Hydraulic distribution of water and air over a membrane module using AirFlush®

J.Q.J.C. Verberk*, P.E. Hoogeveen**, H. Futselaar*** and J.C. van Dijk*

* Department of Sanitary Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, 2628 CN Delft, the Netherlands. (E-mail: j.q.j.c.verberk@citg.tudelft.nl; j.c.vandijk@citg.tudelft.nl)

** X-Flow B.V., P.O.Box 141, 7670 AC Vriezeveen, the Netherlands. (E-mail: Hoogeveen@xflow.nl)

*** Norit Membrane Technology B.V., P.O.Box 89, 7550 AB Hengelo, the Netherlands (E-mail: H.Futselaar@noritmt.nl)

Abstract

Delft University of Technology, Department of Sanitary Engineering, is researching the fundamentals of air-water flushing (AirFlush®) for membrane cleaning. The research is focused on two topics: velocities of water and air for optimal cleaning and the distribution of water and air over the cross sectional area of the module. In an earlier study the velocities of water and air to achieve an optimal cleaning for tubular membranes have been investigated. In this article the distribution of water and air over the cross sectional area of a 3"-membrane module will be discussed. Experiments have been performed and the fundamental processes that influence the distribution of air and water have been studied.

Keywords AirFlush®, air/water cleaning; flow distribution; two-phase flow; ultrafiltration

Introduction

Dead-end ultrafiltration is used more and more in water and wastewater treatment because of the good permeate quality, the flexible operation and the relatively low cost. As a disadvantage of the dead-end operation the flux decrease in time has to be mentioned. The decrease in flux is a result of the accumulation of particles in the membranes pores (pore blocking) and on the membrane surface (cake filtration). To remove these accumulated particles different cleaning techniques are used, e.g. back flush (BF), forward flush (FF) and chemical enhanced flush (CEF).

Particles deposited in the membrane pores can in principle be removed with a back flush. The back flush is a reversed filtration process. Permeate is pumped for a short time in the opposite direction through the membrane pores with a flux that is about 2.5 times that of filtration. Particles deposited on the membrane surface can in principle be removed with a turbulent flow of feed water (or permeate) parallel to the membrane surface. This cleaning method is called forward flush. Not all particles will be removed with these two hydraulic cleaning methods. Irreversible fouling can only be removed with chemicals which break down the fouling. With a chemical enhanced flush, chemicals are added to the module. After a soaking time of a few minutes the water, together with the chemicals, is flushed out of the module. As a result of the CEF chemical consumption can be high. The use of chemicals is not favoured because of the high costs of the chemicals and disposal and the associated water loss.

A relatively new method to remove the cake layer from the membrane surface is to make use of the beneficial scouring effect of air. By adding air into the feed stream during a forward flush the flow becomes highly turbulent, thus promoting cleaning. In cross-flow ultrafiltration air can be added continuously to the feed stream, resulting in a stable cake layer of a certain thickness and porosity (Cabassud et al., 1997; Laborie et al., 1997, 1998). When using dead-end ultrafiltration the air is dosed discontinuously into the forward flush (only
when a cleaning is performed). The first results of a full scale plant in The Netherlands making use of the AirFlush® cleaning method showed that the chemical consumption is low and that a stable operation is achieved (Van der Meer et al., 2000).

Delft University of Technology, Department of Sanitary Engineering, is researching the fundamentals of the AirFlush. This research is done in close cooperation with the membrane module supplier X-Flow and the membrane solution provider NMT. The research focuses on two topics:

- necessary water and air velocities to obtain an effective cleaning;
- distribution of water and air over the cross sectional area of a module.

In an earlier study (Verberk et al., in press) the effect of flow velocities of water and air on the flow pattern and cleaning in a module with only one membrane was investigated. In this study the different two-phase flow patterns were recorded by taking pictures. The effectiveness of the different flow patterns to remove a cake layer on a tubular membrane was investigated by filtrating backwash water from a rapid sand filter with a known content of suspended matter for some time. The mass of suspended matter inside the module is now known. Then the module was cleaned with different air and water velocities. By collecting the flushed water and determining the amount of suspended matter in this collected water, the effectiveness of different air and water cleaning velocities was compared on the basis of a suspended solid mass balance. It was shown that there was a large beneficial effect of air in removing the cake layer from the membrane surface compared to a forward flush with the same water velocity. It also was shown that the removal effectiveness was larger than a forward flush with a water velocity equal to the sum of water and air velocities of the AirFlush®. Probably the change in flow between water and air slugs results in an additional scouring force. At last the hydrodynamics of the two-phase flow were investigated and it was shown that the head loss of the AirFlush® could be predicted by the theory of two-phase flow.

This study focuses on the distribution of water and air over the cross sectional area of a module. A membrane module consists of about ten to a few thousand membranes. To clean a module more effectively every membrane in the module should in principle be flushed with the same water and air velocity. In this study information on the water velocities in individual membranes in a 3"-module was obtained by collecting the amount of water flowing through the individual membranes and converting these data to actual flow velocities.

**Methods**

The objective of this study is the determination of water and air distribution over the cross sectional area of a membrane module. The parameters of interest are the flow velocities of water and air and the air injection methods. A special test set-up for these experiments has been built, in Figure 1 a schematic drawing of this set-up is given. In the test set-up an X-flow 3"-membrane module (A) containing 109 tubular membranes (outer diameter 6 mm) is the central part. This module is placed vertically in a housing structure. Flexible tubes (B) are adhered to every membrane. All tubes are numbered and discharge into a gutter system (C) that recycles the water to the storage vessel (D). The water is pumped by a submerged pump (E) from the storage vessel to the membrane module. The water flow is measured with an Almometer SC80AS (capacity 600–20,000 l/h) flow meter (F). Air is used from the pressure system (G) in the laboratory. The pressure of the air could be read with a pressure meter (H). The air flow could be controlled with a rotameter from Krohne G19.08 (I). The water and air flow are mixed in the bottom end cap (J). A mass balance (K) is used to weigh the amount of collected water. A second flow meter (L) is used to measure the back flush flow and a PLC (M) is used to open and close the air valve.

An experiment started by adjusting the air and water flow to the desired values. After
about 10 minutes the flow meters were controlled and if necessary the flow was adjusted to the desired value. Then the experiment started. First the mass of the empty measuring cup was weighed (M1). The measuring cup was filled with water flowing through one of the tubes. The mass of the measuring cup, including the water was then weighed (M2). The amount of water flowing through a tube equals M1-M2. This amount of water is processed to average water velocities by dividing by the time period of measuring, the flushed membrane area and the density of water. Then this same procedure was repeated for the next tube, until all tubes were measured. All the velocities are printed in one plot from which the distribution can be read. The water distribution is also expressed in several characteristic parameters like: distribution factor $\gamma$, percentages of membranes not flushed with water and the ratio $u_{\text{max}}/u_{\text{average}}$. The distribution factor $\gamma$ gives information about the uniformity of flow through different tubes in a housing system. To calculate the distribution factor $\gamma$ the local uniformity coefficient for a single tube has to be calculated first. This non-uniformity coefficient is defined as:

$$\omega_i = \frac{\sqrt{(\bar{u}_i - u_i)^2}}{\bar{u}_i}$$

where $\omega_i$ = local uniformity coefficient [-], $\bar{u}_i$ = average superficial water velocity in membrane module [m/s], $u_i$ = liquid velocity in membrane $i$ [m/s].

All local uniformity coefficients are added and divided by the number of membranes, resulting in the overall uniformity coefficient $\omega$.

$$\omega = \frac{\sum_{i=1}^{n} \omega_i}{n}$$

$\omega$ = overall uniformity index [-], $n$ = number of membranes [-]

The distribution factor is defined as
If $\gamma = 1$ the flow is perfectly distributed (equal velocity in all channels), while if $\gamma = 0$ the flow is fully maldistributed, meaning that there is only one channel flowing and the rest have no water flow. With this test installation several experiments have been made, in which the influence of the water flow rate, the air flow rate, the methods to insert the air and combinations of cleaning methods were investigated. In Table 1 an overview of the different tests results is given.

**Results**

Before starting with the experiments, the water distribution was checked when performing a forward flush. Experiments with two different end caps (conical end cap and end cap with water feed from side) have been done, in both experiments the water flow rate was equal to 1.78 m$^3$/h ($= 0.21$ m/s), this value is used in field installations. The results of the experiments are given in table 1. These results indicate that the water distribution is good. A high distribution factor was found and all membranes are flushed with almost the same water velocity.

The influence of the air flow rate on the distribution of water over the cross sectional area was investigated in experiments 3 to 6. The water flow rate was equal to 1.78 m$^3$/h ($= 0.21$ m/s), the end cap was conical. Air was in the range of 0.2 to 0.8 m/s (1.54 to 6.80 Nm$^3$/h). In table 2 the results from the experiments are given, in Figure 2 the graphical result of experiment 5 is depicted. On the right side of the plot a membrane module containing 109 membranes is given. Every square represents a membrane and the color gives information about the water velocity in the membrane. On the left side the input parameters are given, as well as several characteristic parameters.

As can be seen from Figure 2 the water is not distributed equally over the cross sectional area of the membrane module. Some membranes are flushed with water, while other membranes are not flushed at all. The distribution factor is low, even when the air flow rate is increased. The membranes which are flushed have a water velocity more than twice the average velocity. In these membranes, air is also flowing. The tubes which are not flushed with water, have also no air flowing through the membranes.

In experiments 7 air is dosed with the use of a porous tube inserted in the end cap. Also

<table>
<thead>
<tr>
<th>Exp.</th>
<th>$\omega_{\text{water}}$ [m$^3$/h]</th>
<th>$u_{\text{water}}$ [m/s]</th>
<th>End cap</th>
<th>Distribution factor $\gamma$ [-]</th>
<th>Percentage membranes with out water flow [%]</th>
<th>$\frac{u_{\text{max}}}{\bar{u}}$ [-]</th>
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<td>1</td>
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<th>$u_{\text{gas}}$ [m/s]</th>
<th>Variable</th>
<th>Distribution factor $\gamma$ [-]</th>
<th>Percentage membranes with out water flow [%]</th>
<th>$\frac{u_{\text{max}}}{\bar{u}}$ [-]</th>
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</table>
with this air injection method the water distribution is not equally divided. Only the membranes right above the porous tube are being flushed. The other membranes are not flushed with water.

In experiments 8 the AirFlush® is combined with a back flush, in experiment 9 an intermittent AirFlush® (5 seconds of AirFlush®, followed by 5 seconds of forward flushing) is used. The time interval between consecutive AirFlushes and forward flushing was 5 seconds. Air was injected in both experiments by point injection. The results from table 2 indicate that a combination of AirFlush® and back flush (with a back flush flow of 250 l/(m²·h)) does not result in a good water distribution over the cross sectional area of the membrane module. However the intermittent AirFlushing results in a good water distribution. When air was dosed, the water was flushing all the membranes in the first seconds until a stable situation was reached where some membranes were flushing and others not. Then the air valve was closed and all membranes started flushing again. After 5 seconds the air valve was opened again and the situation in which some membranes were flushing and others not was reached.

**Discussion**

An equal distribution of water and air over the cross sectional area of the membrane module is needed to obtain the same cleaning in every membrane. From the results of the different experiments it is obvious that this equal distribution is not always achieved. The reason becomes clear when the hydraulic theory of two-phase flow is considered. The pressure gradient for two-phase flow in a single channel is given by

\[ \Delta p = \varepsilon_{\text{liq}} \cdot \rho_{\text{liq}} \cdot g \cdot L + 2 \cdot \frac{L}{d} \cdot \varepsilon_{\text{liq}} \cdot \rho_{\text{liq}} \cdot \varepsilon_{\text{mixture}} \cdot \frac{u_{\text{mixture}}^2}{2} \]

where \( \varepsilon_{\text{liq}} \) = liquid hold-up (-), \( \rho_{\text{liq}} \) = density of water (kg/m³), \( g \) = gravitational constant (m/s²), \( L \) = length of tube (m), \( f \) = Fanning friction factor (-), \( d \) = diameter of tube (m), \( u_{\text{mixture}} \) = mixture velocity = \( u_{\text{liq}} + u_{\text{gas}} \) (m/s)

The liquid hold-up is defined as:

\[ \varepsilon_{\text{liq}} = \frac{u_{\text{liq}}}{u_{\text{liq}} + u_{\text{gas}}} \]
where \( u_{\text{liq}} \) = superficial liquid velocity (m/s) and \( u_{\text{gas}} \) = superficial gas velocity (m/s).

The friction factor \( f \) follows from

\[
f = \frac{16}{Re_{m}} \quad \text{for laminar flow} \quad \text{or} \quad f = \frac{0.0625}{(\log(Re_{m}/7))^2} \quad \text{for turbulent flow}
\]

(Grolman et al., 1996)

The Reynolds number is defined as

\[
Re_{m} = \frac{\rho_{\text{liq}} \left( u_{\text{liq}} + u_{\text{gas}} \right) d}{\eta_{\text{liq}}}
\]

where \( \eta_{\text{liq}} \) = liquid viscosity (Pa·s)

The first part of the equation of the pressure gradient is the gravitational pressure drop, the second part is the pressure drop caused by friction. With these equations the pressure drop to transport a two-phase flow in a single channel vertically upwards can be calculated. In Table 3 this pressure drop is given for different water and air velocities. From the table it becomes clear that when the water velocity is increased the pressure drop increases. However, when the air velocity is increased, the total pressure drop decreases.

The important and only difference between a membrane and a membrane module is the entrance and exit conditions. In a membrane module all membranes share the same cross section of the enclosing end caps. Within this end cap no pressure difference is possible. Thus all membranes are subjected to the same pressure drop. Even when the gas and liquid flow rates vary between individual membranes.

When only water is flowing through a module, a higher flow velocity in one channel will result in a higher pressure drop in this channel, which in turn will automatically lead to a decrease in flow velocity. The same principle holds for a lower flow velocity. When the velocity in one tube is lower, the pressure drop is lower and thus automatically an increase in water flow rate will occur. With only water flowing through a membrane module a stable situation is therefore obtained where flow velocity variations are automatically balanced.

When air is introduced into the water, the pressure drop will be reduced (see Table 3). The drop in hydrostatic pressure is much larger than the rise in frictional pressure. Membranes receiving much air (low liquid hold-up) will now have a lower pressure drop, while membranes receiving little air (high liquid hold-up) will have a higher pressure drop. Because pressure differences in the end cap can not exist, the membranes that receive much air will automatically transport more water than the membranes receiving little air. This will eventually lead to the situation that some membranes will transport water and air and other membranes will transport none. This principle is also reported when air and water flow co-currently through two parallel placed tubes (Tshuva et al., 1999). In Figure 3 this principle is schematised for a membrane module. In this picture the water pressure can be read from the piezometers. In the left membrane water and air are flowing, which will result in a low pressure drop. In the right membrane, no water and air is flowing, and the water

<table>
<thead>
<tr>
<th>( u_{\text{liq}} ) (m/s)</th>
<th>( u_{\text{gas}} ) (m/s)</th>
<th>( \varepsilon_{\text{liq}} ) (%)</th>
<th>( \rho_{\text{hydrostatic}} ) (Pa/m)</th>
<th>( \rho_{\text{frictional}} ) (Pa/m)</th>
<th>( \rho_{\text{total}} ) (Pa/m)</th>
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</table>
level has dropped to the level equal to the pressure drop of the left membrane. The pressure in both membranes is therefore the same.

Because air and water do not mix well an equal distribution of air into the water is very difficult to achieve. With every air injection method there will be a mal distribution resulting in flowing and stagnant membranes (see results 3 to 8). Only in experiment 9 was the water well distributed over the module. In fact this distribution exists as two parts: a well distributed part (forward flush) and a mal distributed part (AirFlush®). When the AirFlush® is stopped, the system becomes automatically well distributed. Because air is flushed out of the membranes, the pressure drop in every membrane becomes equal and thus the liquid velocity in every membrane becomes the same.

Conclusion
Equal distribution of water and air over the cross sectional area of a membrane module is important to have the same cleaning conditions in every membrane in a module. In this study it was found that water is well distributed over the cross sectional area of a membrane module when a forward flush is performed. All membranes are flushed with almost the same velocity.

When an AirFlush® is performed some membranes are flushed with water and air, while other membranes have a stagnant water level. This principle of flowing and stagnant membranes can be explained with the theory of two-phase flow. A practical solution to the problem of mal distribution could be to apply the AirFlush® intermittently. Then the system is frequently redistributed, which will probably lead to proper cleaning conditions.

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References


