Environment Protection Engineering

Vol. 18 1992 No. 1–2

MAŁGORZATA KABSCH-KORBUTOWICZ*

MEMBRANE BIOFOULING

Nowadays biofouling is the cause of one of the most serious operational problems in membrane use. Biofilm development at a membrane surface is due to several physical, chemical and microbiological processes. Fundamental strategies for controlling biological fouling of membranes include feedwater pretreatment and membrane cleaning.

1. INTRODUCTION

Membrane systems are widely used in water and wastewater purification. Dissolved and particulate matter from the feed stream is deposited during the separation process on the membrane surface and contributes to the overall resistance of the separation system. This phenomenon is well known and is defined as a "fouling". In membrane technology, the most important types of fouling include [1]:

1) crystalline fouling ("scaling"), deposition of minerals due to the excess of the product being soluted;

2) organic fouling (deposition of dissolved humic acids, oil, grease, lipids);

3) particle and colloidal fouling (deposition of clay, silit, particulate humic substances, debris, silica);

4) microbiological fouling ("biofouling", adhesion and accumulation of microorganisms forming biofilms).

B i o f o u l i n g is the unwanted deposition of biological matter from the bulk liquid on any surface of the equipment for water treatment, storing or transport [2].

Biofouling is one of the most serious operational problems in membrane technology, especially in reverse osmosis, but also in other membrane processes. Formation of biofilm on the membrane surface may cause many unwanted effects as, for example:

1. Decline in the rate of water transport per unit area of the membrane surface (a membrane flux decline). The decline in water transport is not the result of an irreversible change in the composition or structure of the membrane polymer, but rather the result

* Institute of Environment Protection Engineering, Technical University of Wrocław, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland.

of the formation of a biological film of low permeability on the membrane surface [5] (figure 1). Following the initial decline phase, the membrane flux may either be stabilized at some equilibrium value, or asymptotically approach it (figure 2), which is dependent upon a variety of interacting physicochemical, hydrodynamic and biological factors [4], [5]. Partial removal of the biofilm by chemical cleaning typically results in a temporary restoration of water flux, often to near prefouling levels [3], [6].

2. Increase in the transmembrane operating pressure which results from the attachment and growth of microorganisms on the membrane surface as well as on support and other elements of installation. In some cases, the operation pressure may

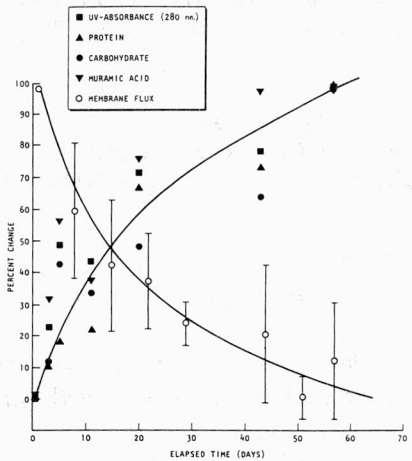

Fig. 1. Relationship between RO membrane flux decline and biological parameters affecting the membrane surface [5]

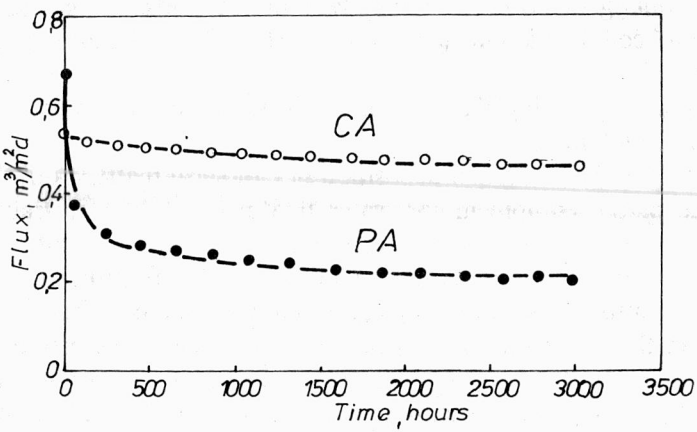

Fig. 2. Normalized flux data for aromatic polyamide (PA) and cellulose acetate (CA) RO membranes [3]

exceed the manufacturer's design specifications for the membrane module, resulting in membrane compression and its physical collapse [4].

3. Increase in energy requirements. Losses and increases in a membrane flux (transmembrane pressure) might be partially relieved by regular membrane cleaning but it requires additional energy. It results in the increase of the operational costs and finally makes application of membrane technology more expensive.

4. Increase in the permeability of the reverse osmosis membranes to dissolved minerals. It was found [4] that the presence of microbial film on the RO membrane surface causes losses in rejection of dissolved ions. It is probably an effect of the concentration polarization phenomenon [7] which is observed near the membrane surface (figure 3). The development of the biofilm on the membrane surface tends to reduce turbulent flow close to its surface. This results in accumulation of dissolved mineral ions in the membrane neighbourhood. The concentration of mineral ions close to the membrane surface is higher than that in the bulk solution. Because the membrane rejection towards mineral ions is constant for a given ion concentration, the concentration of ions in the permeat will be proportional to the degree of the concentration polarization.

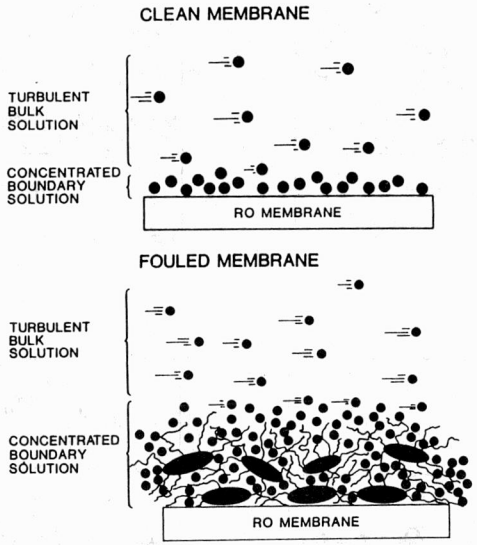

Fig. 3. Effect of surface biofilm formation on concentration polarization at the membrane surface [4]

5. Membrane biodegradation. Microorganisms present in the biofilm on the membrane surface may produce acidic or alkaline metabolites, which destabilize the membrane polymer, making it more susceptible to oxidation and/or hydrolytic cleavage [3]. Bacteria attached to the cellulose acetate membranes may also produce enzymes hydrolyzing the polymer [8]. HO et al. [9] reported that cellulose derivatives became more resistant to enzymatic attack with increasing degrees of acetate substitution.

There is no information concerning biodegradation of noncellulosic polymers like polyamide or polysulfone. Those polymers are more resistant to biological attack, but they might be a potentially rich source of nutrients and in special situations might undergo biodegradation.

2. FORMATION OF BIOFILM ON THE MEMBRANE SURFACE

According to WINFIELD [10], [11] the process of membrane biofouling can be divided into following steps:

1. Adsorption of macromolecules (humic substances, lipopolysaccharides and other products of microorganism metabolism) on the membrane surface.

2. Primary adhesion of fast-adhering cells representing the microflora of the raw water.

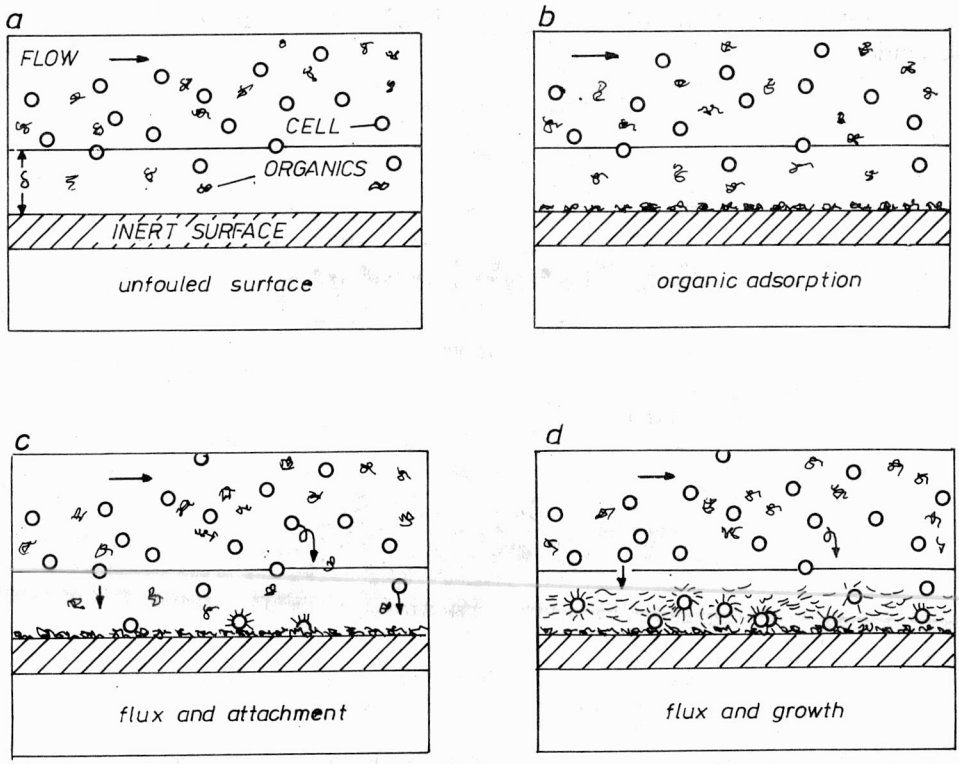

Fig. 4. Processes contributing to biofilm accumulation [12]

a – a clean surface exposed to a turbulent flow of fluid containing dispersed microorganisms, nutrients and organic macromolecules, **b** – transport and adsorption of organic macromolecules on a clean surface, **c** – transport and adhesion of microbial cells to the conditioned surface, **d** – continued transport and adhesion of microbial cells, their growth and other metabolic processes within the biofilm

3. Bacterial colonization and growth with subsequent adhesion of cells representing a number of different species, which excrete extracellurar polymer (slime) and develop a biofilm.

4. The irreversible blocking of the membrane.

The processes contributing to biofilm accumulation are presented in figure 4.

Adhesion of microorganisms to solid substrata is a complex problem, but generally both two-step and three-step mechanisms [13] have been proposed for describing this phenomenon.

In the two-step mechanism, the first step, i.e. reversible adhesion, is defined as a weak adhesion, in which there is observed Brownian movement of the cells. These cells, however, can be readily removed from the surface. The seocnd step, irreversible adhesion, is a time-dependent film adhesion, characterized by the lack of Brownian movement. It is a time-dependent step because an initial bacterial attraction to the surface is preceded by exopolymer synthesis.

In three-step mechanism, three distinct interaction regions are defined by the separation distance between the bacterium and substratum. At separation distances >50 nm, only van der Waals forces act, and this stage is reversible. At separation distances ranging from 10 to 20 nm, both van der Waals forces and electrostatic repulsations are active. This step is initially reversible but may change with time to an irreversible stage. In the third step, with a separation distance less than 15 nm, van der Waals forces, electrostatic and specific interactions, such as the production of adhesive exopolysaccharides, lead to irreversible bonding. The type of adhesive exopolysaccharide produced may vary with such factors as: the bacterial species, the medium they grown in, the growth phase (logarithmic, stationary, death), the nature of the surface (hydrophobic, hydrophilic), the surface texture and the actual flow rate [14].

The chemical analysis of biofilm formed on the membrane surface indicated that in 93% (wt/wt) it is consisted of water [15]. Nearly 90% (wt/wt) of the dehydrated residue was organic, while nonvolatile inorganic substances represented approximately 10% of dehydrated biofilm. The main inorganic constituents of the biofilm are calcium, chlorine, sulfur and phosphorus (in descending order of concentration). Organic fraction of biofilm is composed in 25% of proteins and in 15% of carbohydrates.

In the biofouling process three components are involved: bacteria, surface and liquid. FLEMMING and SCHAULE [16] prepared the list of factors that should be taken into account in analysis of the biofouling process.

2.1. MICROORGANISMS

1. Species. Among different species present in raw water, FLEMMING and SCHAULE [16] isolated fast-adhering cells (*Pseudomonas resicularis*, *Acinetobacter colcoaceticus* and *Staphylococcus warneri*) as well as low-adhering (*Pseudomonas fluorescens*). Among the fast-adhering strains are both gram-negative as gram-positive species.

2. Composition of mixed population.

3. Number of cells. RIDGWAY et al. [17] found that the number of membrane-bound bacteria and the number of bacteria added in the range from 0 to $50 \cdot 10^6$ cells/cm^3 are linearly dependent. Increase in the number of free bacteria (above $50 \cdot 10^6$ cells/cm^3) did not result in a comparable increase in a number of cells attached to the membrane surface (figure 5). It means that on the membrane surface there is a finite number of binding sites available for cell adhesion.

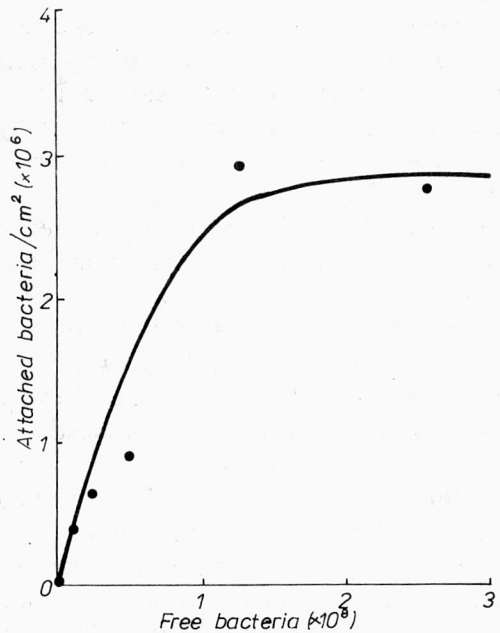

Fig. 5. Adhesion of *Mycobacterium* sp. to CA membrane surface as a function of the number of free bacteria in suspension [17]

4. Growth phase. The influence of culture age on bacterial attachment is probably due to changes in quality or quantity of the surface polymers of cells. Motility of cells greatly increases their chance of finding an attachment surface and reduce the electrical repulsive forces which can exist between the bacteria and the surface. FLETCHER [18] found that cultures characterized by log-phase had the largest number of motile cells. In long-lived cultures the reduction in cell motility was observed (figure 6).

5. Nutrient status. Under conditions of nutrient deficiency, cells show a lower capability of adhesion than "fat" cells of the same strains.

6. Surface charge. The isoelectric point of microbial cells is usually between 2 and 3.5, their surfaces are thus negatively charged in the normal pH range [19]. Electrostatic interactions between the membrane surface and the microbial cells are essential in biodeposition.

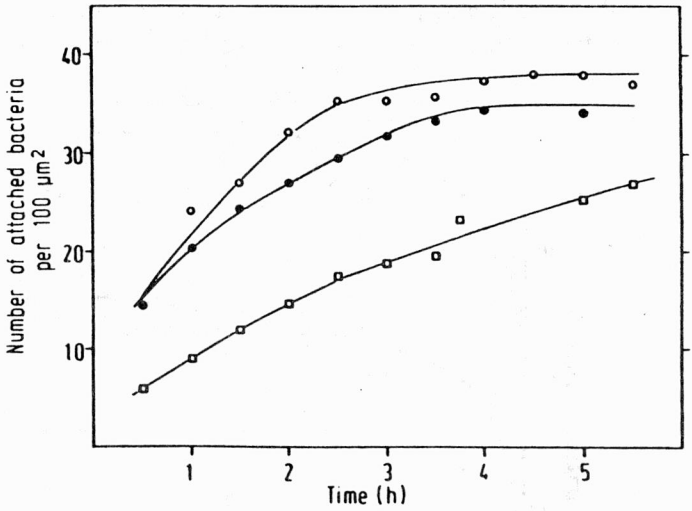

Fig. 6. The relationship between the culture age and the number of cells attached [18]
o – log phase, • – stationary phase, □ – death phase

7. Physiological response to adhesion (exopolymer substances). Production of exopolymers as an effect of bacterial reaction with a membrane surface (figure 7) was postulated by MARSHALL et al. [20] as a step of irreversible adhesion. According to FLEMMING and SCHAULE [16] living anf killed cells show an almost identical behaviour during the initial phase of the adhesion. This means that the cell wall component, which is responsible for the adhesion, is already formed in the bulk solution.

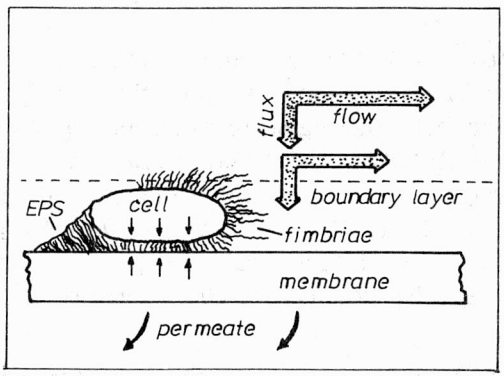

Fig. 7. Schematic description of the primary colonization;
EPS: exopolymer substances [16]

8. Hydrophobicity. Many experiments, e.g. [21], [22], proved that adhesion of bacteria with hydrophobic surface is better than adhesion of bacteria with hydro-

philic surface (figure 8). MOZES et al. [19] reported that bacteria are more hydrophilic as N/P ratio of the bacteria cell increases, whereas yeasts are more hydrophobic.

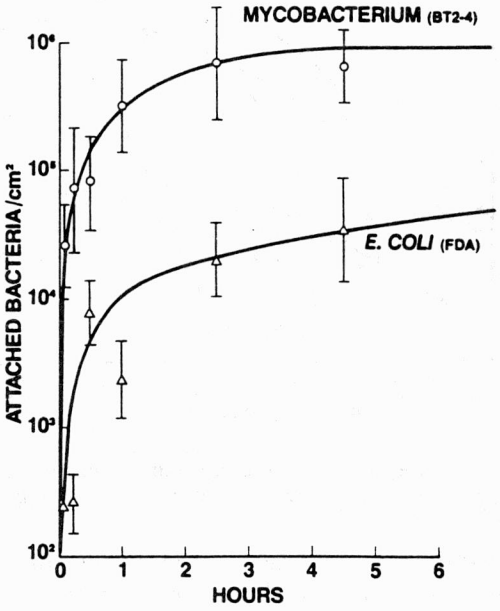

Fig. 8. Kinetics of adhesion of two different bacteria, one with a hydrophobic cell exterior (*Mycobacterium*) and the other with a hydrophilic exterior (*Escherichia coli*), to a cellulose acetate membrane [4]

2.2. MEMBRANE SURFACE

1. Chemical composition. FLEMMING and SCHAULE [16], who had tested four different polymer membranes, found that polyetherurea had a definitely lower biological affinity to the fast-adhering strains than polysulfone, polyethersulfone or polyamide. According to RIDGWAY [4], RO membrane made of polyamide is able to adsorb $3.1 \cdot 10^6$ bacteria/cm^2, while membranes made of sulfonated polysulfone and cellulose acetate adsorb $0.27 \cdot 10^6$ bacteria/cm^2 and $0.33 \cdot 10^6$ bacteria/cm^2, respectively (figure 9). The differences in biological affinity of different types of membranes are probably due to their electrical charge characteristics and micromorphological features.

2. Surface charge. Membrane charge plays an important role in biofilm formation (figures 10 and 11). Electrostatic interaction between the membrane and microbial cell may reduce microbial adhesion (in the case of negatively charged membranes) or increase biodeposition (in the case of positively charged membranes).

3. Surface tensions.

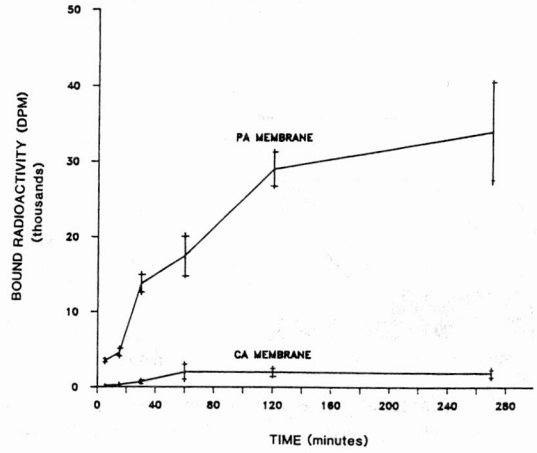

Fig. 9. Kinetics of mycobacterial adhesion to polyamide and cellulose acetate mambranes [4]

4. Hydrophobicity. Data presented in figure 11 suggests that bacterial attachment to the membrane is directly correlated with membrane hydrophobicity and inversely with its hydration capacity.

5. Adsorbed macromolecules ("conditioning film"). Susceptibility of a membrane surface to bacterial attachment is determined by various features of biological macromolecules adsorbed. This phenomenon depends upon the nature of the conditioning molecule, the nature of solid substrata and whether the bacterial attachment experiments take place in the presence of the macromolecules or after formation of the conditioning film [23]. PRINGLE and FLETCHER [24] reported that lipopolysaccharides and dextranes inhibit bacterial attachment.

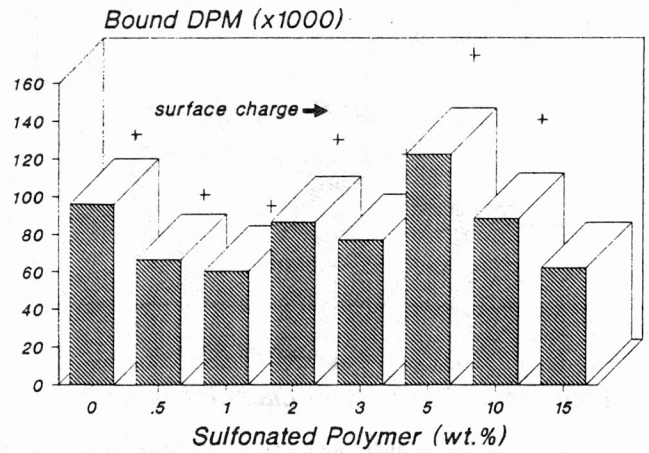

Fig. 10. Influence of membrane sulfonation (negative surface charge) on mycobacterial attachment [3]

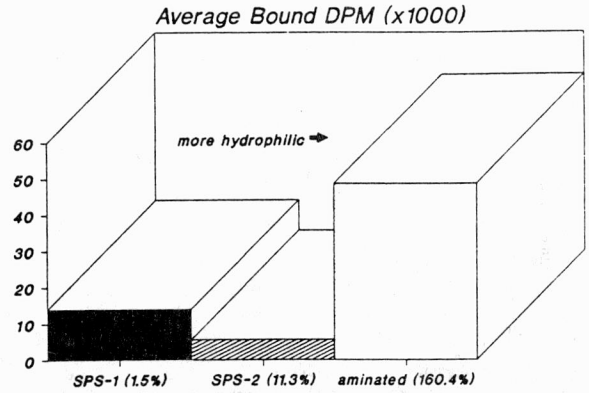

Fig. 11. Mycobacterial adhesion to two types of membranes: sulfonated (i.e., negatively charged) and aminated (i.e., positively charged) [3]

6. Roughness. Surface roughness may significantly influence transport rate and microbial adhesion. According to RIDGWAY and SAFARIK [3] the adhesion of microbial cells is the effect of subtle morphological variations in the membrane surface. A rough membrane surface with shallow depressions and crevices with depths approaching average bacterial dimensions (about 1 μm) would presumably promote microbial adhesion and fouling by establishing localized areas of reduced turbulence and surface shear (figure 13).

7. Porosity. The increase in membrane porosity strongly influences bacterial adhesion (figure 14) even when the membrane pore diameter is much smaller than that of the bacterial cell.

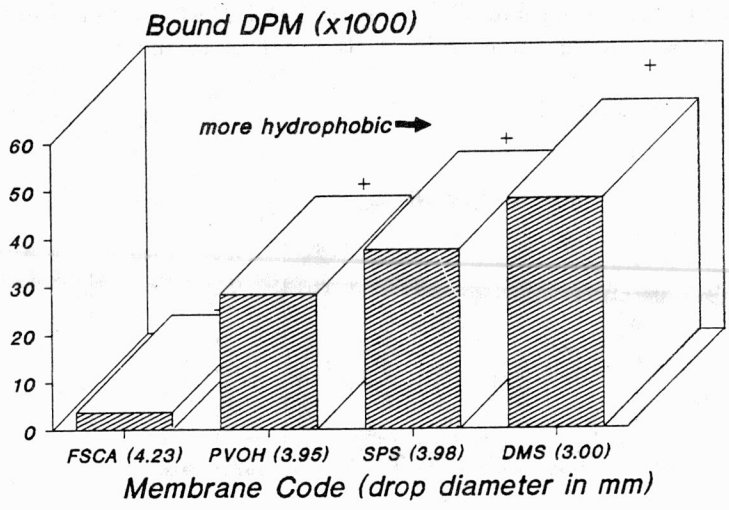

Fig. 12. Influence of membrane hydrophobicity on mycobacterial adhesion [3]
FSCA – cellulose acetate, PVOH – polyvinyl alcohol – coated polysulfone, SPS – sulfonated polysulfone, DMS – dimethyl silicone

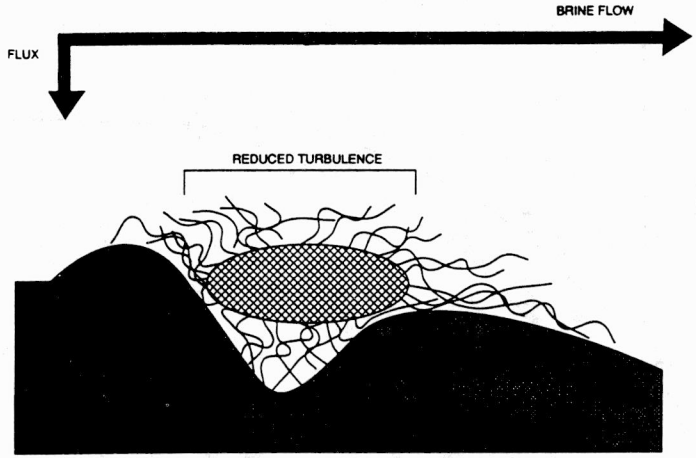

Fig. 13. Concept of entrainment of fouling bacterium in a membrane crevice where fluid turbulence could be expected to be low [3]

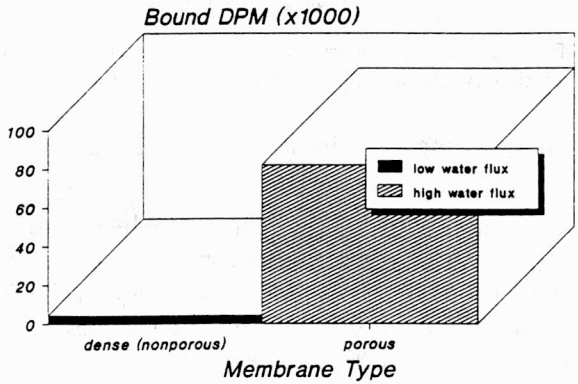

Fig. 14. Influence of membrane polymer density (i.e., porosity) on microbial adhesion [3]

2.3. LIQUID

1. Temperature. It was found [18] that the drop in temperature results in the decrease of the number of the microorganisms attached (figure 15).

FLETCHER [18] gave 3 possible explanations of this phenomenon. They are as follows:

i) the attachment efficiency might be reduced at low temperatures because of an accompanying increase in the viscosity of the medium or of the bacterial surface polymer,

ii) higher temperatures favour chemisorption and certain types of physical adsorption of solutes from solution,

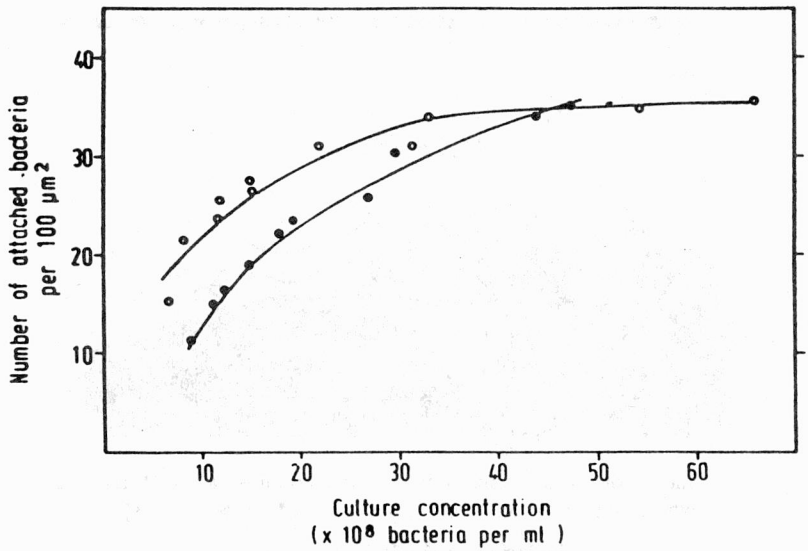

Fig. 15. Effect of temperature on the attachment of the cells entering stationary phase [18]. o – 20°C ± 1, • – 3°C ± 1

iii) temperature may influence adhesion by affecting the physiology of the organisms.

2. pH. Experimental data shows [25] that the reduction of pH results in the lowering of zeta potential of the microorganism cell as a consequence of neutralization of functional groups of cell wall. Neutralization of charge (by reduction of pH) makes the biofouling layer more hydrophobic and less permeable to water.

According to RIDGWAY et al. [26] maximum *Mycobacterium* adherence to the CA membrane was observed at pH approaching 6 (figure 16).

3. Substances forming a conditioning film.

4. Other dissolved organic substances. The effect of various chemical additives on adhesion indicated [26] that ethylenediaminetetraacetic acid, urea and cellobiose had little or no influence on mycobacterial adhesion (figure 17). Significantly less effective bacterial Adhesion was observed in the presence of polyethylene imine and polyoxyethylene ether nonionic detergent.

5. Other dissolved inorganic substances. It was found [20] that the presence of divalent cations, such as magnesium and calcium, influences attachment of microorganisms to surfaces. This effect accounted for a decrease in the thickness of electron double layer. As a result, repulsion forces between the cell surface and the substratum are reduced. RIDGWAY et al. [26] reported that the presence of NaCl and LiBr significantly reduced bacterial adhesion, whereas LiCl had no influence on this phenomenon.

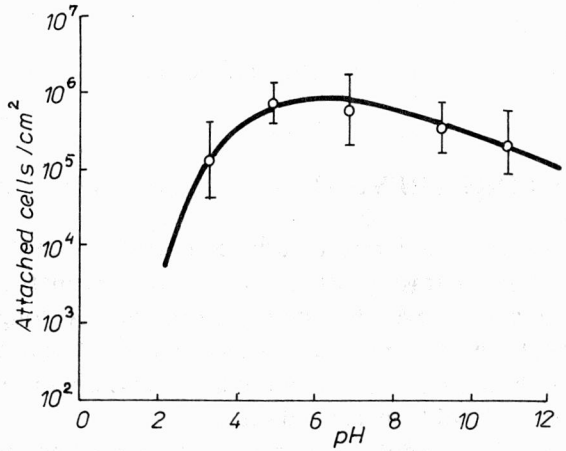

Fig. 16. Adhesion of *Mycobacterium* cells to CA membrane as a function of pH [26]

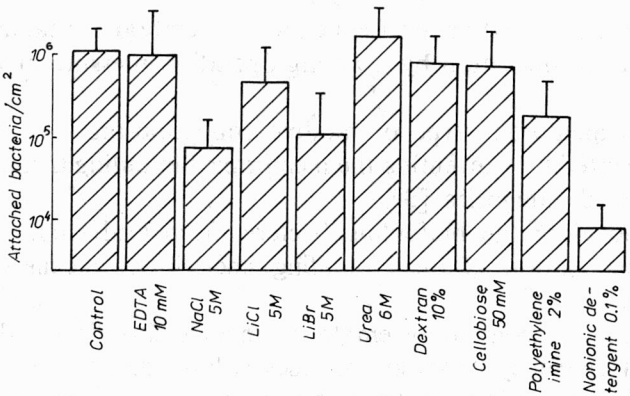

Fig. 17. Influence of various substances on adherence of *Mycobacterium* cells to CA membrane [26]

6. Suspended matter and colloids.

7. Viscosity.

8. Surface tensions.

9. Pressure.

10. Shear forces (flow). Formation of biofilm and concentration polarization effects can be reduced by maintaining turbulence with high velocities, and hence, minimum boundary layer thickness [27]. An increase in Reynolds number, *Re*, results in linear decrease in initial accumulation rate of biofilm [28].

11. Boundary layer.

12. Vertical forces.

All these factors may interfere with each other or be intensified in various combinations.

3. BIOFOULING PREVENTION AND BIOFILM REMOVAL

In every plant operating under non-sterile conditions we deal with a biofilm. This biofilm takes part in the separation process as a secondary membrane. Its separation characteristics influences the overall system performance. As long as the effect of the biofilm does not affect the performance of the system (more than torelated) it will not be noticed. When biofilm growth is fast enough to cause operational problems, some effective undertakings should be carried out.

There are several fundamental strategies for controlling biological fouling of membranes. These general strategies include [3]:

feedwater pretreatment by prefiltration, preflocculation or addition of biocides,

changing the type, method or frequency of membrane cleaning,

modifying system operation by lowering operation pressure or reducing system recovery,

changing the membrane type or module configuration.

Strategies adopted for preventing the membrane biofouling through pretreatment fall into two broad categories [3]:

physical removal of the biofouling bacteria from feedwater,

metabolic inactivation of the biofouling bacteria by means of antimicrobial agents or disinfectants.

Removal strategies commonly employed include filtration and/or flocculation and settling, but efficiency of these processes is limited. Moreover, in some cases, chemicals added to water in a treatment process (e.g., coagulants) can be a source of nutrients promoting bacterial growth.

An alternative to conventional filtration and flocculation might be the use of high-volume affinity adsorption columns [3].

The most effective pretreatment method preventing membrane biofouling is the continuous addition of a chemical biocidal agent to feed solution. The most popular biocidal agents are [3]: free chlorine, monochloramine, chlorine dioxide, formaldehyde, glutaraldehyde, isothiazolone, bisulfite, UV irradiation, iodine, hydrogen peroxide, ozone, peracetic acid, quaternary amines, sodium benzoate, EDTA and extreme values of pH.

Le CHEVALLIER et al. [29] evidenced that combined chlorine (i.e., monochloramine) is significantly more effective than free chlorine in terms of its ability to penetrate and inactivate the biofilm attached. RIDGWAY et al. [30] tested whether the chlorine disinfection of the feedwater will inhibit or retard the rate of membrane biofouling and thus it will cause a decline in a flux passing through the cellulose

acetate membranes. They have found that the increase in chlorine dose from 1–3 mg/dm^3 to 15–20 mg/dm^3 caused the increase in the rate of flux decline. Two possible explanations of this phenomenon [5] can be presented as follows:

1. The biofilm on the surface of the membranes treated with a high dose of chlorine is composed largely of chlorine-inactivated and autolyzed bacterial cells [15]. At high pressures, the layer formed by inactivated organisms is denser than that formed by living organisms and the membrane permeability decreases.

2. The chloramines formed may chemically react with the surface of cellulose diacetate polymer, reducing its flux characteristics. It was suggested that the presence of certain organochlorine derivatives may directly modify the molecular structure of polymer network.

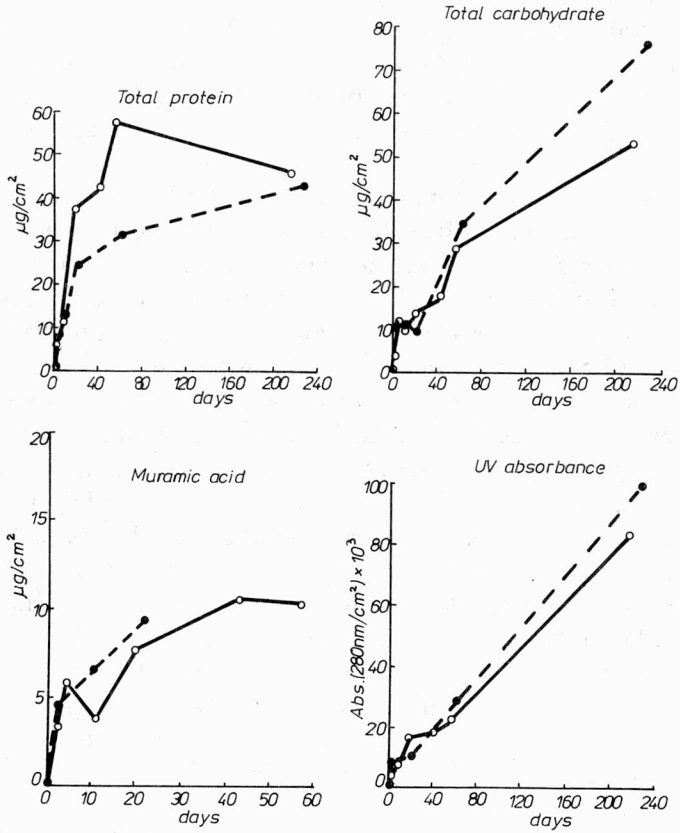

Fig. 18. Accumulation of total protein, total carbohydrate, muramic acid and UV-adsorbing substances on membrane surface [30]
o – low chlorine dose; • – high chlorine dose

RIDGWAY et al. [30] have also noticed that the chlorine strongly influences the composition of biofouling layer formed on the membrane surface (figure 18).

It should be emphasized that chemical biocides may be insufficient to prevent biofilm development if membranes are not regularly cleaned. This is because most of the biocides acting alone include free or combined chlorine. They only inactivate the bacteria, but do not result in cellular lysis and complete destruction and/or physical removal of microorganisms. Inactivated microorganisms and the products of biolysis can adhere to membrane surfaces and form a metabolically inactive film [3]. The accumulated biological material can then serve as an available nutrient source for viable microorganisms. Such a nonliving organic matter can also form a protective cover which decreases the effectiveness of biocide activity.

The use of broad-spectrum biocides is gradually falling out of favour due to direct and indirect damage of biocides to plants and the hazards of handling the biocides. In addition, strict environmental regulations limit use of many biocides.

Another method of biofouling prevention has been reported by SHARMA et al. [30]. In order to decrease adsorption of bacteria on porous walls, they successfully used polyelectrolytes (heparin, lignosulphonate, polyacrylic acid and phosphate), which are adsorbed irreversibly on the cell wall and increase the net negative charge.

A new approach for controlling the biofilm growth is to reduce the concentration of nutrients in the feed solution [6]. Biological treatment promotes microbial activity, which is sufficient to remove all nutrients that might support significant bacterial growth in the effluents treated. Biological removal of organic material have been reported [32] for aerated submerged reactors, fluidized bed filters, slow sand filters, rapid sand filters and granular activated carbon filters.

As it was stressed above, even when pretreatment of feed solution was applied, membranes should be cleaned at regular intervals. Membranes must be cleaned at intervals frequently enough to prevent the development of a mature biofilm, whose removal in this stage is more difficult than in an early stage [33]. The frequency of membrane cleaning depends on the rate of biofilm growth in a particular system. Membranes and membrane modules might be clean either chemically of physically.

When chemical cleaner is selected, the compatibility of the membrane and the type of foulant should be taken into account, because the use of inproper cleaner might cause severe membrane damage [34]. Cationic surfactants form bonds with some polyamide membranes; nonionic surfactants soften the polysulfone support used in spiral wound thin film membranes. Oxidizing agents damage most of polyamide membranes. A pH below 3.5 or above 7.5 is destructive to cellulose acetate membranes.

WHITTAKER et al. [33] tested cleaning properties of the following chemicals and their combinations:

surfactants and detergents which neutralize charged colloidal particles and resolubilize or resuspend them,

chaotropic agents which denature proteins and therefore readily solubilize organic constituents,

bactericides which destruct or dissolute microorganisms due to their bacteriolytic properties,

enzymes which hydrolyze the proteinaceous and glycoprotein exopolymers surrounding microorganisms,

antiprecipitants which remove metals and other precipitated ions from the layer of fouling.

WHITTAKER et al. have noticed that enzyme–antiprecipitant–dispersant combination formed most of the very good cleaners. EDTA, a chelate compound, was added to the enzyme solutions to chelate any toxic metals that could retard enzymatic ativity. Nonionic detergent, because of its surfactant activity, faciliated penetration of the biofouling layer by the enzyme. Unfortunately, the use of enzymes under operating conditions has two major drawbacks: high cost and lack of stability.

Another efficacious cleaner was the combination of chaotropic and bactericidal agents, e.g., urea with an anionic detergent, SDS. A major drawback of anionic detergents are their foamy properties.

ALASRI et al. [35], who had tested cleaning properties of typical bactericides, observed that the highest bactericidal activities were characteristic of peracetic acid and chlorine. On the contrary, hydrogen peroxide and formalin show weak bactericidal activities.

Numerous investigators have observed a rapid resumption of biofouling immediately following biocide treatment and have termed this phenomenon as "regrowth". Regrowth may be due to one or all of the following [2] reasons:

residual biofilm induces an increase in a relative roughness of the surface and thus enhances transport and sorption of cells to the surface,

chlorine reacts preferentially with EPS and does not reach the biofilm cells,

EPS is formed rapidly by surviving organisms as a response to chlorine irridation,

selection of organisms less susceptible to biocides, which proliferate better at each interval between successive biocide applications.

Among physical cleaning methods the most popular [2] can be itemized as follows:

flushing – the simplest method but with limited efficiency; biofilms thinner than the viscous sublayer are not removed,

backwashing – effective for loosely adhering films,

air bumping,

hot water stream,

ice nucleation – temperature lower than – 12°C destabilizes the biofilm matrix and detaches it from the support,

irradiation – very low efficiency.

Among different physical methods, ultrasonic treatment [36] seems to be the most effective to clean membrane surfaces from bacteria. 95% detachment of biofilm was achieved when the membrane was exposed to ultrasounds of the intensity of 2 watt for 60 s. It can also be assumed that ultrasounds of a lower intensity might be useful to prevent biofilm formation.

WHITTAKER et al. [33] reported that mechanical cleaning gave the best results in terms of biofilm removal from membranes. The application of this method of membrane cleaning is limited because of membrane configurations and their low mechanical resistance.

4. CONCLUSIONS

Biofouling of membranes has not been resolved to date. Although it is impossible to eliminate biofilms, we should not fight against them with the large amounts of toxic biocides which pollute environment. Biofilms are always present in non-sterile systems, and it is nearly impossible to remove them totally. Their control is the best way to maintain a process efficiency. Optimization of layer thickness by applying proper shearing forces and nutrient control as well as optimization of its permeability by application of suitable chemical agents may create an effective alternative strategy for biofouling reduction.

When MARSHALL was asked [2] about prospects of biofouling control, he answered: *The organism always wins*, and this is the best comment on the subject that was the purpose of this work.

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BIOFOULING MEMBRAN

Biofouling membran jest jednym z najpoważniejszych problemów, na jakie napotykamy, stosując techniki membranowe. Rozwój biofilmu na powierzchni membran jest rezultatem wielu procesów fizycznych, chemicznych i mikrobiologicznych. Główne działania, których celem jest ograniczenie tego zjawiska, obejmują wstępne przygotowanie roztworu zasilającego oraz czyszczenie membran.

МЕМБРАННЫЙ БИОФУЛИНГ

Мембранный биофулинг является одним из важнейших вопросов, с какими мы встречаемся, применяя мембранные техники. Развитие биофильма на поверхности мембран является результатом многих физических, химических и микробиологических процессов. Деятельность, целью которой является ограничение этого явления, охватывает предварительную подготовку питающего раствора, а также чистку мембран.