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Quantification of the defect size of ultrafiltration membrane system using mathematical model

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HIGHLIGHTS

- A prediction model was developed to calculate the membrane defect size.
- The measured data goes with similar trend with the prediction model.
- The mathematical model could estimate the defect size as a function of applied pressure and pressure decay rate.

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ABSTRACT

The estimation of the damaged part size could be conducted by using a relationship between the value of pressure decay rate and the size of the damaged part, since pressure decay rate performs as a good indicator for the molar flow of air leakage or diffusion airflow. This study presents the development of a predictive model for estimating the air leakage through a defect and its contribution to pressure decay, and develops a prediction model of the size of membrane damage to evaluate the size of the defect. The results obtained from nitrogen flow rate measurement and pressure decay rate (PDR) allowed for the consistent determination of membrane defect size. The results also indicated that nitrogen flow rate and PDR are relatively dependent on holdup volume and independent on membrane area for a specific membrane under certain margin of applied pressure with the same water temperature. The experimental results demonstrated that the mathematical model could estimate the defect size as a function of applied pressure and pressure decay rate.

1. Introduction

Low-pressure ultrafiltration membrane system has been used to produce drinking water to meet the more stringent regulations on water quality because of its capacity of removing protozoa and bacteria [1]. A compromised membrane may no longer be an effective barrier against protozoa and bacteria. The presence of defects, oversized breaches or broken fibers may result to the passage of protozoa and bacteria and their entry into the public drinking water [2]. In order for a membrane process to be an effective barrier against pathogens and other particulate matters, accurate and efficient integrity tests of the membrane system should be applied to guarantee the quality of filtered products and detect the presence of oversized pores or defects that can compromise the retention capability of the filter [3]. The tests for broken fibers or defects should be sensitive to breaches as small as 3 μm which is based on the lower size range of *Cryptosporidium* oocysts, then the tests could make sure that any integrity breach large enough to pass oocysts will contribute to a response from the direct integrity test being used [4].

The most widely-used membrane integrity test method would be the pressure decay or pressure hold test [5] cooperating with particle counting method. The diffusive air flow test is another pressure-driven integrity test that is used to a less degree by some membrane manufacturers [6]. A detailed review of current integrity tests is provided elsewhere [7–21].

The basis of all pressure-driven integrity tests is founded on the bubble-point pressure concept [22]. Pressure decay or diffusive air flow tests are typically carried out at pressures below the bubble-point pressure of a non-defective membrane [23]. The upstream side of a wetted intact membrane is pressurized with air or other gases to a specific pressure and the pressure source should be isolated. Lack of membrane integrity would be signaled if the rate of pressure loss or air flow is above an acceptable value. Loss of pressure during a pressure-driven integrity test results either from the diffusion of air through the wetted membrane pores or from bulk flow of air through a defect. This test relies primarily on the measurement of pressure decay rate. A measurable pressure decay rate, which is in excess of the pressure decay rate due to diffusion air or higher than a pressure

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decay rate empirically established for a membrane without defect, should signal the presence of a defect. Since pressure decay rate performs as a good indicator for the molar flow of air leakage or diffusion airflow, the estimation of the size of the damaged part can be conducted by using a relationship between the value of pressure decay rate and the size of the damaged part. In actual membrane integrity tests, the minimum direct integrity test pressure commensurate with the required resolution of 3 μm for the removal of *Cryptosporidium* should be firstly determined and then the LRV (Log Removal Value) was verified by applying values for the variables specific to the test event [24]. If the verifiable LRV is significantly higher than the required LRV, the test would still allow the membrane system to maintain applicative. But the LRV could not indicate the existence of the membrane defect and reveal the relationship between the quality of pressure decay and the size of the defect.

K. Farahbakhsh [22] developed a mathematical model to estimate the amount of air diffusion through an intact wetted membrane as a function of applied pressure and its contribution to pressure decay test. Therefore, estimating and accounting for the contribution of air flow through a defect to pressure decay during a pressure decay test would produce much more reliable and sensitive results for membrane integrity tests. Some defect size prediction models of marker integrity test were established. B. Choi [12] developed a functional relationship between membrane damaged area and the mass of permeated fluorescent nanoparticle using a dimensional analysis, but it is not available to estimate the degree of membrane damage due to its uncertainty and inaccuracy. C. Suh [25] used genetic programming (GP) to develop a prediction model to predict the area of membrane breach with other experimental conditions (concentration of fluorescent nanoparticle, the permeate water flux and transmembrane pressure). W. Songlin [15] proposed a calculating model to predict membrane defect size and this integrity test method had about 39.33% probability to have a theoretic resolution of 3 μm or less under common experimental conditions. While few work on membrane defect size prediction of pressure decay test has been reported.

This paper presents the development of a predictive model for estimating the air leakage through a defect and its contribution to pressure decay, and develops a prediction model of the size of membrane damage to evaluate the size of the defect.

2. Theoretical background

2.1. Air diffusion contribution to pressure decay rate

As has been developed by K. Farahbakhsh [22], once the diffusive airflow rate is known for a given integral membrane and assuming ideal gas behavior for air, the pressure decay rate due to diffusion can be estimated from the following relationship:

$$PDR_{diffusion} = [\beta\gamma DH(p_1 - p_2)A]\frac{RT}{V} \quad (1)$$

$$PDR_{diffusion} = \frac{\alpha(p_1 - p_2)A}{V} \quad (1a)$$

where $PDR_{diffusion}$ is the pressure decay rate due to diffusion for a given membrane system (Pa s^{-1}); β is the ratio of saturation concentration of air in natural water to that of air in pure water; γ is the membrane characteristics parameter (m^{-1}); D is the diffusivity constant for air–water system (m^2 s^{-1}); H is the Herry's law constant (mol atm^{-1} m^{-3}); α is the $PDR_{diffusion}$ constant; p_1 is the applied test pressure (Pa) and p_2 is the downstream pressure (Pa). A is the membrane surface area (m^2); R is the universal gas constant (L atm mol^{-1} K^{-1}); T is the temperature (K); V is the hold-up volume or pressurized volume (L).

2.2. Model assumption

Fig. 1 shows the leaking model of membrane system. Assuming that: (1) The air in the hold-up volume or pressurized volume in the membrane system is in the quasi equilibrium state; (2) the hold-up volume or pressurized volume in the membrane system is unchanged, the internal temperature changes with the air leakage process. The internal air quality changes with the internal air pressure, but the external pressure is constant. (3) The defect is round in cross-section; (4) the air flow through thin-walled orifice should be an unsteady adiabatic flow process for high-pressure air flow. But for a specific moment, the flow could be seen as a steady flow and the flow loss could be only a local loss.

2.3. Energy equation

The energy equation between internal 1–1 cross-section and external 2–2 cross-section was established as following [26]:

$$H \cdot g + \frac{\kappa + 1}{\kappa}\frac{p_1}{\rho_1} + \frac{v_1^2}{2} = \frac{\kappa + 1}{\kappa}\frac{p_2}{\rho_2} + \frac{v_2^2}{2} \quad (2)$$

where, H is the height difference between two cross-sections (m), g is acceleration of gravity ($m \cdot s^{-2}$), κ is the adiabatic constant (non-dimensional), p_1 is the applied test pressure (Pa), p_2 is the downstream pressure (Pa), ρ_1 and ρ_2 are the air density, v_1 and v_2 are the flow rate of air through corresponding cross-section. Here, adiabatic flow makes the flow energy loss completely convert to internal energy, $\frac{\kappa+1}{\kappa} \cdot \frac{p}{\rho}$ in the equation is the internal energy in the adiabatic flow process, so no internal energy and loss occur in the equations.

Here, the air density could be expressed as:

$$\rho_2 = \rho_1\left(\frac{p_2}{p_1}\right)^{\frac{1}{\kappa}}. \quad (3)$$

According to assumption (1),

$$\frac{p_1}{\rho_1} = RT. \quad (4)$$

For H tends to zero and v_1 is far less than v_2, Eq. (2) could be transferred as following:

$$\frac{\kappa}{\kappa\text{-}1}RT\left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{\kappa-1}{\kappa}}\right] = \frac{v_2^2}{2} \quad (5)$$

$$v_2 = \delta_1\sqrt{\frac{2\kappa}{\kappa-1}RT\left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{\kappa-1}{\kappa}}\right]} \quad (6)$$

$$Q = \delta_1 \cdot A_d \cdot \sqrt{\frac{2\kappa}{\kappa-1}RT\left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{\kappa-1}{\kappa}}\right]} \quad (6a)$$

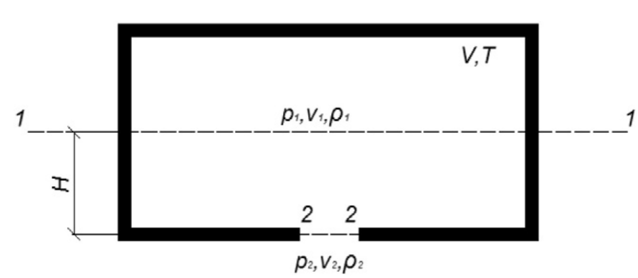

Fig. 1. The diagram of pressure membrane system with defect.