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Monitoring and maintaining the integrity of immersed ultrafiltration membranes used for pathogen protection

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Abstract Membrane filtration has become the preferred alternative to conventional technology to remove water-borne pathogens in the preparation of drinking water. This paper presents the integrity monitoring and maintenance options for the ZeeWeed® immersed membrane. Results from two versions of air-based tests, a pressure decay test and a vacuum decay test are presented and shown to be conservative when compared to challenge results from independent studies.

Keywords *Cryptosporidium*; disinfection; integrity; membrane; microfiltration; ultrafiltration

Introduction

During the past decade, membrane filtration (microfiltration and ultrafiltration) has become widely accepted as a viable alternative to conventional drinking water treatment technologies such as coagulation, settling, and sand filtration. Over the past few years, continuous advances in cost and reliability, coupled with increasing concerns about water-borne pathogens (such as *Cryptosporidium*), have made membrane filtration the preferred alternative to conventional technology.

Membrane-filtered water quality is essentially independent of feed water quality or process conditions. A membrane is a physical barrier to pathogens that provides removal rather than inactivation. The process does not form by-products. It is very reliable; unlike conventional methods, process upsets may affect quantity but never quality.

Recognizing that pathogen removal is a primary end-user concern, various methods, direct and indirect, have been developed for monitoring the integrity of membrane systems. Indirect methods include turbidity and particle counting; they are on-line and continuous, but suffer from low resolution and sensitivity. In addition, they allow verification of integrity only to the extent that particles of interest are present in the feed water. They will not be addressed further in this paper.

Direct methods include many versions of air-based tests. Measuring membrane integrity with an air test involves starting with membrane pores filled with water and exposing one side of the membrane to air. Differential pressure is applied across the membrane to force air through defects. Integrity is typically quantified by measuring the rate of pressure decay. An air-based test allows quantification and location of defects, but requires that a unit be taken off-production for a period of 5 to 15 minutes. As such, they are typically performed once per day.

Many regulators have accepted an air-based test as a primary membrane integrity monitoring technique. Typically, test conditions must be selected to provide information on defects larger than 3 μm to ensure the removal of *Cryptosporidium* oocysts (size ranging between 4 and 7 μm). In addition, results are often converted to a log reduction value (LRV) using a method presented in this paper. This approach is currently the object of a standard method development (ASTM, 2001).

The ZeeWeed® ultrafiltration immersed membrane

Key features of the ZeeWeed® immersed membrane are illustrated in Figure 1. The membrane is a hollow fibre with filtration from the outside-in under gentle suction. The module is shell-less and immersed directly in the water to be filtered. Air is used to scour the membrane surface and de-concentrate the hollow fibre bundles. Feed and purge operations are done at the tank level.

ZeeWeed® is an asymmetric ultrafiltration membrane with nominal and absolute pore sizes of 0.04 and 0.1 µm, respectively. The basic membrane material is polyvinylidene difluoride (PVDF). The same membrane is used in two module configurations, the ZeeWeed® 500 series and the ZeeWeed® 1000 series. This paper focuses on the ZeeWeed® 500 series.

The ZeeWeed® 500 series is built with reinforced, large diameter hollow fibres which are flexible and have a very high tensile strength, two properties that allow vigorous air scouring in difficult applications.

Modules are rectangular frames containing thin bundles of hollow fibres. The hollow fibres are mounted vertically between headers with some slack to allow movement, air penetration and water renewal within the bundle. Modules are assembled side by side into cassettes, leaving space for water circulation and air scouring. Cassettes have integrated headers for permeate collection and air distribution. Cassettes are the building blocks that are immersed into the filtration tank and connected to permeate and air headers.

ZeeWeed® systems are equipped with on-line turbidity and/or particle counting devices. Direct integrity is measured with an automated pressure decay test (PDT) or a vacuum decay test (VDT). Alert and alarm levels are set to call for operator attention. A typical operator response involves 3 steps: 1) location of the leak, 2) isolation of the cassette or group and 3) repair of the leak. A leak is located simply by repeating the test and observing for a continuous stream of air bubbles rising to the surface of the tank. Cassettes or groups of cassettes (depending on plant size) are provided with isolation valves to restore integrity and schedule repair at a later date. A repair involves pulling the cassette from the tank and fixing the leak on-site (i.e., replacing an O-ring or sealing a damaged fibre).

Air-based integrity tests

Two test configurations are possible for determining the integrity of a ZeeWeed® immersed membrane system in accordance with the draft method (ASTM, 2001).

In the pressure decay test (PDT) air is introduced under pressure on the permeate side by isolating a group of cassettes. When the selected air pressure has stabilized, the group is isolated and the pressure decay is measured over 5 minutes. The pressure decay rate is then used to calculate an LRV as described below.

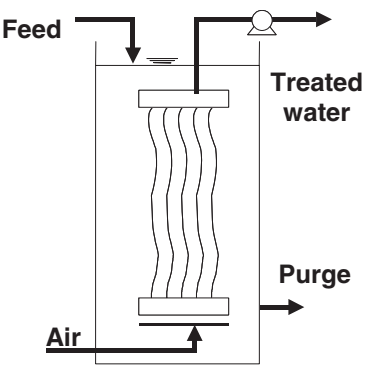

Figure 1 The ZeeWeed® immersed membrane principles of operations

In a vacuum decay test (VDT), the tank is drained and a vacuum is applied to the water on the permeate side of the membrane. The permeate header is also drained to provide a vacuum chamber (but the water is not drained from the modules). A vacuum pump is used to create the trans-membrane pressure required for the test and the LRV is calculated in the same way as in the PDT procedure.

The sensitivity of an air-based test is limited by the smallest pressure decay that can be measured reproducibly. This value is approximately 2 kPa or the equivalent of 5–5.3-log when converted to an LRV. Other factors can also affect the reproducibility of the PDT, such as temperature and test-to-test variability in the test pressure.

In the PDT, a significant pressure decay may result from diffusion of air through the membrane wall and dissolution into the water phase. This phenomenon is affected by the test pressure and the thickness of the membrane. A higher test pressure and a thinner membrane both increase diffusion-related pressure decay. This translates into background noise for the PDT (i.e. a pressure decay is measured even for a perfectly integral membrane).

The effect of air diffusion is neutralized in the VDT because 1) air is not pressurized, 2) the air-water interface is established at the surface of the membrane where the pores are the smallest, and 3) the diffusion path (between the air and the vacuum source) is practically infinitely long. The VDT is also a more representative test because the applied trans-membrane pressure gradient is in the same direction as during filtration.

The minimum defect size measured by an air test is estimated based on the bubble point equation (Eq. (1); ASTM, 2001):

$$d = \frac{4B\gamma\cos\theta}{BP} \tag{1}$$

where:

BP = The bubble point for the defect of diameter d
B = Capillary constant
d = Defect size
γ = Surface tension at the air-liquid interface
q = Liquid –membrane contact angle

Eq. (1) is used to determine the smallest defect contributing to airflow as a function of the test pressure for different membrane materials. For the theoretical case of a perfectly wettable membrane, $\theta = 0$, whereas $\theta = 65$ for PVDF ($\gamma = 72$ dynes/cm and $B = 1$).

An Estimated Log Removal Value (LRV_e) can obtained from a pressure decay test by performing a mass balance on the membrane system. Assuming that particles of interest (e.g., parasites or bacteria) are completely rejected by the membrane and freely pass through defects leads to the following simple equation:

$$LRV_e = \log_{10}\left(\frac{Q_{filt}}{Q_{bypass}}\right) \tag{2}$$

where:

Q_{filt} = Flowrate of filtrate leaving the membrane
Q_{bypass} = Flowrate bypassing the membrane through defects or leaks
LRV_e = Log Removal Value of particles of interest across the system

Q_{bypass} is a water flow rate under filtration conditions. It must be obtained from the results of the pressure decay test. The first step is to convert the pressure decay rate into a volumetric airflow rate through the defects using Eq. (3)

$$Q_G = PDR\frac{V_{system}}{P_{atm}} \quad (3)$$

where:

Q_G = volumetric air flow rate through defects expressed at atmospheric pressure, $m^3 \cdot s^{-1}$

PDR = pressure decay rate expressed as pressure per unit time, $Pa \cdot s^{-1}$

V_{system} = the hold-up volume of the system, m^3

The second step is to convert the airflow rate to a water flow rate and to go from the transmembrane pressure of the test to the transmembrane pressure during filtration.

$$f_1 = \frac{\mu_{water}}{\mu_{air}} \quad (4)$$

$$f_2 = \frac{P_{test}{}^2 - (P_{atm} + H_{static})^2}{2P_{atm}\,TMP} \quad (5)$$

$$Q_{bypass} = \frac{Q_G}{f_1, f_2} \quad (6)$$

where:

f_1 = air-to-water conversion factor

f_2 = transmembrane pressure conversion factor

m_{water} = viscosity of water, Pa.s

m_{air} = viscosity of air, Pa.s

P_{test} = average test pressure, Pa

H_{static} = static head of water above membrane, Pa

TMP = transmembrane pressure during filtration, Pa

Placing Eqs (3)–(6) into Eq. (2):

$$LRV_e = \log_{10}\left(\frac{Q_{filt}\,P_{atm}}{PDRV_{system}} f_1\, f_2\right) \quad (7)$$

Challenge study results

LRV_e calculated from the ASTM method provides a conservative estimate of the actual log removal value (LRV_a) for *Cryptosporidium* oocysts and *Giardia* cysts based on a comparison with challenge test data (Figure 2). These data were taken from independent studies with commercial-scale ZeeWeed® 500 modules (Montgomery Watson & City of San Diego, 1999; NSF International, 2001).

The lower values shown on the graph correspond to tests where fibres were intentionally pin-pricked or cut. No parasites were detected in the test with an intact membrane and the LRV data points should be read as "larger than". These data show that the LRV_e from the pressure decay test is correlated to the measured LRV_a, but is conservative, providing values about one log unit lower.

Impact of test variables

Pressure decay (PDT) and vacuum decay (VDT) tests were conducted on the same module to determine the impact of test configuration and pressure on the estimated LRV_e. Three observations can be made based on the results shown in Table 1.

1. At the lower pressure of 35 kPa, the two tests give identical LRV of 5.1 because the impact of air diffusion is not significant.

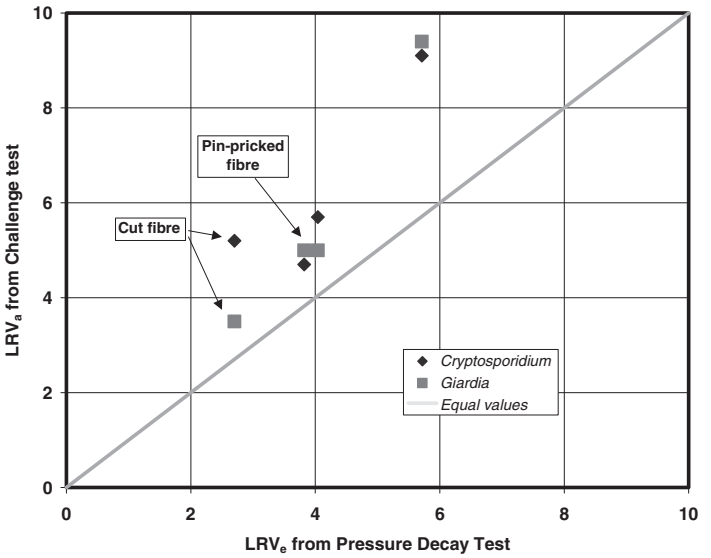

Figure 2 Comparison of actual and estimated LRV for the ZeeWeed® 500 membrane challenged with *Cryptosporidium* and *Giardia*

Table 1 Comparison of PDT and VDT on a ZeeWeed® 500 module

Test pressure	*Air-based test LRV*	
(kPa)	PDT	VDT
35	5.1	5.1
62	4.6	5.0

2. At 62 kPa, the PDT gives a significantly smaller LRV of 4.6 because of increased air diffusion.
3. The VDT results are essentially independent of test pressure for the reasons given above.

Conclusions

Both pressure decay (PDT) and vacuum decay (VDT) tests can be used to determine the integrity of immersed membranes. The results can be converted to a log reduction value providing conservative estimates of pathogen removal when compared to challenge tests. While the PDT is better accepted in the industry, the VDT is a more sensitive test because it practically eliminates the impact of air diffusion. The VDT is also a more representative test because the applied trans-membrane pressure gradient is in the same direction as during filtration.

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