Monitoring of rapid sand filters using an acoustic imaging technique

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Abstract
A novel instrument is developed to acoustically image sand filters used for water treatment and monitor their performance. The instrument consists of an omnidirectional transmitter that generates a chirp with a frequency range between 10 and 110 kHz, and an array of hydrophones. The instrument was extensively tested in a lab before being deployed in an industrial rapid sand filter, made available by a Dutch drinking water company. This filter was monitored over a period of 10 days. We performed a scan every two hours. The obtained images are processed and compared. Clear changes in acoustic response were detected mainly at the top 20 cm of the filter bed. Two important observations can be made from the analysed data. First, the filter bed is compacting during filtration. This seems to be linearly increasing with the filter run time. The second effect is the relative acoustic “transparency” of the filter bed directly after backwashing. Small-scale accumulations of particles are detected. These observations show the great potential of this acoustic-based tool in monitoring the performance of a rapid sand filter.

Keywords
Acoustic waves, rapid sand filters, monitoring techniques

INTRODUCTION
Rapid sand filtration, often employed in municipal areas, is a fully automated and complex part of the water treatment process. Coagulation and flocculation followed by sedimentation are performed before rapid filtration can take place. Remnants of flocculants, suspended in water, are then removed. Graded sand with an effective grain size of 0.35 to 2.6 mm are used for this purpose, sometimes with an additional coarser layer of material on top such as anthracite. The accumulation of particles occurs over the whole depth of the filter bed that is periodically cleaned by reversing the flow direction, a procedure known as backwashing.

While in use, the state of a sand filter changes over time due to short-term processes such as clogging or long-term processes such as the mixing-up of layers. Currently, the state of a filter can only be assessed indirectly through measurements of turbidity and pressure or simply by taking samples. However, these measurements provide information averaged over the whole filter bed and are therefore not sufficient to detect local changes that may affect the long-term performance of a rapid filter. Acoustic imaging is a more suitable method to reveal these effects. Acoustic waves carry information about the media they travel through. They are reflected at boundaries representing a change in medium parameters. For a sand filter, this can be either a layer with a different grain size or a local accumulation of suspended particles in the
pores. Therefore, in theory, acoustic waves can be very useful for the characterization of filters. A few acoustic-based techniques with applications in water technology can be found in the literature. Acoustic waves were used by researchers to detect immiscible liquids in sand (Geller 2000). Another example involves the monitoring of ion exchange between pore-fluids and sediments in situ (Li 1998). Here, a reduction in the acoustic wave amplitude was correlated with a decrease in the total number of ions in the pore water. In this paper, we describe a method to monitor sand filtration using acoustic waves. An instrument, composed of an omnidirectional broadband transducer and an array of hydrophones, is developed in order to test the method in practice. A monitoring experiment, using the novel instrument, was conducted on a sand filter during a complete run time. The processing applied to the data and the obtained results are discussed in detail.

PRINCIPLES OF ACOUSTIC IMAGING

Acoustic imaging is a widely used technique based on the propagation of sound waves. These waves are mechanical disturbances that are carried through the inspected object and reflected at boundaries separating layers with contrast in density $\rho$ and sound speed $c$. For a sand filter, these boundaries can either represent a sand layer with a different grain size or an accumulation of impurities that resulted locally in the clogging of the pores. The amplitude of the reflected signal depends on the contrast in acoustic impedance, i.e. the product of the sound speed and density, whereas its arrival time is affected only by the sound speed. At an interface, a part of the acoustic energy is reflected and the other part is transmitted to deeper layers. The amplitude of the reflected wave is also affected by attenuation inherently present in the medium or caused by small-scale scattering.

In the water treatment process, suspended particles and colloidal solids are removed from the water and accumulated in the pores reducing hereby the pore volume in the sand filter and hence the porosity. The saturated bulk density of the sand is expected to increase with decreasing porosity. The sound speed is also affected by the accumulation of particles in the pores. Overall, the amplitude of the reflected acoustic wave is expected to increase as the filter is in use.

INSTRUMENT DESCRIPTION

To test the proposed method in practice, we developed an instrument that is able to image the state of a filter while in use. Figure 1 shows a schematic of the instrument, it is composed of an omnidirectional transmitter and a hydrophone array. Both the signal emitted by the transmitter and the signal measured by each hydrophone are recorded. A dedicated software package is developed to control the parameters of the transmitted signal and visualize the recorded response. The transmitter sends out a chirp with linearly increasing frequency. This type of signal is chosen over a single frequency pulse in order to improve the vertical resolution of the images. In the case of a linear chirp, the vertical resolution, $\Delta z = c/2B$, is inversely proportional to the bandwidth $B$, whereas the
vertical resolution of a single frequency sinusoid depends linearly on the pulse duration. We typically sweep the frequency from 10 to 110 kHz. Assuming an average sound speed \( c \) of 1500 m/s, this range of frequencies allows us to achieve a vertical resolution of approximately 1 cm. This implies that clogging in the filter bed of similar size can potentially be detected by the instrument.

The reflected signals are recorded by 5 hydrophones arranged along two perpendicular lines. The single hydrophones are omnidirectional. Using an array instead of a single hydrophone improves the sensitivity in the vertical direction and helps suppress undesired reflections arriving, in this case, from the sides of a filter. The response function of this array depends on the distance between the hydrophones, the frequency of the transmitted waves and the direction of the incoming wave. The distance between the hydrophones is 1.25 cm, corresponding to \( \lambda/2 \) at a frequency of 60 kHz, with \( \lambda \) being the wavelength. The -3 dB points of the response function defines the beam opening angle \( \theta \), which equals 34° at 60 kHz. The beam opening angle directly relates to the horizontal resolution of the instrument via \( \Delta x = 2 \, d \tan (\theta/2) \), where \( d \) is the distance between the target and the hydrophone array. Extending the size of the array by adding more hydrophones will improve the horizontal resolution.

The transmitter and the hydrophone array are attached to a robot which can move in three directions along an aluminum frame. The robot is controlled via the computer and can be programmed to perform a scan in two directions and repeat it over a given period in time.

Figure 1: A sketch of the developed instrument: an omnidirectional transducer sends a signal out which is then recorded by a hydrophone array with a beam opening angle of 34°. Reflections arriving outside the beam opening angle are strongly suppressed. The recorded acoustic signal is subsequently processed to a final image.

**MONITORING EXPERIMENT**

To test the developed instrument, we performed a monitoring experiment in a rapid sand filter put at our disposal by a Dutch water company. The filter served at the early stages of the water treatment process and was typically 156 hours in use before the cleaning procedure is started. The filter is about 10 m long and 5 m broad and is divided in two compartments separated by a channel built to drain water used in the backwashing
procedure. The filter bed is 1.3 m thick and is composed of fine sand with a grain size between 0.8 and 1.25 mm. A stack of sand layers with increasing grain size is placed below the filter bed for support. The water height above the filter bed is 1.25 m and is variable during the filtration process. The instrument was placed on top of the filter as shown in Figure 2. The monitoring experiment was conducted over a period of 10 days where the state of the filter was imaged before the cleaning procedure and continued until a full cycle elapsed. A 2D scan along the x-direction, indicated by the green line in Figure 2, was repeated every two hours. We selected this specific location of the scan because no interference between reflections from the filter bed and the filter walls are observed. The sensors were positioned 45 cm below the water surface and moved in 1 mm increments. A 90 cm long scan took about 15 minutes to complete.

Figure 2: A picture showing the instrument placed on a sand filter. The green line indicates the location of the scan.

**Data processing**

The signal emitted by the transducer is a 2 ms long chirp with a frequency range of 10 to 110 kHz. The chirp is compressed by applying a specific processing flow aimed at enhancing the resolution of the recorded data. To this end, we use deconvolution to recover the impulse response and then apply a low-pass filter to reduce the artifacts introduced at high frequencies. The chirp and the recorded signal are combined to obtain the final reflected response. The processing flow is applied to the sum of the five hydrophones and is repeated at recordings acquired at an increment of 1 mm. Figure 3 shows a typical image obtained for a 90 cm long profile. In this image, the depth axis is computed from the arrival time assuming a constant sound speed of 1500 m/s. The reflection from the top of the sand bed is identified at a depth of 80 cm. Reflections from the water surface and the filter walls are also detected in the scan. They are strongly present because of the large impedance contrast encountered at the water/air interface and the water/filter wall interface. However, they are not interfering with the reflection from the sand bed and can then be removed from the scan.
Results and interpretation

The monitoring experiment started by acquiring a scan of the filter which was already 4 days in use. After cleaning the filter by backwashing, the scans were repeated every two hours until it was cleaned again after 10 days. The effect of backwashing on the filter can be evaluated by comparing the images before and after the cleaning procedure. These images are displayed in Figure 4. It is clear that the amplitude of the signal, reflected at the top of the sand, decreases after backwashing. Lateral variations in the amplitude of the reflected response are also observed at the top of the sand bed. Some spots, indicated by the white circles, appear to be more clogged than others. However, the locations of these spots are variable. They seem to be impurities originating from deeper parts of the filter which were not entirely removed due to the limited duration of cleaning procedure. In the data, we observe that these spots get clogged faster than other parts of the filter. This is because the pore volume is reduced there initially, making it easier for suspended particles to be retained from water. These spots act as a filter with smaller pores and become more effective in removing particles from the water. As the filter is in use, the rest of the sand bed gets clogged as well, increasing by that the amplitude of the reflected response as shown in Figure 4c.
Figure 4: Acoustic images of the filter: a) at the start of the monitoring experiment, b) after backwashing, c) after 10 days of filter use and d) after backwashing again.

When we look deeper in the filter bed, more differences between the clean and the clogged states of the filter show up. Small-scale variations in acoustic response corresponding to accumulations of impurities are distributed over the top 20 cm of the sand bed as it can be seen in Figure 4b. These accumulations, with sizes in the order of a few centimeters, are only detectable shortly after backwashing. The relative "transparency" of the filter occurs only at the early stage of the filter run when the pores in the upper 5 cm of the filter are not clogged, allowing more acoustic energy to penetrate deeper parts of the filter.

Scans of the filter were repeated every two hours. Figure 5 shows the changes in acoustic response with respect to time, averaged over the length of the profile for all scans. The direct wave and the wave reflected at the water surface are included in the figure to evaluate whether changes in the emitted signal or the water level have taken place. A clear trend, showing a slow compaction of the sand bed, can be observed, i.e. reflection from the top of the sand bed is placed at greater depths. This effect is reversed when the cleaning procedure is started. The sand bed is then expanded. Few hours after backwashing was completed, the depth of the filter bed stabilizes to a level less deep than before. The variation in the depth of the sand bed as a function of time is...
plotted in Figure 6a. Over a period of about 200 hours, the total compaction is 3.5 cm. The changes in the filter bed depth correlate well with changes in the pressure difference measured between two levels in the sand (see Figure 6b).

![Image of acoustic response and filter bed depth](image-url)

**Figure 5:** The average acoustic response over the 90 cm long profile plotted for all scans performed every two hours.

![Image of pressure difference](image-url)

**Figure 6:** The average depth of the filter bed plotted for each scan. b) The difference in pressure measured during the monitoring experiment.

**CONCLUSIONS**

An acoustic-based instrument was developed as a monitoring tool for the water treatment process. This instrument, composed of a broadband transmitter and an array of hydrophones, was tested in an experiment conducted in a rapid sand filter used in practice. The state of the filter was monitored for a period of 10 days. An overall
increase of the reflected acoustic response was observed in the data. Acoustic waves are sensitive to changes in porosity. The density and sound speed increase when the water in the pores is replaced by suspended particles, increasing by that the amplitude of the reflected acoustic response. The increase was mainly observed at the upper 5 cm of the sand bed. The performed scans showed also a slight compaction of the filter bed, when put in use, and expansion after backwashing was completed. Once cleaned, the upper 30 cm of the filter becomes "transparent" and small accumulations of particles appear. The information provided by the developed instrument demonstrates its great potential in monitoring the filtration process.

REFERENCES
