharge zone during a discharge are shown in Fig. 3.

The photographs demonstrate the cavity, created during the discharge (Fig. 3a) and its collapse (Fig. 3b and c). The photographs (d) of Fig. 3 demonstrate also the cavitation, caused by the shockwave in the liquid; which is an evidence of the generated oscillations.

In order to estimate the penetration depth of the generated shockwave the parameters of the pressure pulse were measured in the vicinity of the device. A pressure sensor, which was placed 150 mm from the discharge zone, was used. The experiments were performed in water. The shape of the pulse, which was measured, is shown in Fig. 4. The pressure sensor was connected to the fourth channel of the oscilloscope. The vertical scale is 30 bar in a field. Channels 1 and 2 show the voltage between the electrodes (5 kV in a field) and the discharge current (260 A in a field) respectively.

To model the temporal behavior of the signal near the borehole, a Fourier analysis was performed. The signal was modelled by the following equation (as a pulse with a fading sinusoidal signal, where the coefficients were obtained empirically):

$$P(t) = \begin{cases} 141\left(1 - \frac{t}{11.25}\right) * \sin(2t), & 0 < t < 11.25, \\ 0, & t > 11.25 \end{cases} \tag{1}$$

where P is the pressure in bar and t is the time. The form of the modelled signal at the starting point near the discharge zone is shown on Fig. 5.

The spectrum of the signal was determined by means of Fourier analysis. In detail the procedure is described in [31].

The pressure amplitude P_r (for each component of the spectrum) as a function of the distance r can be determined by the following equation:

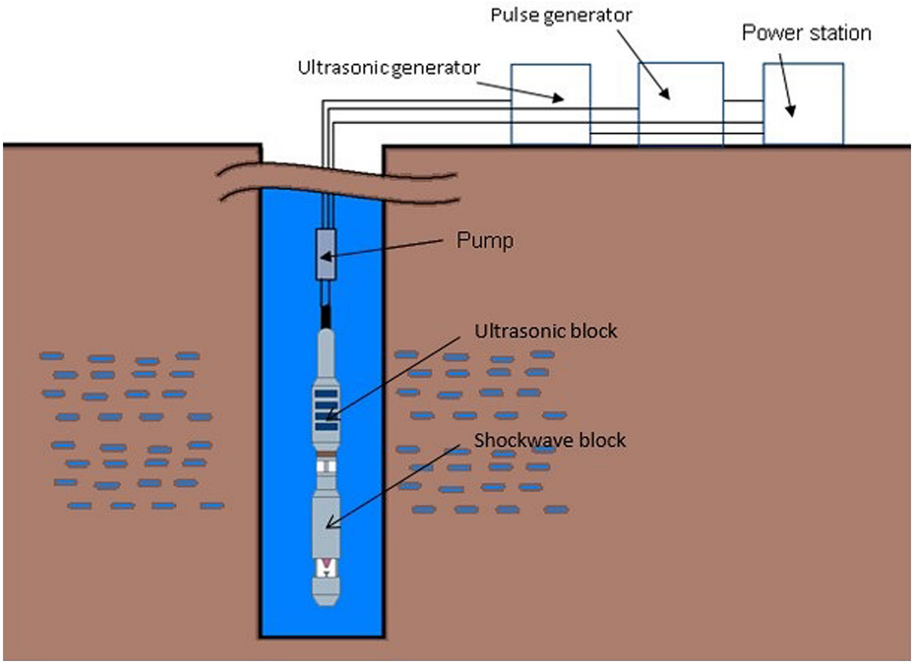

Fig. 2. Scheme of equipment configuration during the field tests.

$$P_r = P_a e^{-\alpha r}, \quad (2)$$

The attenuation constant α of acoustic waves is dependent on the frequency f of the wave [33]:

$$\alpha = \omega / c * 1/Q, \quad (3)$$

where c is the speed of sound, $\omega = 2\pi f$, Q is the quality factor (2π times the ratio of the total energy stored in the wave divided by the energy lost in a single oscillation cycle).

In case of the shockwaves, which penetrate deeper, than the gravel pack, we have used in our model average values, typical for earth crust [34]: c = 2000 m/s, Q = 300. Here one must remember that we deal with a porous medium (and the gravel pack) and the sound wave is attenuated more. Therefore, it was suggested in [35] using the quality factor of 30 in this case.

After calculating the amplitude of the individual components of the signal, the inverse Fourier transformation was used to analyze the form of the signal at a defined distance from the wellbore tool. With this method, the signal 1 and 5 m from the downhole tool was calculated. The shapes of the signal in the various zones, which were obtained using Matlab, are shown in Fig. 6(a and b).

Taking into account, that the pressure amplitude is significant even 5 m away from the tool, the effect of the pressure pulses is relevant also in the second colmatation zone. Thus, the effect of the shockwave should be enough to detach the deposits from the rock and the gravel. However, one must bear in mind that the duration of the pulse is less than 12 µs. Consequently, this type of treatment is not suitable, to facilitate the removal of the deposits after detachment and prevention of secondary colmatation of the well during pumping out. It is therefore to be expected that the combination of shockwave and ultrasonic methods will be more effective in cleaning the drinking water wells than the use of only one of these methods. To confirm this hypothesis, experiments were performed in the field.

In order to develop a treatment plan for the field experiments, we have modelled the acoustic field distribution of the ultrasonic block of the downhole tool. It was important for us to understand the limitations of ultrasonic cleaning, in order to determine, in which extend ultrasonic precleaning is possible.

The ultrasonic block had a diameter of 102 mm, the length of the emitting part was 353 mm. The electrical signal from the ultrasonic generator was transferred into mechanical oscillations via two ring-shaped magnetostrictive transducers. The form of the caused oscillations was determined using the Eclipse software. The calculated oscillations shape is shown in Fig. 7.

The calculated oscillations shape was used as the border conditions for the model of the penetration of the oscillations into the gravel. For gravel rock Q is between 100 and 200 (depending on the oscillation type) [36]. Taking into account, that the gravel is made of single grains and reflections and refractions, which cause additional damping, occur [34], we have used the quality factor 15 in our model. For the speed of sound we have used c = 2000 m/s. The calculation of the acoustical field distribution was done using the software Eclipse. In the model the space between the 50 mm (wall of the tool) and 150 mm (the filter tube) was filled with water, and the space further away from the tool – with gravel.

The calculated sound pressure distribution is shown in Fig. 8. The vertical line at 150 mm marks the filter tube. The second vertical line at 350 mm marks the third colmatation zone.

As it is shown in Fig. 8, the energy of the ultrasonic wave generated by the ultrasonic block affects mainly the filter tube and the second colmatation zone. The energy, which reaches the third colmatation zone is not sufficient to detach the deposits from the gravel. However, the signal is still detectable near the third colmatation zone and can contribute to the removal of detached deposits during pumping out of the well.

4. Field tests

Field tests were carried out on two “flat” water wells. The depth of the wells was about 13 and 16.5 m respectively. The inner diameter of the filter tube was 150 mm; the filter tube was surrounded by a gravel pack. The photograph of the filter tube type, used in the test wells is shown in Fig. 9.

The widths of the productive zones were 2.5 and 7 m respectively.

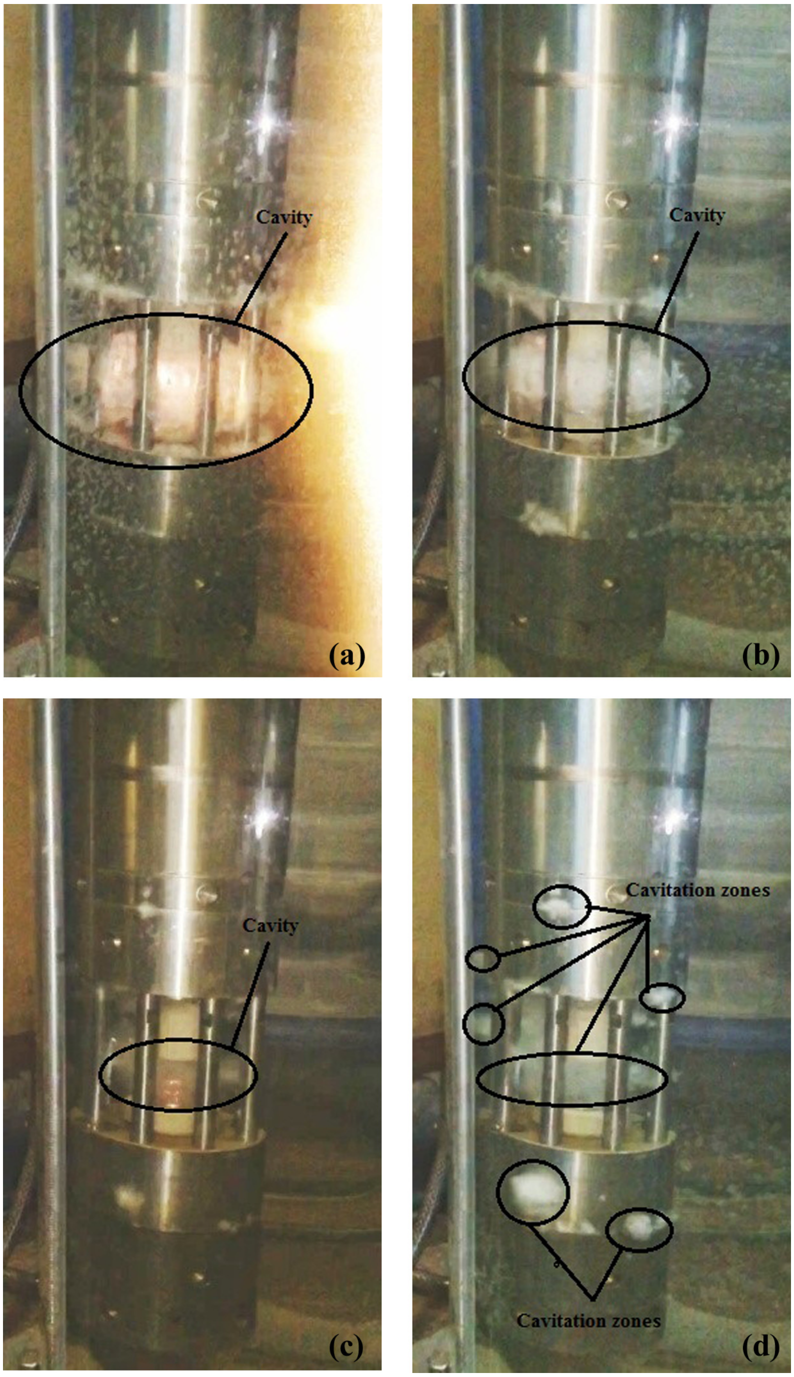

Fig. 3. Photographs of the discharge zone of the electrohydraulic block during the discharge: a) the moment of the discharge; b) the cavity, created by the discharge; c) closing of the cavity shortly after discharge; d) cavitation created by the shockwave around the discharge zone; e) relaxation of the liquid after the discharge.

Taking into account the modelling results, we have decided to perform a precleaning with ultrasound in order to remove the deposits from the filter and from the gravel directly behind the filter in order to avoid deeper penetration of those deposits further into the gravel during the discharge.

Thus, for the first test well the precleaning was done at full power for 15 min per 50 cm of production zone. The ultrasonic block was moved in 50 cm steps from the lowest point of the production zone up. The steps of movement were chosen taking into account the width of the oscillation zone. Simultaneously to the ultrasonic treatment, water was produced from the well using the pump. That was done to create a flow in the well and ensure removal of deposits.

In order to control the regeneration process during the operations, measurements of the dynamic water level in the well (the distance from the surface to the water level during pumping on the full pump power) and the turbidity of the pumped out water were performed. The treatment program was modified during the operations based on the measured data.

The precleaning was followed by a shockwave treatment. We have performed two discharges per 15 cm of formation using the full power of the shock wave block. Initially, treatment of the lower

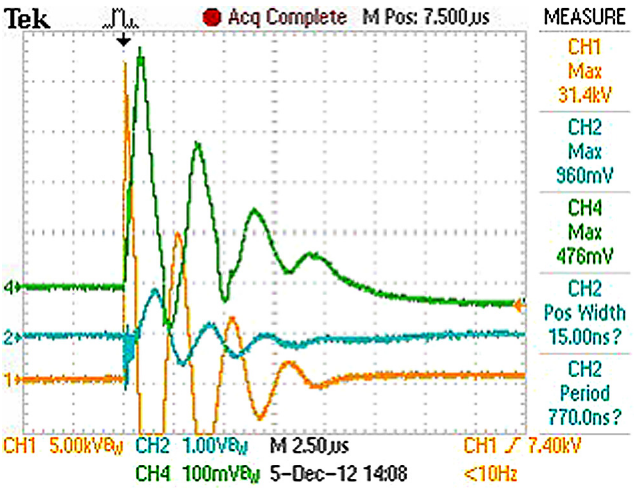

Fig. 4. Form of the pressure pulse caused by an electrical discharge between the two electrodes of the electrohydraulic block.

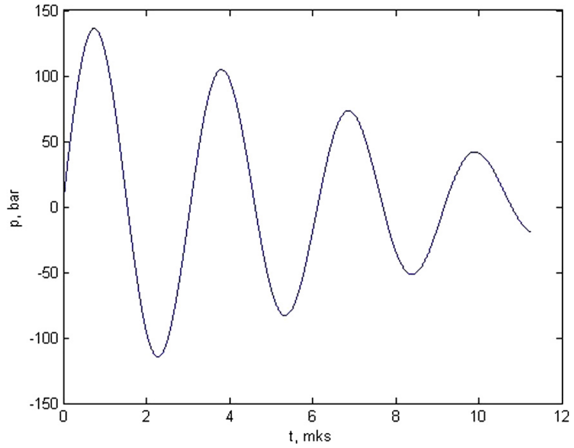

Fig. 5. Form of the model pressure signal from the shockwave block.

1.5 m zone was carried out. We have separated the well into two treatment zones in order to reduce the time between the shockwave treatment and the follow up ultrasonic treatment. The treatment was followed by pumping in order to remove the detached deposits. Results of the treatment of the first zone of the first test well are presented in Table 1 below:

Once the turbidity of the pumped out water returned to the initial value (which was the indication, that the deposits, which were separated were removed [20]), we have started the follow up ultrasonic treatment of the lower half of the production zone. The treatment's goal was to remove the detached deposits, which could not be removed during conventional pumping out. Thus, the follow up ultrasonic treatment was done in combination with pumping out of the well. Based on the measured turbidity and dynamic level, we have determined the optimal time of the follow up treatment: 20 min per 0.5 m. The results of the ultrasonic follow up treatment of the lower half of the production zone of the first test well are presented in Table 2 below.

The treatment of the second half of the production zone (1.5 m) was carried out using the same sequence of operations. The data, measured during the treatment of the upper half of the production zone are presented in Tables 3 and 4.

In order to remove the detached deposits also from the bottom of the well, the pump was positioned near the sump of the well and

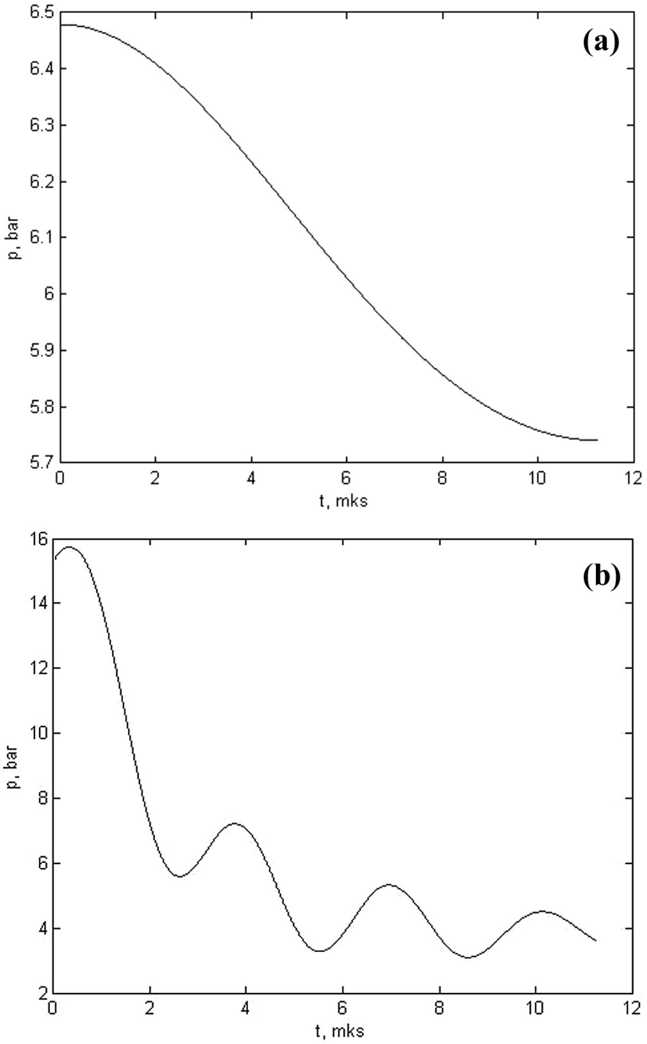

Fig. 6. Form of the model pressure signal from the shockwave block: a) 1 m from the downhole tool; b) 5 m from the downhole tool.

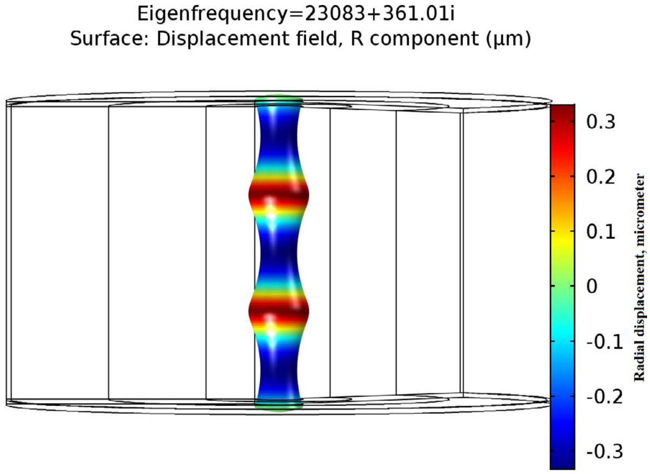

Fig. 7. Oscillation shape of the emitting part of the ultrasonic block.

the water was pumped out, till the turbidity returned to the initial level. The turbidity measurements, obtained during this process are presented in Table 5.

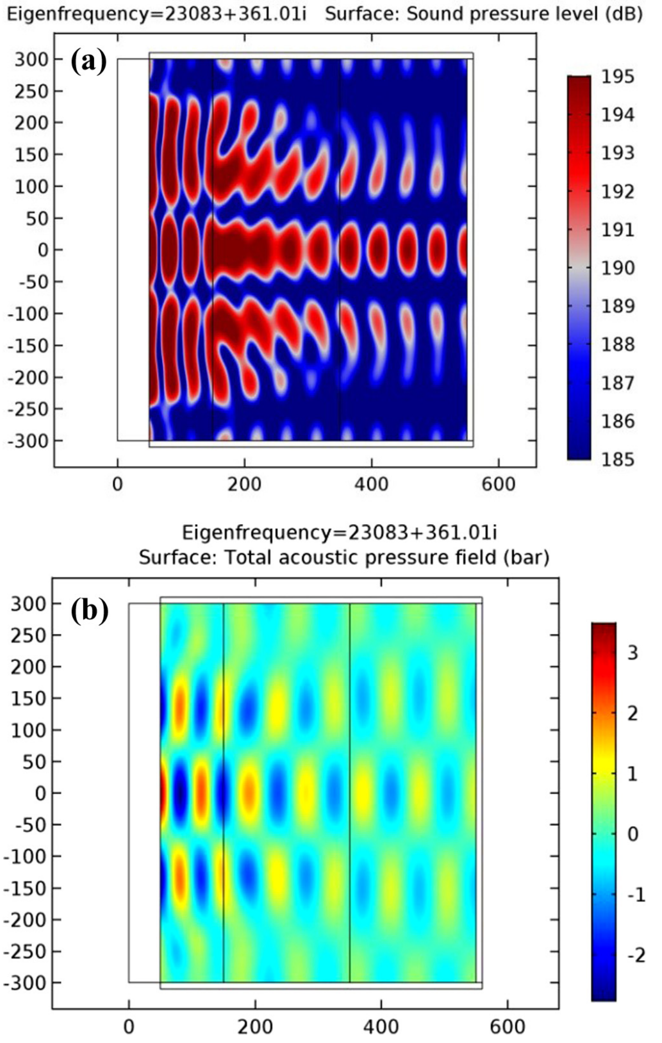

Fig. 8. Distribution of the acoustical field generated by the ultrasonic block in a water well: a) sound pressure penetration distribution and damping (in dB); b) aggregated pressure distribution (in bar).

Taking into account the turbidity measurements, we have concluded, that the deposits near the sump settle relatively quickly (within the first 15 min), thus it would be more effective to remove those particles by powerful pumps, during a pumping out operation after the regeneration. Thus, for test well two we skipped this step.

In order to estimate the treatment results of the first test wells pictures of the filter tube before and after treatment were done using and underwater camera. The photographs are presented in Fig. 10.

Apart of that a flow test was carried out, results are presented in Fig. 11.

For the flow test, the well was pumped out and afterwards the flow at different heights was measured, while the pump was moved upwards. The flow per meter was calculated as the derivative of the measured curve. That is the standard procedure, used by the operator of the wells.

As it can be seen, the aggregated flow of test well one increased from 9.5 m^3/h to 19.8 m^3/h. The maximum aggregated flow in this case is measured in such a way, that the dynamic water level during pumping is kept in a predefined range. In case of test well one the dynamic level before treatment was 6.5 m at 9.5 m^3/h

Fig. 9. Filter tubes in the test wells.

Table 1
Parameters of test well 1 after ultrasonic precleaning and shockwave treatment of the lower half of the productive zone.

		Dynamic level, m	Turbidity, FNU
Initial		4.45	0.8
After treatment	in 0 min		72
	In 5 min		5
	In 10 min		1.2
	In 30 min	3.98	0.8

Table 2
Parameters of test well 1 after ultrasonic follow up treatment of the lower half of the productive zone.

Treatment zone (0.5 m per treatment zone)	Time after treatment starts, min	Dynamic level, m	Turbidity, FNU
1	0	3.98	1.9
	10	3.86	4
	20	3.83	1.4
2	10	3.77	2.6
	20	3.77	1.3
3	10	3.74	1.5
	20	3.74	0.7

Table 3
Parameters of test well 1 after shockwave treatment of the upper half of the productive zone.

		Dynamic level, m	Turbidity, FNU
Initial		3.74	0.7
After treatment	in 0 min		100
	In 5 min	3.74	1.3

Table 4
Parameters of test well 1 after ultrasonic follow up treatment of the upper half of the productive zone.

Treatment zone (0.5 m per treatment zone)	Time after treatment start, min	Dynamic level, m	Turbidity, FNU
1	0	3.74	14
	10	3.72	1.9
	20	3.72	0.8
2	0	3.72	15
	10	3.70	1.7

Table 5
Turbidity measurements, obtained during cleaning of the sump of the well after treatment.

Time after treatment, min	Turbidity, FNU
0	66
2	274
15	4.3
20	4.6
30	0.75
45	0.5

(in operation the pump is different from the pump used in the tests) and 6.88 m after the treatment at 19.8 m^3/h.

The flow distribution represents the geological cross-section of the well, demonstrating, that there are two water bearing layers, relatively close to each other.

For test well 2 we have modified the treatment program taking into account the length of the perforation zone and the flow distribution of the well, which was measured prior to the works and is presented in Fig. 12.

Taking into account the length of the production zone we have reduced the time of preliminary ultrasonic treatment to 10 min per 50 cm of production zone. The results of the ultrasonic pretreatment are presented in Table 6.

It can be seen here, that immediately after the start of ultrasonic treatment of the well the dynamic level of the water increased. The same was observed in test well 1. This can be a confirmation of the hypothesis, that ultrasonic treatment facilitates the removal of deposits, which are not attached to the gravel, but cannot be removed during normal operation of the well. Also the turbidity change indicates that during ultrasonic treatment some particles appear in the water, the amount of which decreases over time,

Table 6
Parameters of test well 2 during ultrasonic pretreatment.

Depth, m	Time after treatment start, min	Dynamic level, m	Turbidity, FNU
Initial values	–	3.17	1.02
15.5	10	3.07	1.9
15	10	3.07	23
14.5	10	3.07	3.2
14	10	3.07	–
13.5	10	3.06	–
13	10	3.06	1
12.5	0	–	20
	10	3.06	25
12	0	–	16.8
	10	3.05	2.8
11.5	0	–	22
	10	3.03	3.7
11	10	3.03	17.4
10.5	0	–	7.5
	10	3.02	3.2
10	0	–	20
	10	3.01	3.8
9.5	0	–	24
	10	3.01	3.3
9	0	–	58
	10	3.01	4.6

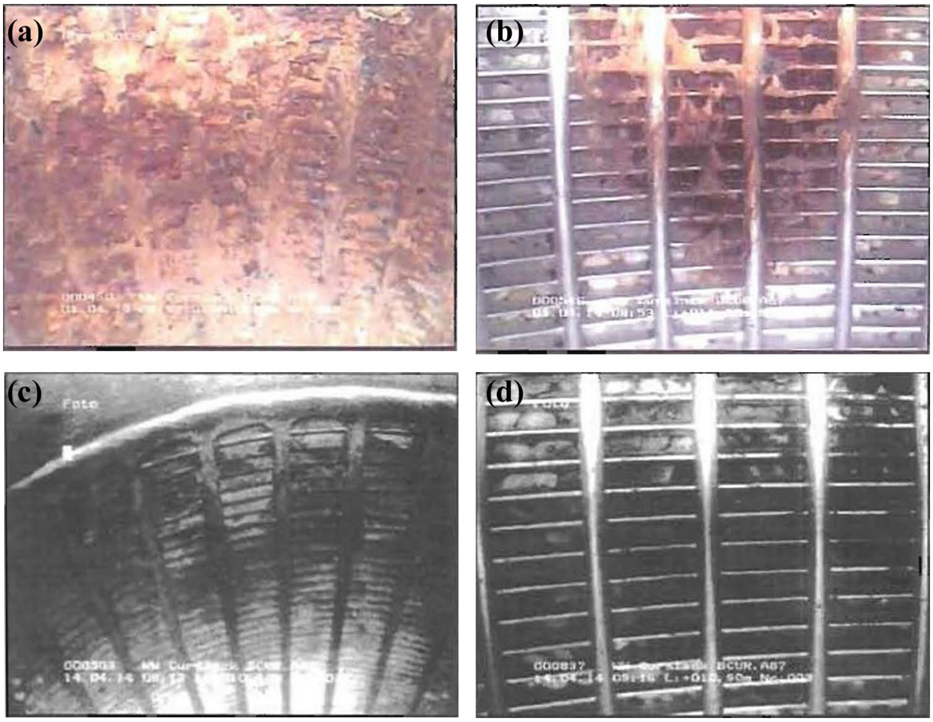

Fig. 10. Photographs of the filter tube a) before treatment at 10.60 m from the surface; b) before treatment at 11.00 m from the surface; c) after treatment at 10.60 m from the surface; d) before treatment at 10.90 m from the surface.

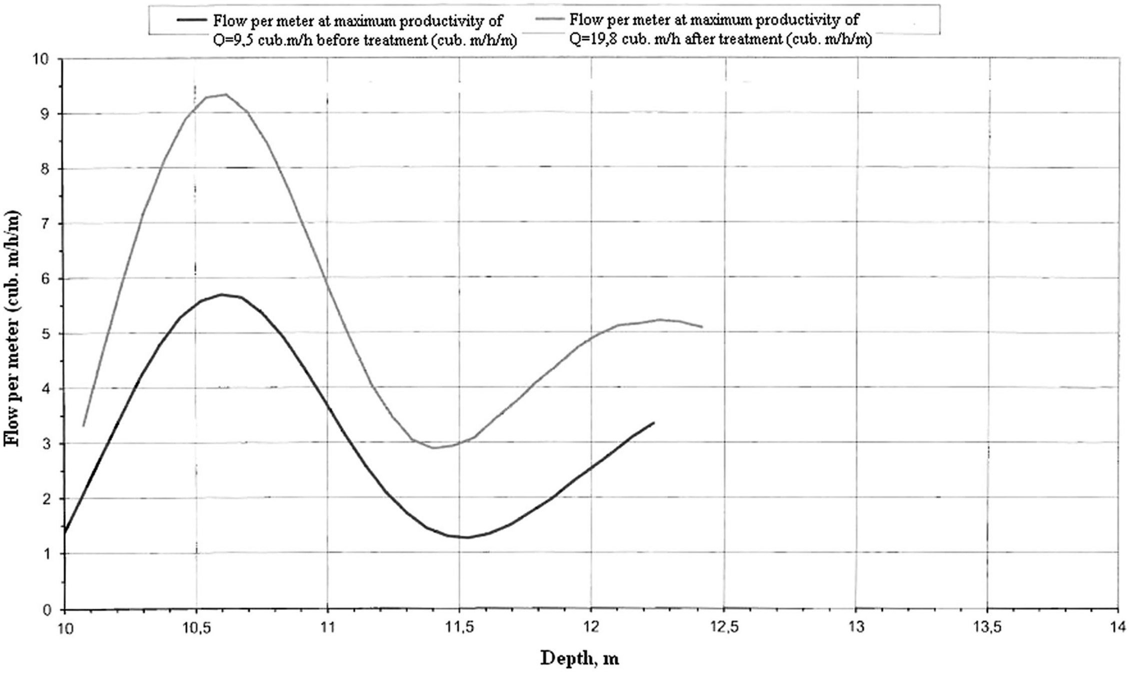

Fig. 11. Flow test of the first test well before and after treatment.

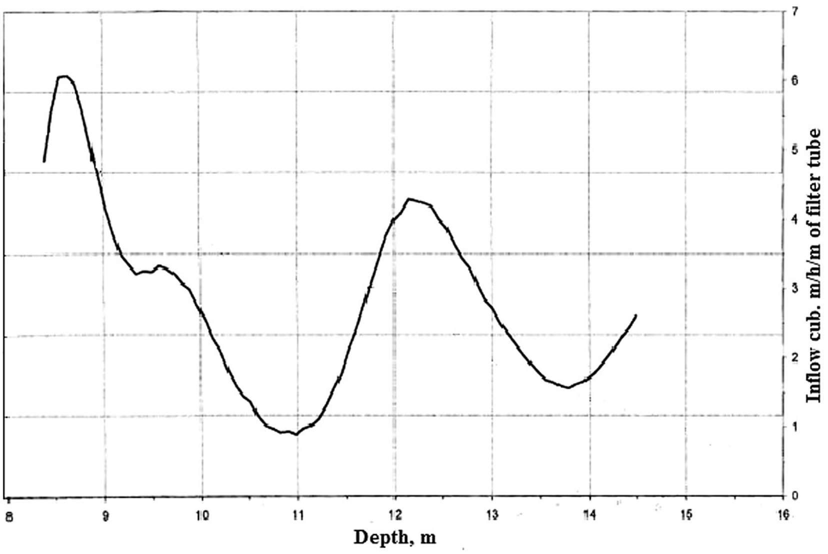

Fig. 12. Flow test of test well 2 before treatment.

since only a limited amount of particles can be removed by ultrasound and further improvement of productivity may be achieved with the shockwave treatment. In case of the preliminary treatment we have not treated the zones till the initial turbidity values were obtained, since the treatment should be followed up by a shockwave treatment and additional ultrasonic treatment, during which the remaining lose particles would be removed.

The preliminary cleaning was followed by the shockwave treatment of the zone between the depth 15.5 m and 14 m. We performed 2 discharges per 15 cm of production zone at maximal power. Taking into account the flow diagram, we have performed 5 discharges per 15 cm of production zone between the depths 14.7 m and 15.2 m, where we expected to see a flow pick. It was important to remove the detached deposits relatively quickly after the shockwave treatment, thus we have performed the ultrasonic follow up treatment of this zone immediately after the shockwave treatment. The duration of the ultrasonic treatment was chosen similar to test well 1, since this time proved to be optimal, based on the turbidity measurement. The results of this treatment step are presented in Table 7.

As it can be seen from Table 7, the changes of the dynamic level are observed only after the follow up treatment with ultrasound and not after the shockwave treatment alone (dynamic level changed after the shockwave treatment from 3.01 m to 3.04, which indicates that there is no flow improvement). Thus, the shock wave treatment alone would not be as effective as the same treatment combined with ultrasound, since the detached deposits should be removed afterwards.

The zone between the depths 14 m and 12 m was treated using the same sequence of operations: a shockwave treatment with 2

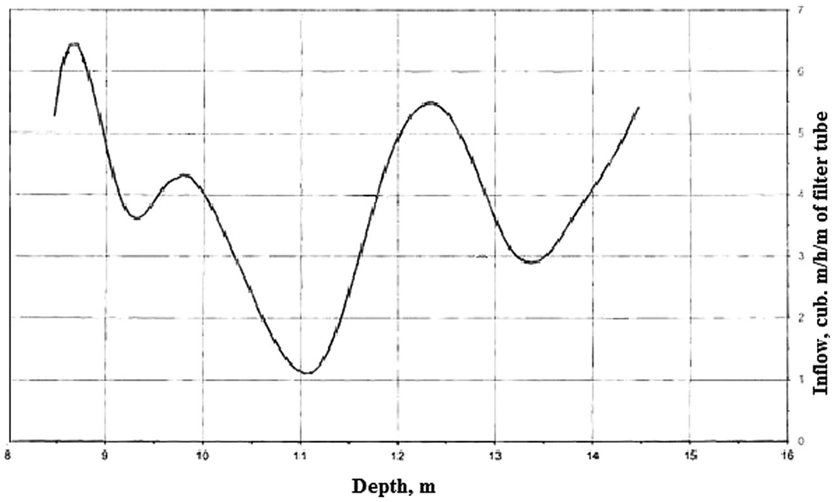

Fig. 13. Flow test of test well 2 after treatment.

Table 7
Parameters of test well 2 after shockwave treatment and ultrasonic follow up treatment of the productive zone at the depth between 14 m and 15.5 m.

Depth, m	Time after treatment start, min	Dynamic level, m	Turbidity, FNU
15.5	0	3.04	29
	20	3.02	3
15	0	3.02	7.4
	20	3.01	3
14.5	0	3.01	10.8
	20	2.99	2.8

Table 8
Parameters of test well 2 after shockwave treatment and ultrasonic follow up treatment of the productive zone at the depth between 12 m and 14 m.

Depth, m	Time after treatment start, min	Dynamic level, m	Turbidity, FNU
14	0	2.99	66
	20	2.99	2.8
13.5	0	2.99	13
	20	2.96	2.6
13	0	2.96	3.8
	20	2.96	2.8
12.5	0	2.96	17
	20	2.95	3.5

discharges per 15 cm of production zone followed by a ultrasonic treatment of 20 min per 50 cm of production zone. Taking into account the flow peek between the depths 12 m and 12.5 m, we have performed 5 discharges per 15 cm of production zone in this zone. The results of the ultrasonic treatment of the second zone of test well 2 are presented in Table 8.

Based on the flow diagram, we have assumed, that the flow drop between the depths 10 m and 12 m is determined by the geology, and not by colmatation, since colmatation is very unlikely to cause such a big production drop. Thus, we have carried out the treatment of the zone between 8.5 and 12 m at once. In the zone between 9.25 m and 10 m we have performed 5 discharges per 15 cm of production zone. At all other depths within the zone between 8.5 m and 12 m we have performed 2 discharges per meter of production zone. The shockwave treatment was followed by an ultrasonic treatment of 25 min per 50 cm of formation. The results of the treatment are presented in Table 9.

Table 9
Parameters of test well 2 after shockwave treatment and ultrasonic follow up treatment of the productive zone at the depth between 8.5 m and 12 m.

Depth, m	Time after treatment start, min	Dynamic level, m	Turbidity, FNU
12	0	2.97	18.5
	25	2.95	3
11.5	0	2.95	6.8
	25	2.95	3.8
11	0	2.95	9.2
	25	2.95	4.6
10.5	0	2.95	12.8
	25	2.945	3.1
9	0	2.945	18.3
	25	2.94	3.8

The flow test of test well two after the treatment is presented in Fig. 13.

As it can be seen, the flow increased in particular in the zones, where 5 discharges were performed instead of 2. Thus, it can be assumed, the amount of 2 discharges per 15 cm of production zone is not the optimal amount, and that an increase of this amount could potentially lead to an improvement of the method. However it should be beard in mind that the increase of the discharge amount would lead to an increase in the duration of the treatment and, consequently, the cost. In this way, the optimal amount of discharges per meter of production zone has to be determined in future research. However, it should be taken into account that the larger increase of the flow in the mentioned zones could also be due to geological conditions and peculiarities of the concrete wells. Thus, more field tests would be necessary to determine the optimal procedure.

In test well two the total water production increased from 22.7 m^3/h to 31.5 m^3/h; the dynamic water level during production was 6.5 m before treatment, and 5.57 m after treatment.

Taking into account the results of both wells we can conclude, that the combined shockwave and ultrasonic method of water well regeneration proved to be an effective technique. The observed increase in production was between 40% and 109%.

5. Conclusions

A new technology that uses high- power ultrasound and shock waves to remove formation damage of water wells has been developed. The analysis, carried out in this article, has shown that a combined ultrasonic and shock wave method of well regeneration is a more efficient method, then the sole ultrasonic method. The modelling of the induced signals in the borehole environment has revealed that the effect of the two methods is relevant in various colmatation zones. Whereas the ultrasonic method has a strong impact on the area of the filter tube, the impact of the shock waves is focused on the gavel pack, the wall of the well and the adjacent aquifer. A shockwave treatment, which is normally more effective due to larger impact zone, needs to be followed by ultrasonic treatment in order to facilitate the removal of the detached deposits.

The field test confirmed the effectiveness of the combined shockwave and ultrasonic method for regeneration of water wells. The productivity of the two test wells showed an increase of production, while the dynamic fluid level was kept in a predefined range. This is an indication of a permeability improvement around the well.

The measurements of the dynamic level, performed during the test indicated, that the water level raised only during the ultrasonic treatment, thus, we can conclude, that the detached during the shockwave treatment deposits are not removed directly, but during the follow up treatment with ultrasound. This confirms our hypothesis, that the combination of both methods would be more effective, that the methods alone.

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