AN ULTRASONIC METER TO CHARACTERIZE DEGREE OF
FOULING AND CLEANING IN REVERSE OSMOSIS FILTERS

M. Morra, L.J. Bond, G.R. Golcar
Pacific Northwest National Laboratory
P.O. Box 999
Richland, WA 99352

ABSTRACT. The development of prognostic capabilities that predict the condition and
remaining service life for key industrial systems has the potential to significantly impact
performance and the economics of operation for both current and next generation plants. This
paper describes an on-line real-time ultrasonic meter that can be used to monitor both fouling
and cleaning in reverse osmosis filters. It provides a measure for the degree of fouling. A suit
of ultrasonic transducers is mounted to operate through the filter-housing wall on a pilot-scale
service water system. A “Degree of Fouling” index is given during both fouling and cleaning
for the filters during operation for processing of saline solutions (simulated sea and brackish
waters) and solids contamination. The fouling index is transmitted to a central computer
where it is integrated in a system level prognostic algorithm.

INTRODUCTION
In many systems including nuclear plant pure water supply it is necessary to develop
on-line self-diagnostic monitoring capabilities [1]. Such systems supply critical pure water
sources for safety system and makeup requirements. The development of prognostic
capabilities that predict the condition and remaining service life for key systems has the
potential to significantly impact performance and the economics of operation for both
current and next generation plants.

Ultrasonics has been used for more than 50 years for nondestructive testing [2] and is
now an increasingly common tool used for process monitoring and characterization [3,4,5].
Corrosion, erosion and fouling are common in service water systems. As a model system
to demonstrate the potential of ultrasonic measurements in prognostic methodologies, the
monitoring of fouling and cleaning in reverse osmosis (RO) filters was selected for study.
The fouling of such filters is a process that can be studied on system operational condition
changes induced and detected in operating fouling runs between 1 and 7 days.

Fouling in RO and other membrane based filters is also a topic of interest to the
membrane and process separations communities. The single most critical problem limiting
the application of membrane processes for liquid separation is fouling. For industrial
applications the optimization of the performance of spiral wound reverse osmosis filters
used for desalination, water reclamation or other industrial chemical processing it is
necessary to quantify condition in terms of a degree of fouling, during both fouling and
cleaning. Current technologies employ indirect measures that monitor either or both
pressures or permeate flux and do not provide data during the cleaning cycle. The
development of real-time measurement techniques using ultrasonic methods for the characterization of both membrane compaction and fouling represented a major advance [6]. This approach has now been used in a number of laboratory studies on flat-sheet membranes [4,7,8,9,10].

This paper describes the development and demonstration of acoustic time domain reflectometry for on-line and real-time monitoring of fouling and cleaning on a pilot scale service water system. The method is able to monitor early stage contamination, which does not result in either a pressure or permeate flux change. It provides a measure for the degree of fouling, which is a useful prognostic in that it allows anticipatory operations and maintenance (O&M) responses to developing system degradation. The net result is higher throughput and significantly increased reliability of the effected water dependent safety systems.

EXPERIMENTAL INVESTIGATION

A suit of ultrasound transducers mounted to operate through the filter-housing wall was deployed during the operation of a pilot-plant scale service water system to purify saline solutions (simulated sea and brackish waters) and also to remove solids. Combinations of both pulse-echo and transmission measurements are employed. Transducers operate with a multiplexer, digitization and distributed signal processing to give feature extraction that forms the bases for an index that quantifies “Degree of Fouling.” This index can be measured during both fouling and cleaning, and provides a direct linkage to the impurity concentration or input stressor level of the fluid stream. The fouling index is then transmitted to a central computer where it is integrated in a system level prognostic algorithm [11].

Apparatus

Most RO technology uses a process known as crossflow that allows the membrane to continually purge impurity accumulation while in operation. Because of the effectiveness of this design, it was necessary to provide for the management and control over the filter’s performance range. The pilot scale service water system [1,11] in a laboratory setting provided the experimental mechanism to establish operational parameters and maintain the performance characteristics of commercially available reverse osmosis filters.

FIGURE 1. System graphic user interface.
The pilot scale water treatment system used for the fouling experiments is a closed flow loop system. This is shown in the user interface display in Figure 1. A central computer provides real time operational system parametric updates of pressures, flow rates and temperatures at key locations throughout the system. Control for motorized valves and temperature is also provided. The system is able to render flow rates, pressures and temperatures consistent with the filter manufacturer’s specifications. The filter bank consists of six filters that are aligned in parallel and in series, where there are two (2) sets of three (3) parallel filters in series as shown in Figure 2.

Fouling trials were conducted separately for both the saline solution and solid suspensions. In this closed flow loop system, fouling in the filters was induced by gradually increasing the concentration of the solution and solid suspension in a source water holding tank. Cleaning trials were conducted for the saline solution only.

The concentration levels of saline solution and sand suspensions were increased to a point beyond the normal performance range of the filters. Table salt was added to the holding tank and dissolved in water with a large electric mixer impellor. For tests employing salt-water, a WTW Multiline P4 Universal Multimeter was used to measure salinity. Data from the meter were provided in both weight percent salinity and micro Siemens per cubic centimeter. To investigate the effect of particulate fouling diatomaceous earth and sand were added to the water in the holding tank and kept in suspension with the motorized impellor.

---

**FIGURE 2.** Filter bank with flow direction and transducer placement. (1) Concentrate inlet flow, (2) Concentrate outlet flow, (3) Permeate flow clean water outlet.

**FIGURE 3.** Signal captured for through transmission a) covering complete transit time across filter housing and membrane layers. b) Pulse/Echo signal with multiple reflections of filter casing and membrane layers. Time covers range from transducer face to center bore region of filter.
Ultrasonic Measurement Systems

The ultrasonic system consisted of several 1” (2.5 cm) diameter 500 kHz and 1” x 0.5” (2.5 x 1.25-cm) 500kHz flat compression wave transducers. The frequency utilized was the highest frequency that could penetrate the fiberglass composite filter casing and the RO membrane layers to provide acceptable signal to noise ratios (Figure 3a – 3b). Stand off shoes were attached to the transducers to enable a more secure attachment to the curved surface of the filter casing. Transducers were coupled to the filter casing with both a high viscosity ultrasonic gel couplant and a thin layer of solid skin type couplant to conform to the irregular fiberglass surface. The transducers were placed at locations throughout the filter system layout using both pulse echo and transmission time domain reflectometry to monitor evidence of filter fouling and membrane compaction at various locations and to determine if fouling in filters is position dependent. The equipment used with the suit of transducers were commercial units: Ritec square wave broad band pulser-receiver, LeCroy digital oscilloscope, and Krautkramer and Staveley multiplexers.

Ultrasonic measurements were taken through transmission across the entire filter and pulse-echo mode, where the time of flight signals were limited to the distance between the outer casing and the center bore of the RO filter. Examples of RF data are shown in Figure 3a and 3b.

The transmission signals were zoomed in to focus on the received signal’s time domain and relative amplitude in a limited window as shown in Figure 4. Each measurement configuration was implemented with four (4) transducers or transducer pairs. The signals for each transducer were collected individually by stepping through the multiplexers. At each step of the fouling process signals were collected and stored on floppy disk. At the end of each run, digitized signals were transferred to a desktop computer for display, analysis and output.

Solute Fouling Trial

Fouling trials for the saline solution was conducted on the flow loop system with clean filters installed and under normal operating conditions set within the manufacturer’s performance ranges. There are multiple of variables that establish this range. Some are based on the filter diameter, length and backpressure requirements [12]. Each trail began with system flush using pre-filtered de-ionized water where ultrasonic signals could be verified and established as a baseline reading through the filter casing and membrane layers with the system in operation.

![Waveforms shown superimposed as an expanded view of three signals received through the filter geometry.](image-url)
Permeate Salinity/Flow Rate

FIGURE 5. Salinity concentration of the permeate water flow (■). The flow rate for the permeate flow with change in source water salinity (○).

Ultrasound signals from the pulse-echo measurements gave data that were complex to analyze and results were inconclusive due to effects of constructive and destructive interference at the filter casing and membrane layer interfaces. Although there was a detectable change, the signals were not readily intelligible.

An alternate approach using transmission measurements with transducers placed on opposite sides of the filter casing provided a more reliable measure for filter status in real time. Ultrasound signals captured over time as the salt concentration was increased, show a measurable shift in arrival time of the signals, as shown in Figure 4. There is also a measurable change in amplitude of the received signal as the salt concentration increases.

The effective operating range of the filters used in this trial is shown in the data given in Figure 5. There is a maximum source salinity where the filters reach their saturation point and are no longer able to provide clean water. This occurs at approximately 12% source water salinity, after which the permeate flow or clean-water side experiences a dramatic increase in salt concentration that continues to rise as the source concentration is increased. Feed flow is shown to level off at approximately 14% salt concentration. At this point any increase in source salinity has no effect on the permeate flow rate when all other system parameters remain the same.

The trends in the ultrasonic data over the performance range of these filters are shown as graphs in Figures 6a and b. Relative signal amplitude rises with the increase in salt-water concentration. The time required to travel across the filter membranes is reduced, which indicates an increase in the ultrasonic sound velocity through, the membranes and solution system, as a function of salinity. The received signal does not show a dramatic shift or change at the 12% concentration level when the filter has reached saturation. The

FIGURE 6. Ultrasonic time-of-flight (TOF) and amplitude. a) Trend line showing increase in signal amplitude. b) Ultrasonic (TOF) sound velocity increase as a function of source salinity.
ultrasonic signals from all the various positions on the filter bank were observed to behave similarly.

In measured data the received signal does not show a dramatic shift or change at the 12% concentration level when the filter has reached saturation, and there is no visible measure of build up or membrane compaction shown in the time domain data. The received ultrasonic signals cover the entire range of the filter’s performance and effects are found to be reversible during cleaning. Therefore, when clean water is reintroduced in to the system and is used to flush the filters, the ultrasonic signals return to the baseline readings.

**Solids Fouling Trials**

For fouling trials measuring the effects of solids on ultrasonic signals, using the pulse-echo method once again proved inconclusive. The transmission method data was found to exhibit similar trends as in the case of the salt-water trials. The ultrasonic signals captured over time as the solid suspension was increased, exhibited a measurable shift in arrival time as shown in Figure 7. There is also a measurable change in amplitude of the received signal, which is shown to decrease unlike signal amplitude for the saline fouling trials, which increased in amplitude with the solution concentration.

The range of performance for the filters was achieved by closing the valve that controls backpressure on the filters. The backpressure provides the differential pressure required to maintain the filter mechanism.

**FIGURE 8.** Transmission signal first arrival time. a) At the filter inlet end, and b) At the discharge end.
It was observed through the range of valve operation that there is a point at which the flow of water through the filters will level off and the filters are no longer able to provide additional clean water flow. For our experiment, the valve was closed in steps up to 95%. For the range of closure from 55% to 95% there was no improvement in clean water flow, the filters are essentially fouled. It was this parameter that was used as a measure of performance and to correlate with the ultrasonic data.

In the case of solid particle fouling, it was observed that there were differences in the signals collected from each end of the filter, as well as at various locations for the transducers throughout the filter bank. This is shown in the example of data given as Figures 7 and 8. This effect may be attributed to the degree of compaction on the membrane surface as it relates to the filter’s ability to operate under cross flow self cleaning. To identify optimal transducer location for the monitoring of fouling, data was taken at opposite ends of the filter and compared. It was observed that the filter bank that was first in series experienced the most severe fouling and the inlet end of these filters also had a great build up then the outlet end.

Examples of data from particulate fouling runs are shown as Figures 8 and 9. The data from the inlet end of the filter exhibits a more dramatic change in the signal amplitude and sound velocity than those measured near the outlet. The filter was able to maintain the crossflow self-cleaning process until it was brought to a fouled state by changing process parameters, after which the ability to self-clean was limited by the additional concentration of solids. It is also probable that under these conditions solids are forced deeper into the filter and this has the effect of redirecting a portion of the flow to a different filter bank that was operating in parallel. The one anomalous data point seen in Figure 8a is believed to be due to shifting solids within the filter as the backpressure was increased.

CONCLUSION

The ability of ultrasonics to provide data for use in prognostics methodologies has been demonstrated. It has been shown to be possible to use a non-invasive ultrasonic method to monitor early stage contamination in real-time for the effects of fouling in reverse osmosis filters. The method was shown to operate over the full range of operational conditions.

The fouling ultrasonic meter was shown to have the ability to monitor fouling from solids and identify the specific location where build up and compaction occurs. This method can be applied to monitor both the fouling process and cleaning in filters and provide a metric for the degree of fouling.
ACKNOWLEDGEMENTS

The DOE-NERI program supported this work. Pacific Northwest National Laboratory is operated for the United States Department of Energy by Battelle under Contract DE-AC06-76RLO 1830.

REFERENCES

12. www.osmonics.com