Desalination 266 (2011) 154–161

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

# Impact of gas bubbling and backflushing on fouling control and membrane cleaning

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ARTICLE INFO

*Article history:*
Received 12 January 2010
Received in revised form 12 August 2010
Accepted 12 August 2010
Available online 15 September 2010

*Keywords:*
Microfiltration flat sheet membrane
Gas bubbling
Backflushing
Fouling control
Membrane cleaning

ABSTRACT

Membrane fouling is an inherited phenomenon in microfiltration membrane processes which significantly impairs the filtration efficiency. This makes membrane regeneration an integral part of the microfiltration systems and necessitates the need for effective membrane cleaning in order to maintain higher efficiencies of the separation process. Experiments were carried out to evaluate the potentials of air bubbling and backflushing for reducing membrane fouling and for improving the membrane cleaning efficiency. Commercial yeast was used as test suspension with 10 g/L concentration whereas microfiltration experiments were conducted through a submerged flat sheet microfiltration membrane with a nominal pore size of 0.2 µm. Membrane regeneration efficiency was evaluated for five different filtration methods. The experimental results of this study show that effect of air bubbling and backflushing on fouling control and membrane cleaning was synergetic. However backflushing proved to be more effective in controlling fouling and improving membrane cleaning efficiency. The combination of backflushing and air bubbling was found to be the most effective method for both membrane cleaning and fouling reduction as this technique caused 80% of the solids to be retained within the feed stream. This combination of two filtration techniques resulted in 268% permeate flux enhancement due to reduction of particle deposition on membrane surface and helped in improving membrane cleaning efficiency in which case membrane was regenerated up to 98.5% in a minimum time of 30 min.



## 1. Introduction

Rapid developments in membrane filtration technology have resulted in increased industrial applications including dairy, beverages, brewery, food, pharmaceutical, wastewater, and desalination process industries. For the success of any membrane application, it is imperative to adopt certain methods or techniques to reduce the membrane fouling and an appropriate membrane cleaning protocol. Nevertheless even with the best feed treatment schemes, some fouling potential remains in microfiltration, ultrafiltration and reverse osmosis systems [4]. Fouling is an inherited and unavoidable drawback of all microfiltration membranes. The fouling phenomena impair the membrane performance and the permeate flux could decrease as low as 3–4% of initial pure water flux [22]. This necessitates the cleaning and disinfection sequences for removal of fouling layer and microorganisms from the membrane surface and makes membrane cleaning an integral part of microfiltration membrane operation. The high shear stress generated by enhanced cross flow velocity and gas sparging has been known to be effective for control of fouling by reduction of particle deposition in microfiltration membrane processes for different membrane module geometries. Laborie et al. used gas dispersion in the filtration of clay and mixture of clay and dextran suspension through hollow fiber ultrafiltration membranes [14]. They showed that there was an optimum air flow velocity of 0.35 m/s beyond which there was no further increase in the permeate flux for both clay and the mixture of clay and dextran. At this air velocity, the increase in flux was found to be 155%. Wall shear stress was the reason they assigned for this flux improvement. Optimum bubbling rates were also observed by Mercier et al. in which the optimum gas velocity was found to be 0.43 m/s [20]. Chang and Fane investigated the effect of gas bubbling on an 'out–in' submerged hollow fiber module [5]. They used a special cell for this purpose in order to generate slug flow between the fibers. With a commercial yeast suspension, they were able to enhance the permeate flux up to 20–30% as compared to that of without bubbling. The recent studies carried out by Mikulasek et al. [21], Chua et al. [6], Cui and Taha [8] and Taha et al. [27] all confirmed the effectiveness of gas–liquid two phase flow in different membrane modules. More recently Ndinisa applied gas bubbling in a submerged flat sheet membrane module [23]. He studied the impact of various hydrodynamic parameters on flux enhancement while filtering yeast suspension. He found wall shear stress and flow reversal as fouling control mechanisms. These studies linked flux enhancement to bubble induced secondary flow which was responsible for promotion of turbulence and shear force along the membrane surface and hence flux was enhanced. Using CFD simulations, Cui and Taha observed high shear rates in the falling film between the bubble and the membrane wall in the tubular membranes [8]. Later Ndinisa applied

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doi:10.1016/j.desal.2010.08.019

CFD simulation for characterizing of bubbles in flat sheet microfiltration membrane. According to these CFD simulations, he was able to prove that larger bubbles rise faster and generate high shear stresses on membrane wall.

Similarly backflushing has been studied by many researchers for flux enhancement in microfiltration and ultrafiltration membranes. The results from Baker et al. [1]; Riesmeier et al. [26]; and Bertram et al. [2] have shown that the higher the cross flow velocity, the higher is the permeate flux. This was attributed to increased shear-induced particle back-transport to the bulk flow. Similar results were quoted by Cui and Wright in their downward ultrafiltration study of dextran [7]. Kroner et al. achieved 50% enhancement in the net flux during the removal of *E. coli* bacteria from a fermentation broth using cross flow microfiltration with a 0.3 µm membrane which was backflushed by reversing the transmembrane pressure for 5 s every 5 min [13]. Matsumoto et al. reported up to 10-fold flux increase with backflushing (for 5 s every 3 min) for yeast suspensions [18,19]. Their work also compared different backflushing techniques and found backwashing with permeate to be most effective. Nipkow et al. reported initial improvements of 42% in the permeate flux with backflushing of a microfiltration cell-recycle pilot-scale system for continuous cultivation of *Clostridium thermosulfurogenes* [24]. Most recently Gabrus and Szaniawska conducted a study on application of backflushing for microfiltration of yeast suspension with 0.8 µm ceramic MF membrane [10]. They found that backflushing was effective for removal of deposited cake on membrane surface while it was less effective for internal pore blocking. Sonication or application of high energy ultrasonic waves is yet another method for removal of foulants from the membrane surface. The high energy involved in the ultrasonic pulses breaks the bond between the surface and adsorbed material. Lim and Bai applied sonication to clean a PVDF hollow fiber membrane after microfiltration of activated sludge [16]. They found that sonication was effective against the external fouling or cake formation whereas they found it less effective against internal fouling. The results from all these studies prove that hydrodynamic parameters like cross flow velocity, air flow rate and backflushing influence the fouling significantly and that these parameters play a significant role in enhancing the microfiltration process.

Membrane cleaning is yet another important aspect of any membrane process. It is necessary to regenerate the membrane after certain period of operation in order to achieve optimum process efficiency. Most of the research carried in the field of the membrane filtration is related to fouling and its control. The issue of the membrane cleaning has not been properly addressed. According to Blanpain-Avet et al. though mechanisms of the membrane fouling are now well understood and documented, there has been much less published information on membrane cleaning [3]. Whereas Liu et al. are of the view that the issue of the membrane cleaning has not been adequately addressed primarily for two reasons: (1) cleaning protocols are typically recommended from membrane manufacturers and some cleaners are proprietary; (2) the issues of the membrane fouling are poorly understood and are related to site-specific water quality issues [17]. The published work on membrane cleaning reveals that the application of chemicals is inevitable and is considered to be an integral part of the microfiltration and ultrafiltration processes. The effectiveness of the membrane cleaning is dependent upon the hydrodynamic parameters and chemical action. The hydrodynamic parameters like cross flow velocity, transmembrane pressure, cleaning time, gas dispersion, and backflushing influence the cleaning process. Blanpain-Avet et al. applied a non-formulated alkaline chemical cleaning agent with 1 wt.% NaOH for cleaning of a ceramic tubular MF membrane fouled with whey proteins [3]. They applied the cleaning solution at various cross flow velocities ranging from 1 to 6 m/s and at different TMPs from 0.25 to 0.84 bar at a temperature of 55 °C. They found from this study that cleaning time had a significant effect on membrane cleaning efficiency. They observed that cross flow velocity did not play a significant role for improving the chemical cleaning efficiency of the membrane. They were able to regenerate the membrane up to 90% with this cleaning protocol. Leiknes and Silalahi also used ceramic tubular membranes for microfiltration of oil-contaminated water [15]. They applied three pore sizes of 0.1, 0.2 and 0.5 µm and used different commercially available cleaning agents for their study on membrane chemical cleaning. They concluded from the study that all the cleaning agents used could not be employed as a direct single step to fully restore the fouled membrane. They however achieved good cleaning efficiencies for 0.1 and 0.2 µm membranes at a high temperature of 80 °C and by applying a combination of alkaline and acidic cleaning agents. From all aforesaid studies it becomes clear that the membrane cleaning is dependent upon the hydrodynamic parameters like feed concentration, TMP, cross flow velocity, air bubbling, etc.

There have been many studies in which air bubbling and backflushing techniques were used for permeate flux enhancement by reducing cake layer deposition on membrane surface. However there is no study to date which specifically addresses the influence of air bubbling and backflushing on membrane performance and its cleaning efficiency. Furthermore no study has been found in which air bubbling has been combined with backflushing for enhancing permeate flux in submerged microfiltration membrane process. Therefore it remains a matter of great interest to investigate how air bubbling and backflushing, both in singular and combined mode, influence the membrane fouling and membrane cleaning efficiency. Furthermore most of the research carried out on flux enhancement and membrane cleaning involves tubular and hollow fiber membrane modules similar to that of fouling control with little or no attention to flat sheet membrane modules. This work therefore focuses more specifically on the role of hydrodynamic parameters like enhanced cross flow velocity, air bubbling and backflushing on membrane performance and the cleaning of a vertically mounted submerged flat sheet microfiltration membrane. The influence of air bubbling and backflushing has also been studied for control of fouling in this study. It is important to mention here that combination of backflushing with air bubbling has been applied first time in this study for finding out its influence on membrane fouling and membrane cleaning efficiency. In the end, a comparison has been made to show which filtration method influences the membrane fouling and membrane regeneration efficiency the most.

### 1.1. Particle deposition on membrane surface

An effective fouling control and membrane cleaning strategy can be devised if the mechanism of particle deposition on membrane surface is understood. There are various forces which act upon the particles. These forces determine particle deposition behavior on the membrane surface in the microfiltration process. The forces which influence the particle motion include drag force of filtrate flow, drag force of cross flow, lift force due to cross flow, friction force, shear force due to cross flow, the pressure force, particle–particle interaction adhesive force, double layer force, Brownian force, gravitational force and Van der Waals forces. Some of these forces are causing the particle to move towards the membrane surface while others are forcing the particle to stay in the suspension stream. The balance of these forces determines whether the particle will deposit on the membrane surface or will remain within the suspension stream. It is still not clear which forces are dominant forces which cause the particle to deposit on membrane surface. Hwang et al. (1996) found that normal drag force, Brownian diffusion, Van der Waals attraction forces and double layer repulsion force to be dominant force in their study of styrene particle microfiltration experiments [11]. Whereas Chang et al. showed that normal drag force, lateral lift force, tangential force and double layer repulsion to be the dominant forces in their study on microfiltration of polystyrene latex particles [4].

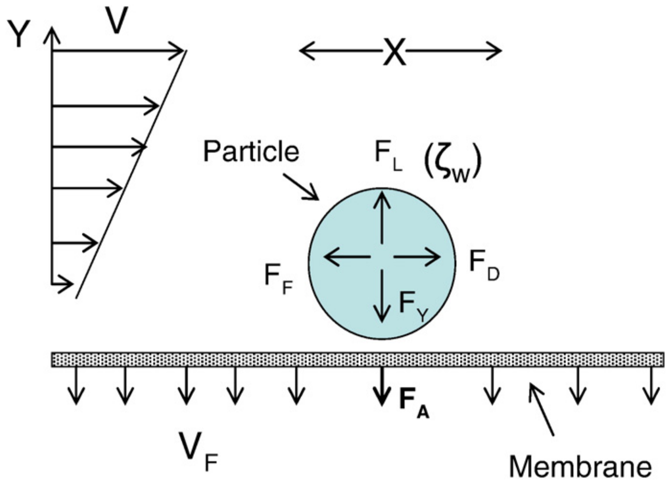


**Fig. 1.** Forces on a particle in a single particle on membrane model (V is cross-flow velocity: X and Y are coordinates of plane: $F_L$ is lift force due to wall shear force $\zeta_W$; FD is drag force due to cross-flow; $F_F$ = friction force; $F_A$ is adhesion force; $V_F$ is cross-flow velocity).

The action of different forces on the particle can be explained with the help of a simplified model where only one particle has been considered near the vicinity of the membrane. Fig. 1 shows this simplified model of a single particle on membrane surface. This model is a good tool which provides a basic understanding about the action of different forces acting on the particle in cross flow microfiltration. The condition for fouling can be determined from the balance of the forces as represented in this model of single particle on membrane. If the sum of adhesive forces (pressure, drag force of filtration, friction force, etc.) is greater than the sum of lift forces (shear stress, cross flow velocity, etc.) then the particle will deposit on the membrane surface otherwise it will keep floating within the suspension. It has been found in various studies that backflushing [10] and gas bubbling [23] enhance the lift forces. This implies that backflushing and air bubbling can help not only to reduce the particle deposition but also they will enhance the membrane cleaning efficiency as both these techniques will enhance the lift forces in the system resulting in reduction of cake deposition on membrane surface.

## 2. Materials and methods

### 2.1. Materials

Microfiltration experiments were conducted using the experimental unit represented in Fig. 2. The membrane cell with two and three dimensional views is shown in Fig. 3.

The filtration unit consists of two major parts: the membrane cell consisting of flat sheet membrane module and the backflushing system connected to the permeate line via a three-way manual valve. A positive displacement pump was used to generate cross flow for experiments at varying feed flow rates and also for rinsing and clean-in-place (CIP) cleaning of the membrane system. Air was injected at the bottom of the membrane cell with 5 equal sized circular nozzles. The permeate was collected in a vessel through a vacuum pump. All experiments were conducted at room temperature and at the same transmembrane pressure. A flat sheet lab scale module was designed and fabricated indigenously for this study. Microfiltration membrane with a nominal pore size of 0.2 μm was provided by Microdyn-Nadir, Germany. The effective surface area of the membrane was 0.016 $m^2$. Commercial yeast was used to form the suspension for this study. Atomic Force Microscopy (AFM) was used to determine the size and size distribution of the yeast cells. AFM imaging has successfully been used by researchers for yeast cell imaging. Dufrene et al. used AFM technique for imaging the surface topography of living yeast (*Saccharomyces cerevisiae*) cells [9]. The yeast samples were prepared in water and were coated on glass slides. The surface morphology of

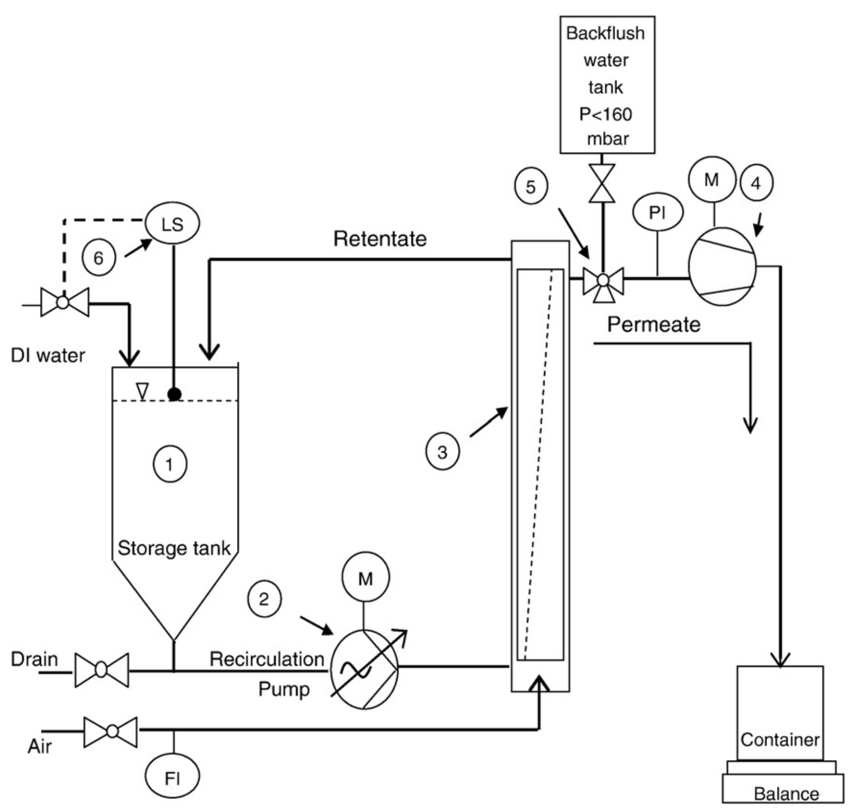


**Fig. 2.** Experimental set-up for microfiltration and backflushing (1 = Feed tank; 2 = Feed recirculation pump; 3 = Membrane cell; 4 = vacuum pump; 5 = 3-way valve; 6 = level control switch).

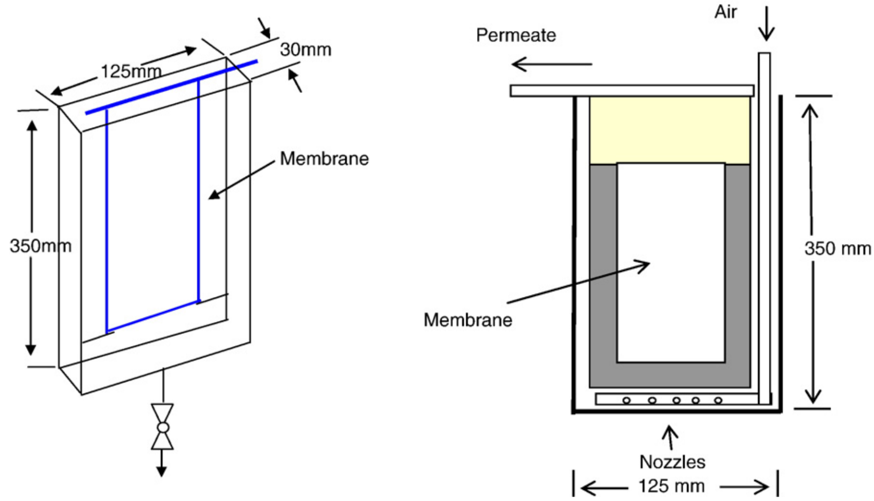


**Fig. 3.** Two and three dimensional views of the membrane cell.

yeast cells deposited on glass slide was determined with a digital atomic force microscope-3100 in a non-contact mode.

The data from AMF imaging was analyzed for particle size and particle size distribution and the results are shown in Fig. 4. The AMF imaging showed that the average particle size of yeast cell was 4.5 μm. It is evident from this diagram that suspension contains particles with size ranging from 1 μm to 10 μm. Therefore it can be deducted from Fig. 4 that the mechanism of fouling will be cake formation as the yeast particles are of the size well above the membrane pore size. Membrane cleaning was performed by using a commercially available enzymatic membrane cleaning detergent Ultraperm-53 by Henkel, Germany. The feed concentration was measured in terms of turbidity units. For this purpose, a WTW-Turb 550 turbidity meter was used to measure the turbidity of feed and the permeate.

### 2.2. Methods

The permeate flux for pure water was measured by using Milli-Q pure water for the new membrane as a standard pure water flux. The yeast suspension was prepared by mixing the yeast into water with the help of a mechanical stirrer for half an hour. The experiments were conducted at a feed concentration of 10 g/L. This value of concentration was selected in order to have severe fouling conditions during microfiltration experiments. Each filtration and cleaning experiment consisted of different stages which included: initial pure water flux, yeast suspension filtration, first water rinsing at zero TMP to remove the lose particles, detergent cleaning, second rinsing with pure water, conditioning with HCl solution, third pure water rinsing and final pure water flux. Clean-in-place (CIP) method was applied for membrane cleaning and no TMP was applied during cleaning procedure. All filtration experiments were conducted at a constant TMP of 0.4 bar. The pressure value of 0.4 bar was chosen keeping in view the recommendations of the membrane manufacturer. The manufacturer recommended a pressure of 0.3 to 0.5 bar for this particular membrane in submerged module configuration. Therefore a pressure of 0.4 bar was selected and no value of pressure was calculated for a limiting flux in the current series of experiments. Each filtration experiment lasted for 120 min. Transmembrane pressure for filtration was obtained with a vacuum pump by Vacuubrand, Germany with a suction capacity of 2.4 $m^3$/h. The permeate was collected in a glass vessel placed on the balance. The permeate flux obtained during backflushing experiments was calculated after deducting the loss of permeate during backflushing and relaxation time. A positive displacement pump was used for only generating cross flow when experiments were conducted with enhanced cross flow. A cross flow velocity of 0.3 m/s was used for this study as at this cross flow velocity, highest permeate flux was attained at steady-state conditions. The sequence for backflushing was adopted as provided in the membrane manufacturer's manual. This membrane backflushing sequence is shown in Table 1. Membrane cleaning efficiency has been evaluated in terms of the membrane permeability recovery using the parameter of percent membrane recovery. This parameter is discussed in detail in Section 3.2.2.

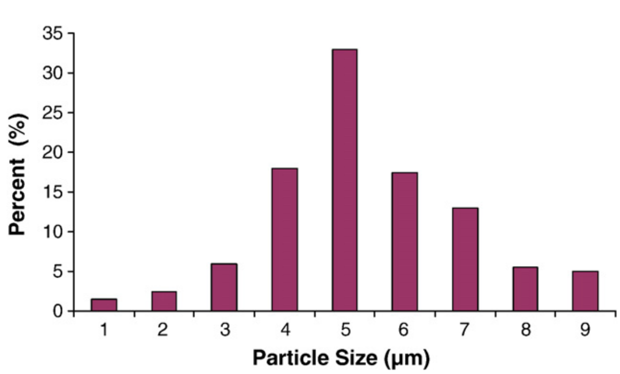


**Fig. 4.** Particle size distribution of yeast suspension obtained from AFM.

## 3. Results and discussion

### 3.1. Effect of filtration techniques on membrane performance

The degree of microfiltration membrane performance varies for different flux enhancing techniques as particle deposition rate varies for each method. In order to find out the most effective technique for fouling reduction and membrane cleaning, filtration experiments

**Table 1**
Sequence for backflushing.

| Sequence name | Duration |
|---|---|
| Filtration | 8 min |
| Relax phase I | 30 s |
| Backflushing <160 mbars | 30 s |
| Relax phase II | 30 s |
| Filtration | 8 min |

were carried out with dead-end filtration and for four different filtration techniques which included: enhanced cross flow velocity, air bubbling, backflushing and combination of backflushing and air bubbling. It was necessary to carry out dead-end filtration in order to find out the bottom line of the membrane performance and for comparison purpose at given operation conditions of pressure, temperature and feed concentration. Fig. 5 shows the variation of permeate flux with time for each filtration method.

The data presented in this figure is for cross flow velocity of 0.3 m/s and air flow rate of 40 L/h. These values of cross flow velocity and air flow rate were selected due to the reason that highest permeate flux was achieved at these values for each of the filtration experiment with enhanced cross flow velocity and air bubbling [25]. Dead-end filtration was performed as a reference for all other filtration experiments. The order of permeate flux increase was found to be: Combination of backflushing and air bubbling > Backflushing > Air bubbling > Enhanced cross-flow velocity > Dead-end filtration. For the given set of conditions, enhanced cross-flow velocity contributed very little in enhancing the permeate flux. This is due to the reason that at the applied cross-flow velocity, the generated shear force was insufficient to carry the suspended particles away from the surface. On the contrary, air bubbling generated much higher shear force value due to which deposition of cake layer was reduced and a 2 times increase in permeate flux as compared to enhanced cross flow velocity method, was observed with air bubbling. The enhancement in permeate flux was even higher for backflushing and for combination of backflushing and air bubbling techniques. The phenomenon of flux enhancement by these two methods is explained in detail in Section 3.1.1.

In order to find out the reason for difference in permeate flux for different filtration methods, cake layer resistance was calculated for each filtration method by using Darcy's law as under:

$$J_v = \frac{\Delta P}{\mu(R_m + R_c)}. \quad (1)$$

The cake resistance decreased significantly for all flux enhancing methods from enhanced cross flow velocity to backflushing. The cake layer resistance was found to be lowest when backflushing was combined with air bubbling. Fig. 6 shows the variation of cake resistance for various filtration methods adopted at the same experimental conditions as those in Fig. 5.

Moreover the membrane surface was observed at the end of each filtration experiment in order to check the membrane surface for any cake layer deposition. It was found that apparently cake deposition was the maximum for filtration with enhanced cross flow velocity whereas it was the minimum when filtration was carried out with

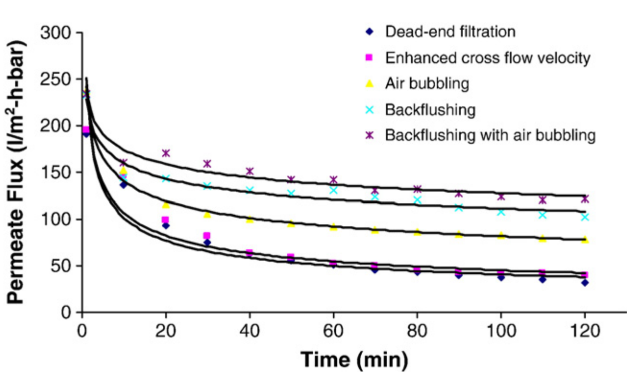


**Fig. 5.** Effect of hydrodynamic parameters on permeate flux for C = 10 g/L; ΔP = 0.4 bar; V = 0.3 m/s; $Q_a$ = 24 L/h for air bubbling; $Q_a$ = 32 L/h for backflushing with air bubbling; temperature = 22 °C.

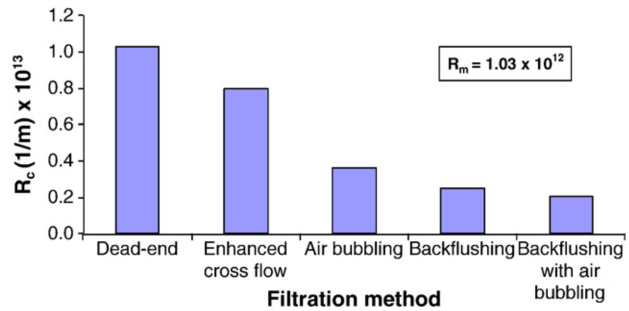


**Fig. 6.** Cake resistance for different filtration methods after 2 h of filtration (operating conditions are the same as those in Fig. 5).

backflushing combined with air bubbling. The cake layer deposition for various filtration methods is shown in Fig. 7. The photographs in Fig. 7 give an idea about lowest value of cake resistance achieved during filtration with backflushing combined with air bubbling.

*3.1.1. Mechanism of fouling control*

The analysis of forces on a particle helps in understanding the influence of hydrodynamic parameters on fouling in microfiltration membrane process. Fig. 8 reveals the influence of hydrodynamic parameters on the balance of the forces acting on the particle.

The impact of cross flow velocity, air dispersion and backflushing has been highlighted in Fig. 8 by green, orange and blue coloured arrows respectively. The impact of cross flow velocity is effective only on the top section of the particle because cross flow velocity is the minimum near the membrane surface. Therefore the particle once deposited on the membrane surface cannot be detached from the surface by cross flow velocity. Similar results were quoted by Hwang and Wang in their study of particle deposition on microfiltration membrane surface at various cross flow velocities [12]. The impact of backflushing works at the base of the particle and this impact loosens and detaches the particle from the membrane surface. On the other hand air bubbling generates very high shear force and turbulent cross flow conditions. The impact of air bubbling is at the base of the particle near the membrane surface. Therefore when backflushing is combined with air bubbling, maximum impact for particle removal is generated. The backflushing action loosens and detaches the particle from the membrane surface and the cross flow due to air bubbling wipes the particle away from the membrane surface. The lift forces generated by combination of backflushing and air bubbling become greater than the adhesive forces and thus particle cannot deposit on the membrane surface. This is the reason that cake resistance was found to be minimum and membrane performance was enhanced to a maximum when filtration was carried out with combined backflushing and air bubbling (Figs. 5 and 6). This also gives an indication that the techniques of backflushing and air bubbling, when combined together, can be effective for removal of internal fouling (pore blocking) due to the reason that the thrust generated by liquid backflushing will take out the foulants from the pores of the membrane and the air bubbles will carry these particles away from the membrane surface thus enhancing the permeate flux.

*3.2. Effect of hydrodynamic parameters on permeate flux, particle deposition and membrane cleaning*

*3.2.1. Influence of air bubbling and backflushing on permeate flux*

Experiments were conducted for finding out the influence of air bubbling alone and combination of backflushing with air bubbling on permeate flux at steady-state conditions. Fig. 9 shows the results of this experimentation.

The results from Fig. 9 reveal that permeate flux increased with increase in air flow rate and reached a maximum value at air flow rate

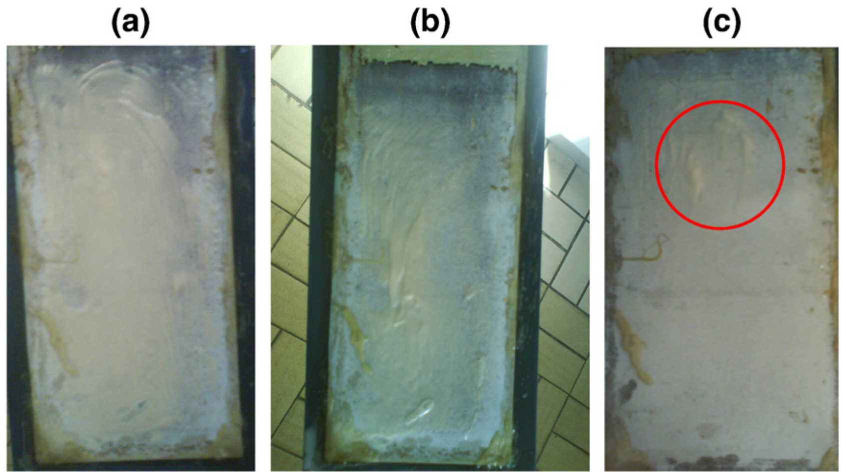


**Fig. 7.** Membrane surface with cake layer for (a) = enhanced cross flow; (b) = air bubbling, and (c) = combination of backflushing and air bubbling.

of 40 L/h and then started to decline when air flow rate was increased beyond this limit. In order to explain this effect, it is important to know the effect of air bubbling on bulk feed concentration. Fig. 10 shows the effect of air bubbling upon the final bulk feed concentration after 2 h of operation, that is, on steady-state conditions. From this figure, it is clear that as air flow rate increased, the concentration of solids in the bulk feed suspension also increased. This implies that there should be no deposition of solids on the membrane surface at further higher air flow rates. If there is no cake layer deposited then, the flux should also keep increasing with air dispersion. However this was not the case as seen in Fig. 9. The permeate flux started to decrease after reaching a maximum at air flow rate of about 40 L/h. This phenomenon can be explained with the help of bubble size and air flow rate relationship. Bubble size is directly proportional to air flow rate. Therefore, bubble diameter increased with increase in air flow rate. It seems that after the optimum air flow rate of 40 L/h, the size of the bubbles became so big that it started to hinder the liquid to reach the membrane surface, that is, the bubbles acted as cushion along the membrane surface so that permeation was decreased resultantly, the permeate flux decreased with increase in air flow rate. A similar effect of flux decline was observed when backflushing was combined with air bubbling though the flux decline was not as sharp as in the case of air bubbling alone. This is because backflushing kept removing the deposited mass from membrane surface with each backflushing cycle. However the increase in bubble size with air flow rate showed its influence by declining the permeate flux when air flow rate was increased beyond 40 L/h in the presence of backflushing.

*3.2.2. Influence of filtration technique on particle deposition*

In order to evaluate the impact of hydrodynamic parameters on membrane cleaning, it was necessary to find out that how much cake was being deposited on the membrane surface during filtration for each filtration method.

For this purpose, the data for bulk feed concentration ($C_b$) was collected at the start and end of each experiment. The bulk feed concentration is an index to roughly quantify the cake layer deposition on the membrane surface. The results for bulk feed concentration are shown in Fig. 11 against each filtration method. Fig. 11 shows that enhanced cross flow filtration was able to retain only 45% of the particles in the feed stream. Retention of particles in the feed suspension after filtration with air bubbling and backflushing was found to be 60% and 70% respectively. The best retention of 80% was achieved when process was run by combining backflushing with air dispersion. This analysis of particle retention on membrane surface explains the effectiveness of each microfiltration technique in terms of permeate flux enhancement.

*3.2.3. Effect of backflushing and air bubbling on membrane cleaning and recovery*

Membrane cleaning or regeneration time is the total time required to clean the membrane at such a level at which pure water flux

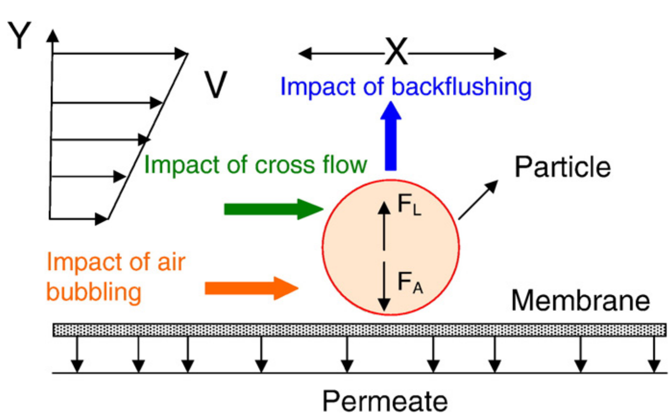


**Fig. 8.** Influence of hydrodynamic parameters on forces acting on particle.

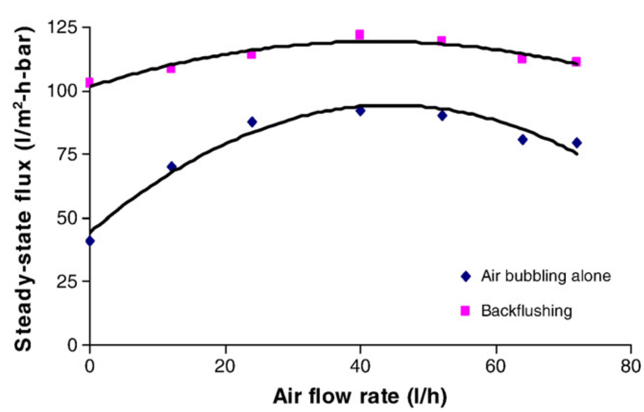


**Fig. 9.** Influence of air bubbling and backflushing on steady-state flux.

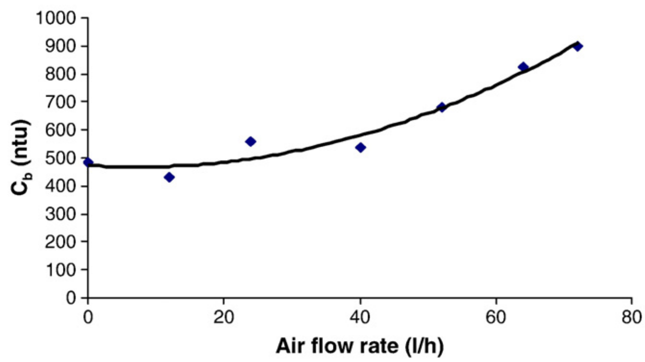


**Fig. 10.** Effect of air flow rate on bulk feed concentration after 2 h of operation for nozzle size = 2 mm; ΔP = 0.4 bar.

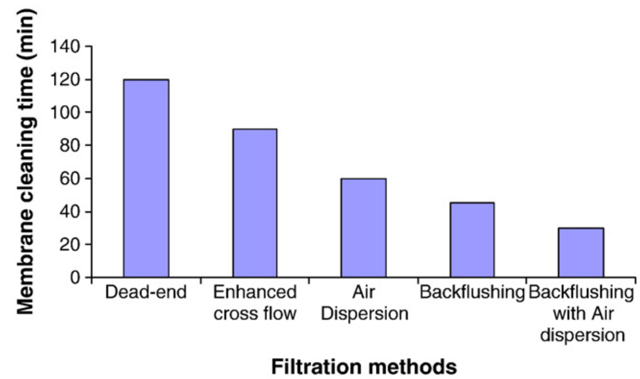


**Fig. 12.** Membrane cleaning time for each filtration method after 2 h of filtration with each filtration method.

becomes exactly or almost equal to that of a virgin membrane. This time starts with first rinsing after filtration and ends with the step of pure water flux after cleaning. For finding out the membrane cleaning time for each filtration method, the membrane cleaning was carried out as per protocol described in Section 2.2 until 100% pure water flux as that of new membrane was recovered. The time of cleaning was recorded for each method and is shown in Fig. 12. The results in Fig. 12 are in line with the findings of Fig. 11. As the particulate deposition was the minimum for combined backflushing and air bubbling, therefore, membrane cleaning time was also found to be the minimum for this filtration method. A total time of 30 min was required for complete regeneration of the membrane for combined backflushing and air bubbling which is one third of the time required after filtration with enhanced cross flow and is half the time required for complete regeneration after filtration with air bubbling alone. This implies that the membrane cleaning efficiency in terms of cleaning time and flux recovery will be highest for combined backflushing and air dispersion as compared to all other filtration methods. The following section discusses this aspect in detail.

Percent membrane recovery is another way to check the degree of cleanliness of the membrane. Percent membrane recovery (%MR) can be defined as:

$$\%MR = (J_c / J_w) \times 100. \tag{2}$$

Where $J_w$ is pure water flux of new membrane and $J_c$ is pure water flux after cleaning. After finding out the minimum time required for membrane regeneration, the membrane recovery was calculated from Eq. (2) after cleaning the membrane for that minimum time of 30 min for all filtration processes applied in this study. Fig. 13 shows the results of the membrane recovery for all filtration methods.

The membrane was recovered up to 98.5% after running the filtration process with combined backflushing and air bubbling where as it is 69, 78 and 87% for enhanced cross flow, air bubbling and backflushing respectively. The level of the membrane regeneration achieved by combined air bubbling and backflushing is far higher than that achieved by chemical cleaning as reported in the literature [3,15,17]. The reason for this nearly-complete regeneration for combined backflushing and air bubbling is the effective two-way action generated by backflushing and air dispersion, that is, the impact of backflushing loosened the deposited particle from the membrane surface and turbulences generated by air bubbling took the particle away from the surface. These results confirm the correctness of fouling control model presented in Fig. 8 in Section 3.1.1. It is to be noted from Fig. 13 that membrane was recovered up to 98.5% and not 100%. This might be due to the phenomenon of pore plugging though particle size analysis in Section 2.1 gave no hint of any particle below 1 μm size. Nevertheless the combination of air bubbling and backflushing techniques produced a very high degree of the membrane recovery even without addition of any chemical reagent or temperature assistance.

## 4. Conclusions

The main objective of this study was to evaluate the potentials of air bubbling and backflushing for microfiltration membrane regeneration. Five filtration methods namely dead-end, enhanced cross flow, air bubbling, backflushing and combination of backflushing and air bubbling were applied. The effectiveness of air bubbling and backflushing for fouling control was also studied in parallel. The performance of cleaning protocol was evaluated in terms of the

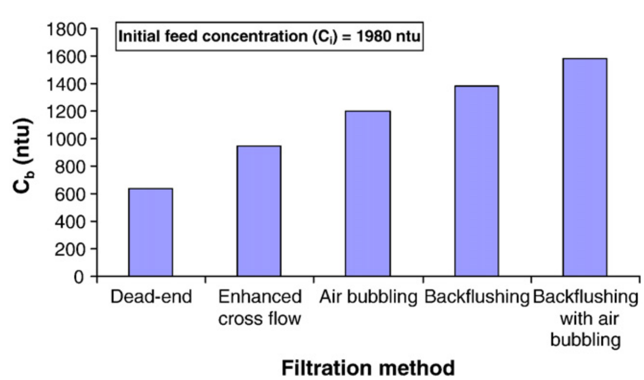


**Fig. 11.** Bulk feed concentration ($C_b$) for each method after 2 h of filtration.

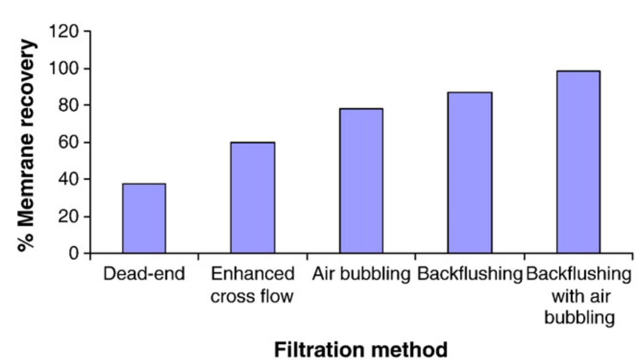


**Fig. 13.** Percent membrane recovery for different filtration methods.

membrane cleaning time and percent membrane recovery. Following are the important conclusions derived from the results of this study:

1. Air bubbling alone was found to be effective in reducing cake layer deposition and increasing permeate flux up to an optimum air flow rate of 40 L/h beyond which air bubble size stated to reduce the permeate flux though cake deposition on membrane surface kept decreasing with increase in air flow rate beyond optimal value of 40 L/h.
2. Backflushing technique proved to be highly efficient for fouling control by reducing cake layer deposition on membrane surface as compared to techniques of enhanced cross flow velocity and gas bubbling. Particle retention in bulk feed was found to be 70% for backflushing whereas it was 60% for gas bubbling and 40% in case of enhanced cross flow. It was because of this reduced particle deposition that reduced the membrane cleaning time significantly. However best fouling control was achieved when backflushing technique was combined with air bubbling which resulted in 80% of particle retention in bulk feed stream.
3. The combination of backflushing and gas bubbling was found to be the best method for improving the membrane performance both in terms of fouling control and membrane cleaning time. This combined backflushing and gas bubbling reduced particle deposition up to 80% which is the maximum as compared to other filtration methods applied in this study. A membrane recovery of 98.5% was achieved in only 30 min of the membrane cleaning time when filtration was carried out with this combination of backflushing and gas bubbling. Whereas it required 90, 60 and 45 min for attaining the same level of the membrane recovery when filtration was carried with enhanced cross flow velocity, gas bubbling and backflushing respectively. This is found to be the minimum time required for maximum membrane regeneration among all the filtration processes applied in this study.
4. The shear forces generated by the combination of backflushing and air bubbling methods produced a very high degree of the membrane cleaning/regeneration (98.5%) without any support of chemical cleaning agent or temperature enhancement.

*List of symbols*

(All quantities are in SI units)

| | |
|---|---|
| $C_i$ | initial feed concentration (kg/m$^3$) |
| $C_b$ | bulk feed concentration (kg/m$^3$) |
| $F_L$ | lift force (N) |
| $F_F$ | friction force (N) |
| $F_D$ | drag force (N) |
| $F_A$ | Adhesive force (N) |
| $J_c$ | pure water flux after membrane cleaning (m$^3$/m$^2$-s) |
| $J_v$ | volumetric permeate flux (m$^3$/m$^2$-s) |
| $J_w$ | pure water flux for new membrane (m$^3$/m$^2$-s) |
| $R_c$ | cake resistance (1/m) |
| $R_m$ | membrane hydraulic resistance (1/m) |
| V | cross flow velocity (m/s) |
| $V_F$ | filtrate flow velocity (m/s) |
| $\Delta P$ | transmembrane pressure (Pa) |
| $\mu$ | kinematic viscosity of permeate (Pa-s) |
| $\tau_w$ | wall shear stress |

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