ULTRAFILTRATION IN WATER TREATMENT AND ITS EVALUATION AS PRE-TREATMENT FOR REVERSE OSMOSIS SYSTEM

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Abstract

The use of ultrafiltration technology for municipal drinking water applications is a relatively recent concept, although in the beginning, it is already commonly used in many industrial applications such as food or pharmaceutical industries. Ultrafiltration is proven to be a competitive treatment compare with conventional ones. In some cases, the combination of ultrafiltration with conventional process is also feasible particularly for high fouling tendency feed water or for removal of specific contaminants. Recently, ultrafiltration has been recognized as competitive pre-treatment for reverse osmosis system. A system designed with an ultrafiltration as pre-treatment prior to reverse osmosis system has been referred to as an Integrated Membrane System (IMS). The application of IMS is a must for sites require very extensive conventional pre-treatment or where wide fluctuation of raw water quality is expected. However, the UF design was generally dismissed as commercial alternative to conventional filtration due to its high membrane cost. Nevertheless, today the UF membrane price has gone far down, even below conventional treatment system with the new coming Asian membrane industries. Therefore, there is no doubt, UF is now becoming a competitive pretreatment system for RO in a wide range of raw water quality.

I. INTRODUCTION

Membrane can be described as a thin layer of material that is capable of separating materials as a function of their physical and chemical properties when a driving force is applied across the membranes. Physically membrane could be solid or liquid. In membrane separation processes, the feed is separated into a stream that goes through the membrane, *i.e.,* the permeate and a fraction of feed that does not go through the membrane, *i.e.*, the retentate or the concentrate. A membrane process then allows selective and controlled transfer of one species from one bulk phase to another bulk phase separated by the membrane.

The major breakthrough in the development of membrane technology was recorded in the late of 1950s. However, industrial application was just started ten years later, by the application of thin layer asymmetric cellulose acetate reverse osmosis membrane for seawater desalination.

Membrane process can be classified in many ways, *i.e.,* based on its nature, structure, or driving force. Hydrostatic pressure differences are used in microfiltration (MF), and nanofiltration (NF), as well as reverse osmosis (RO) and gas separation (GS) as driving force for the mass transport through the membrane. Ultrafiltration (UF) as the main topic in this paper is also one of the membrane process based on pressure difference as its driving force. Ultrafiltration in its ideal definition as mentioned by Cheryan (1986) is a fractionation technique that can simultaneously concentrate macromolecules or colloidal substances in process stream. Ultrafiltration can be considered as a method for simultaneously purifying, concentrating, and fractionating macromolecules or fine colloidal suspensions.

In the beginning, most application of ultrafiltration is in medical sector, *i.e.,* kidney dialysis operations. Nowadays, ultrafiltration is applied in wide variety of fields, from food and beverage industries to chemical industries. Water and wastewater treatment are also the potential field of ultrafiltration application. Today, UF technology is being used worldwide for treating various water sources. The use of UF technology for municipal drinking water applications is a relatively recent concept, although as mentioned before, it is commonly used in many industrial applications such as food or pharmaceutical industries [Laîné, *et. al.* 2000]. The recent global increase in the use of membranes in water application is attributed to several factors, *i.e.,* increased regulatory pressure to provide better treatment for water, increased demand for water requiring exploitation of water resources of lower quality than those relied upon previously, and market forces surrounding the development and commercialization of the membrane technologies as well as the water industries themselves [Mallevialle, *et. al.* 1996]. In this paper, the application of ultrafiltration in water treatment, the system design, and its performance as pre-treatment for reverse osmosis system are presented.

II. ULTRAFILTRATION MEMBRANE

Ultrafiltration membranes can be made from both organic (polymer) and inorganic materials. There are several polymers and other materials used for the manufacture of UF membrane. The choice of a given polymer as a membrane material is based on very specific properties such as molecular weight, chain flexibility, chain interaction, *etc*. Some of these materials are polysulfone, polyethersulfone, sulfonated polysulfone, polyvinylidene fluoride, polyacrylonitrile, cellulosics, polyimide, polyetherimide, aliphatic polyamides, and polyetherketone. Inorganic materials have also been used such as alumina and zirconia [Mulder, 1996].

The structure of UF membrane can be symmetric or asymmetric. The thickness of symmetric membran (porous or nonporous) is range from 10 to 200 μm. The resistance to mass transfer is determined by the total membrane thickness. A decrease in membrane thickness results in an increased permeation rate. Ultrafiltration membranes have an asymmetric structure, which consist of very dense toplayer or skin with thickness of 0.1 to 0.5 μm supported by a porous sublayer with a thickness of about 50 to 150 μm. These membranes combine the high selectivity of a dense membrane with the high permeation rate of a very thin membrane. The resistance to mass transfer is determined largely or completely by thin toplayer. Figure 1 shows the cross-sections of symmetric and asymmetric membrane.

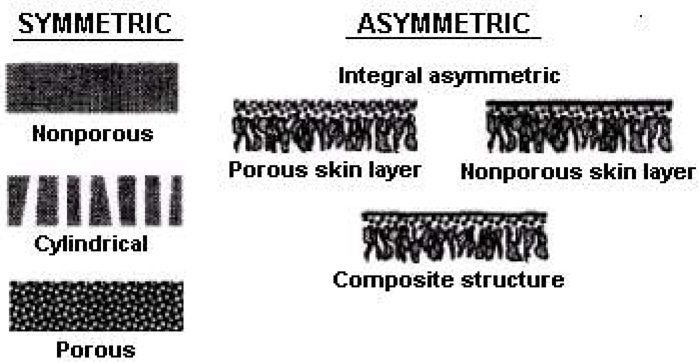

Fig. 1. Schematic representation of symmetric and asymmetric membrane cross-section [Strathmann, 2001]

In porous membranes, the dimension of the pore mainly determines the separation characteristics. The type of membrane material is important for chemical, thermal, and mechanical stability but not for flux and rejection. Therefore, the aim of membrane preparation is to modify the material by means of an appropriate technique to obtain a membrane structure with morphology suitable for a specific separation. The most important techniques are sintering, stretching, track-etching, phase-inversion, sol-gel process, vapour deposition, and solution coating. However, the technique usually use for the preparation of UF membrane is mainly phase-inversion and sol-gel process.

Characterisation method of porous membranes can be performed based on structure-related parameters (determination of pore size, pore size distribution, top layer thickness, surface porosity) and permeation-related parameters (cut-off measurements) [Mulder, 1996]. The molecular weight cut-off (MWCO) is a specification used by membrane suppliers to describe the retention capabilities of UF membrane, and it refers to the molecular mass of a macrosolute (typically, polyethylene glycol, dextran, or protein) for which the membrane has a retention capability greater than 90%. The MWCO can therefore be regarded as a measure of membrane pore dimensions [Anselme & Jacobs, 1996]. UF covers particles and molecules that range from about 1000 in molecular weight to about 500,000 Daltons [Cheryan, 1998]. Other techniques beside cut-off measurements for characterising UF membranes are thermoporometry, liquid displacement, and permporometry.

III. TRANSPORT MECHANISM

One of the critical factors determining the overall performance of an ultrafiltration system is the rate of solute or particle transport in the feed side from the bulk solution toward the membrane. As shown in Fig. 2, the pressure-driven flow across the membrane convectively transports solutes toward the upstream surface of the membrane. If the membrane is partially, or completely, retentive to a given solute, the initial rate of the solute transport toward the membrane, J.C, will be greater than the solute flux through the membrane, $J.C_p$. This causes the retained solute to accumulate at the upstream surface of the membrane. This phenomenon is generally referred to as concentration polarization, *i.e.*, a reversible mechanism that disappears as soon as the operating pressure has been released [Aimar *et al.*, 1993]. The solute concentration of the feed solution adjacent to the membrane varies from the value at the membrane surface, C_w, to that in bulk solution, C_b, over a distance equal to the concentration boundary layer thickness, δ. The accumulation of solute at the membrane surface leads to a diffusive back flow toward the bulk of the feed, −D.dC/dx. Steady state conditions are reached when the convective transport of solute to the membrane is equal to the sum of the permeate flow plus the diffusive back transport of the solute, *i.e.*:

$$J.C - D\frac{dC}{dx} = J.C_p \qquad (1)$$

where J is the permeate flux, C is the solute concentration profile in x direction, D is the diffusion coefficient, and C_p is the solute concentration in the permeate.
The boundary conditions are:

$x = 0 \Rightarrow C = C_w$

$x = \delta \Rightarrow C = C_b$

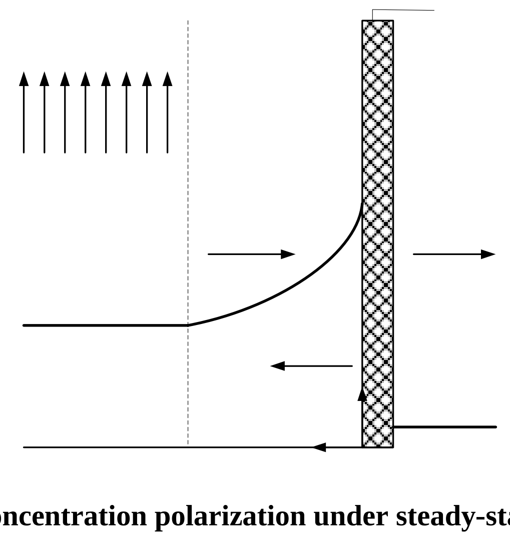

Fig. 2. Concentration polarization under steady-state conditions

Integration of eq. (1) results in

$$\ln\frac{C_w - C_p}{C_b - C_p} = \frac{J\delta}{D} \qquad (2)$$

If we introduce the ratio between the diffusion coefficient D and the thickness of the boundary layer δ called the mass transfer coefficient k, *i.e.*

$$k = \frac{D}{\delta} \tag{3}$$

then eq. (3) becomes

$$J = k \ln\left(\frac{C_w - C_p}{C_b - C_p}\right) \tag{4}$$

The flux-limiting value for a totally retained solute (C_p = 0) at gel layer conditions is given by eq. (4) as

$$J = k \ln\left(\frac{C_w}{C_b}\right) \tag{5}$$

The surface concentration (C_w) may be obtained by extrapolation of a plot of J versus ln C_b. It has, however, been shown that the information obtained on the surface concentrations is frequently not reliable. For identical solutions different authors have found widely varying values at C_w. In addition, it has been shown that feed solutions of various macrosolutes with concentration $C_b = C_w$ did not give zero flux [Nakao *et al.*, 1979]. Assumption of k constant with concentration also remains questionable.

The accumulation of solutes/particles at the membrane surface can affect the permeate flux in two distinct ways. First, the accumulated solute can generate an osmotically driven fluid flow back across the membrane from the permeate side toward the feed side, thereby reducing the net rate of solvent transport. This effect generally will be most pronounced for small solutes, which tend to have large osmotic pressures (*e.g.*, retained salts in reverse osmosis). However, very high concentrations of dextran and whey protein solutions at the membrane surface have a substantial osmotic pressure [Jonsson, 1984]. Second, the solutes/particles can irreversibly foul the membrane due to specific physical and/or chemical interactions between the membrane and various components present in the process stream, thereby providing an additional hydraulic resistance to the solvent flow in series with that provided by the membrane. These interactions can be attributed to one or more of the following mechanisms: (a) adsorption, (b) gel layer formation, and (c) plugging of the membrane pores. Its severity depends on the membrane material, the nature of solutes, and other variables such as pH, ionic strength, solution temperature and operating pressure [Jönsson & Tragardh, 1990].

Membranes fouling typically manifests itself as a decline in permeate flux with time of operation, and consequently, this is often accompanied by an alteration in membrane selectivity. These changes often continue throughout the process and eventually require extensive cleaning or replacement of the membrane. It should be noted that the effect of membrane fouling on the flux can often be very similar to those associated with concentration polarization. For this reason, it is first necessary to distinguish between membrane fouling and concentration polarization, although both are not completely independent of each other since fouling can be resulted from polarization phenomena. In addition, flux decline can also be caused by changes in membrane properties as a result of physical deterioration of the membrane and/or change in feed properties. So far, a number of different mathematical formulations have been proposed to predict permeate flux.

When, the osmotic pressure difference $\Delta\Pi$ across the membrane can then become substantial, the driving force of the fluid transport across the membrane is given by $\Delta P - \sigma\Delta\Pi$ [Zeman and Sydney, 1996]. The reflection coefficient σ indicates the degree of perm-selectivity of the membrane. When σ = 1 the solute is totally retained and when σ = 0 it is totally permeable. The resistance of the accumulated solute at the membrane surface is sometimes represented as a hydraulic resistance R_s. If we introduce hydraulic resistance R_m instead of permeability in Darcy's equation and take the osmotic pressure of the solute into consideration, the flux may be described by the generalized equation:

$$J = \frac{\Delta P - \sigma \Delta \Pi}{\mu (R_m + R_s)} \tag{6}$$

The theoretical models that often be related to eq. (6) are the osmotic pressure model, the gel layer model and the resistance in series model. In the osmotic pressure model, the solute hydraulic resistance R_s is substituted by a continuous, steep, concentration gradient at the membrane, resulting in a substantial osmotic pressure:

$$J = \frac{\Delta P - \sigma \Delta \Pi}{\mu R_m} \tag{7}$$

Taking the osmotic pressure at the membrane wall into account, Wijmans *et al.* [1984] have derived a relation between pressures and permeate flux. They also used the following relationship between the osmotic pressure and the concentration at the membrane wall:

$$\Pi_w = a C_w^n \tag{8}$$

where a and n are solution-dependent constants.

When the solute is completely retained ($\sigma = 1$ and $C_p = 0$), and hydraulic resistance of the solute, R_s, is neglected, combination of eq. (7) and (8) gives the following expression:

$$J = \frac{\Delta P - a C_b^n \exp(nJ/k)}{\mu R_m} \tag{9}$$

Eq. (9) shows that flux declines faster for the high permeability membrane than for the low permeability membrane. In addition, the derivative $\partial J / \partial \Delta P$ shows how the permeate flux changes with pressure:

$$\frac{\partial J}{\partial \Delta P} = \left[\mu R_m + a C_b^n \frac{n}{k} \exp\left(\frac{nJ}{k} \right) \right]^{-1} \tag{10}$$

Combining eq. (8) and (9) and substituting the result into eq. (10) leads to

$$\frac{\partial J}{\partial \Delta P} = \frac{1}{\mu R_m} \left(1 + \frac{\Delta \Pi n}{\mu R_m k} \right)^{-1} \tag{11}$$

Using eq. (11), the extent of the permeate flux deviation from the pure water flux can be easily demonstrated, that is given by the second term, $\Delta \Pi n / \mu R_m k$. It is clear that the effect of a pressure increase depends on membrane permeability (the effect of R_m), solution temperature (which effects μ), osmotic pressure ($\Delta \Pi$ and n), and cross-flow velocity (which effects k).

On the contrary, in the gel layer model the osmotic pressure is assumed to be zero. The fluid flow is then described by:

$$J = \frac{\Delta P}{\mu (R_m + R_g)} \tag{12}$$

The gel layer model predicts the flux to be independent of operating pressure. An increased pressure merely results in a thicker gel layer (larger R_g), which retards the flux to its original value. The gel layer model has been used to correlate experimental limiting fluxes [Porter, 1972; Fane et al., 1981; Chudacek and Fane, 1984]. The limiting flux for a totally retained solute (C_p = 0) at gel layer conditions is given by eq. (5) as

$$J = k \ln \left(\frac{C_g}{C_b} \right) \tag{13}$$

Lastly, resistance to flow may be accounted for by a number of resistances: the resistance of the membrane (R_m), the boundary layer resistance (R_{cp}), the gel layer resistance (R_g), the pore blocking resistance, and the adsorbed layer resistance (R_a) as shown schematically in Fig.3.

Equation (6) may then be written as:

$$J = \frac{\Delta P}{R_m + R_{cp} + R_g + R_p + R_a} \tag{14}$$

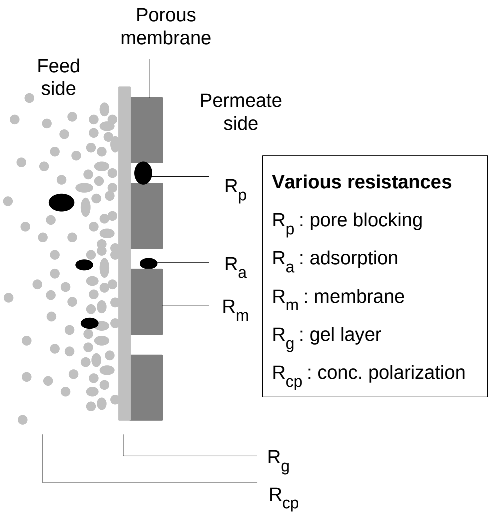

Fig. 3. Various resistances hindering mass transfer through a UF membrane based on the resistance in series model

IV. ULTRAFILTRATION SYSTEM DESIGN

Ultrafiltration (UF) is a low-pressure operation at transmembrane pressures of, typically, 0.5 to 5 bars. This is not only allows nonpositive displacement pumps to be used, but also the membrane installation can be constructed from synthetic components, which has cost advantage.

UF membranes can be fabricated essentially in one of two forms: tubular or flat sheet. Membranes of these designs are normally produced on a porous substrate material. The single operational unit into which membranes are engineered for use is referred to as a module. This operational unit consists of the membranes, pressure support structures, feed inlet, concentrate outlet ports, and permeate draw-off points. Two major types of UF modules can be found in the market, *i.e.*, hollow fibers (capillary), and spiral wound (Figure 4). Other modules are plate and frame, tubular, rotary modules, vibrating modules, and Dean vortices.

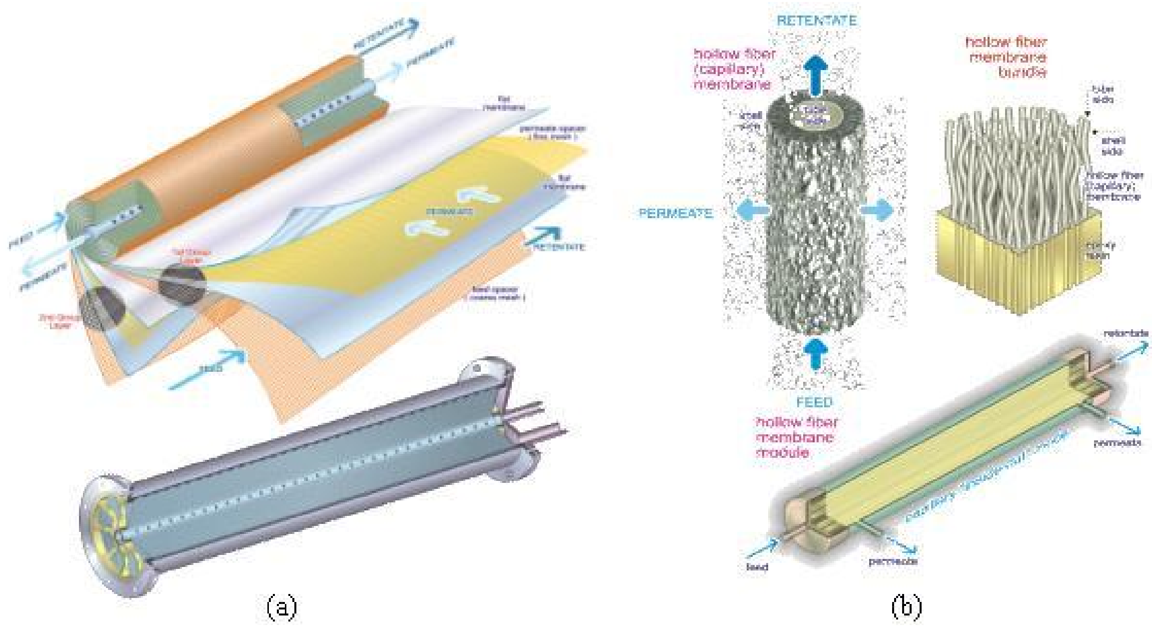

Fig. 4. Major types of UF modules: (a) spiral wound and (b) hollow fiber

Each type of modules have its particular characteristics based on its packing density, ease of cleaning, cost of module, pressure drop, hold up volume and quality of pre-treatment required. Hollow fiber module has the highest packing density compare with other types of modules, including the easiest to clean and relatively cost competitive as well as spiral wound module. Based on pressure drop, the tubular module and rotating disc/cylinder have the lowest pressure drop compare with others. Hold up volume of hollow fiber module is the highest, followed by plate and frame, spiral wound, tubular, and rotating disc/cylinder module. Requirement of pre-treatment is lowest in tubular and rotating disc/cylinder modules [Aptel & Buckley, 1996].

Current membrane modules are typically modular with high packing density. Most are suitable for scale-up to larger dimensions. A broad range of membrane devices, useful for small-scale separation in the laboratory or large industrial-scale operation, is available [Anselme & Jacobs, 1996]. Full-scale membrane facilities comprise series/parallel modules and operate according to various modes, range from intermittent single-stage system to the continuous multistage system [Aptel & Buckley, 1996].

Operation of UF membrane can be performed in two different service modes, *i.e.*, dead-end flow and cross-flow. The dead-end flow mode of operation is similar to that of a cartridge filter where there is only a feed flow and filtrate flow. The dead-end flow approach typically allows optimal recovery of feed water on the 95 to 98% range, but is typically limited to feed streams of low suspended solids (<1 NTU). The cross-flow mode different with dead-end mode in which there is an additional flow aside from feed flow and filtrate flow (permeate), *i.e.*, the concentrate. The cross-flow mode of operation typically results in lower recovery of feed water, *i.e.*, 90 to 95% range [Bates, 1999].

Nowadays, full-scale membrane elements are designed in a number of ways to optimise membrane area to element size. The design of facilities has also been optimised with the increasing plant capacities. Individual units (skids mounted units) are usually used for small plant capacities whereas for larger plant capacities (10,000 m^3/d and above) racks with ancillary equipment designed. Today, racks comprised of up to 48 membrane modules are being constructed and additional scale-up savings are therefore observed [Laîné, *et. al.* 2000]. Typical large scale UF plant is shown in Fig. 5.

Flux decline has a negative influence on the economics of a given membrane operation. Flux decline usually attributed to fouling phenomenon. Consequently, the modules must be cleaned periodically. Membrane cleaning is the removal of foreign material from the surface and body of the membrane and associated equipment to reduce fouling to some extent. The frequency of cleaning is a critical economic factor, since it has a profound effect on the operating life of a membrane. Cleaning and sanitizing membranes is desirable for several reasons, that is, laws and regulations may demand it in certain applications (*e.g.*, the food and biotechnological industries), reduction of microorganisms to prevent contamination of the product stream, and process optimisation. A clean membrane can be defined in three terms according to Cheryan (1998), *i.e.*, physically clean membrane, chemically clean membrane, and biologically clean membrane. Flux recovery to initial flux of a new membrane after cleaning can be used as indication of clean membrane.

Four cleaning methods can be distinguished, *i.e.*, hydraulic cleaning, mechanical cleaning, chemical cleaning, and electrical cleaning. The choice of cleaning method mainly depends on the module configuration, the type of membranes, the chemical resistance of the membrane and the type of foulant encountered.

Hydraulic cleaning methods include back flushing, alternate pressurising and depressurising and by changing the flow direction at a given frequency. In bacfkflush technique, the direction of the permeate flow through the membrane is periodically reversed. However, backflushing also reduces the effective operation time, and gives a loss of permeate to the feed solution. The impact of backflushing in industrial application is very limited, because of its fundamental limitation, *i.e.* loss of permeate and operation time, therefore the backflush process needs adequate optimisation. The backflush process is optimized both for the duration of the backflush and for the backflush interval. The improvement of the product rate upon backflushing is mainly a function of the backflush pressure and the interval between two backflushes. Recently, the time interval of back flushing has been reduced to seconds which implies that the cake resistance remains low since it has no time to built up a layer. A novel backflush technique with a high frequency and extremely short duration times has been introduced. It was found that extremely good results could be obtained using very short backflush time (typically 0.06 second) with an interval time of maximum 5 seconds, preferably 1 to 3 seconds. Since the effective backflush time is very short and the backflush pressure is relatively high (typically 1 bar over the feed pressure) the name "backshock" is introduced. The loss of permeate during backshocking is very low and hardly affects the net permeate flow. The backshock technique in combination with the use of reversed asymmetric membrane structures allows filtration at extremely low crossflow velocities with very stable permeate fluxes. Very frequent backshock prevents the membrane from definitive clogging, and enables a filtration process with an extremely stable flux level [Wenten, 1995].

Mechanical cleaning using oversized sponge balls can only be applied in tubular systems. Several researchers are developing other mechanical cleaning using ultrasonic wave. Chemical cleaning is the most important method for reducing fouling, with a number of chemicals being used separately or in combination. The concentration of the chemical and the cleaning time are also very important relative to the chemical resistance of the membrane. Electrical cleaning is a very special method of cleaning. By applying an electric field across a membrane, charged particles or molecules will migrate in the direction of the electric field. Electrical cleaning can be applied without interrupting the process and the electric field is applied at certain time intervals [Mulder, 1996].

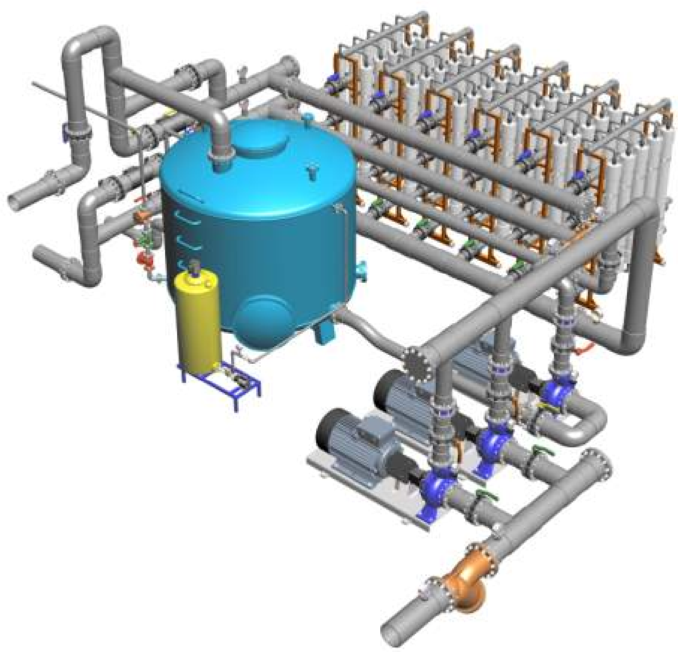

Fig. 5. Typical large scale UF plant

V. ULTRAFILTRATION IN WATER TREATMENT

Water has the ability of dissolving and containing various substances. Fresh water from surface water or groundwater is utilized for industrial or domestic purpose, either for potable or non-potable use. Due to the intended purposes, a water treatment plant is needed to fulfil the requirements of treated water. In general, conventional water treatment plant usually consists of physical treatment (screening, sedimentation, flotation, filtration) and chemical treatment (pH adjustment, coagulation-flocculation process, oxidation-reduction process, adsorption process) [Kurita, 1985]. The degree of the complexity of the treatment plant also depends on the quality of raw water and treated water requirement. In industrial processing, water is used in numerous applications requiring likewise different qualities of water. Examples of different use are cooling water, water for rinsing and chemical production, boiler feed water, purified water, water for injection, *etc*. The growth in population, the increasing costs of treatment and distribution, contamination of fresh water source, and the sophistication of end user, somehow forces the development for better improvement of water treatment technology [Anselme & Jacobs, 1996].

Ultrafiltration (UF) is proven to be a competitive treatment compare with conventional ones. The production of clear and sparkling water that is safe as far as disease is concerned usually require chemical precipitation, adsorption, sedimentation, and filtration [Anselme & Jacobs, 1996]. Each step of this process has to be controlled to get an optimal performance of the overall process, which results in a complex control system [Clever, *et. al.* 2000]. Nowadays, UF is used to replace clarification step in conventional water treatment plant, *i.e.,* coagulation, sedimentation, and filtration and can be defined as a clarification and disinfections membrane operation. UF membranes are porous, however, all particulate contaminants such as viruses and bacteria, including macromolecules are rejected. The main advantages of low-pressure UF membrane processes compare with conventional clarification (direct filtration, settling/rapid sand filtration, or coagulation/sedimentation/filtration) and disinfection (post chlorination) processes are no need for chemicals, size-exclusion filtration as opposed to media depth filtration, good and constant quality of treated water in terms of particle and microbial removal regardless of raw feed water quality, process and plant compactness, and simple automation [Anselme & Jacobs, 1996].

Source water quality directly impacts UF membrane performance. Therefore, in practice, depending on the quality of raw water, UF can be operated as single operation or combination with other process (coagulation, adsorption, *etc.*) or hybrid membrane system (UF/MF). In water application, UF can be the main process or as pre-treatment for example in RO system. In this section, the discussion will only pointed to UF as main process, meanwhile UF as pre-treatment will be discussed briefly in the next other section.

Today, more than 2 millions m^3/d (750 mgd) of drinking water is produced worldwide using low-pressure membranes, including microfiltration (MF) and ultrafiltration. More than 50 UF plants for producing drinking water from surface water are in operation in the world [Delgrange-Vincent, *et.al.,* 2000]. Out of the low-pressure membrane full-scale plants identified worldwide, UF applications represent about 74% of the total installed capacity. A six-years operation of UF membrane in Amoncourt, France showed no loss performances in terms of production capacity and water quality produced. In addition, mechanical properties of the membrane material over time did not show any important losses [Laîné, *et. al.* 2000]. Existing UF membrane plants worldwide treated various source of raw water, *e.g*, groundwater, surface water, clarified surface water, to produce drinking water with the capacity 0.01-14.53 gpd. Some are located in France, UK, US, Tahiti, and Japan [Anselme & Jacobs, 1996].

As mentioned before, application of UF for drinking water supply can be in form of single operation, *i.e.,* without any pre-treatment except a common screen filter [Clever, *et. al.* 2000]. UF can be used on its own for treating drinking water where the feed water is not too high in terms of organic content [Laîné, *et. al.* 2000]. Membrane filtration has become the preferred alternative to conventional technology to remove water-borne pathogens in the preparation of drinking water [Cote, *et. al.*, 2002]. Therefore, it is possible to reduce the necessity of water disinfection after the treatment process [Konieczny & Klomfas, 2002]. UF technology has been found to exceed current water regulation for turbidity, *Giardi*a, and also virus removal [Laîné, *et. al.* 2000]. Removal of viruses and bacteria using UF could achieve a percentage removal 90-100% [Anselme & Jacobs, 1996, Edwards, *et.al.,* 2001].

Apart of the increasing number of UF plant, fouling and membrane costs are still the main limitations to UF development and widespread use [Choksuchart, *et. al.* 2002; Park, *et. al.* 2002]. However the cost of UF technology has significantly decreased within past five years. Capital costs were found to depend not only on the raw water quality (flux) and the plant capacity but also on the year on construction [Laine, *et. al.* 2000]. The term fouling includes the totality of phenomena responsible for decreases of permeate flux over a period of time, except those linked to membrane compaction and mechanical characteristics modification [Anselme & Jacobs, 1996]. Numerous research studies have been conducted to study the mechanisms and factor affecting flux decline as related to the fouling phenomenon including main source of fouling during membrane processes.

Several researchers have studied effects of fouling materials, that is, clay-organic subtances, humic acid, microbial decomposition products, on the fouling of membrane [Kim, *et.al,*, 1994; Kim, *et.al.*, 1996; Bian, *et.al.*, 1999, Maartens, *et.al.*, 1999; Domany *et.al.*, 2002]. Teixeira, *et. al.* (2002) found the important role of the pH on the UF performance controlling the interactions of membrane with fouling matter. Natural organic matter (NOM) rejection and NOM transport across the membrane also had been studied [Cho, *et. al.* 2002]. Natural organic matter present in raw water not only impart colour to water, but can also cause health risks associated with disinfections by-products (DBP). The most common DBPs found in drinking water are trihalomethanes (THMs) and haloacetic acids (HAAs), which are formed when NOM reacts with chlorine or chlorine based disinfectants [Best, *et. al.* 2001]. Membrane processes allow the reduction or elimination of NOM (*e.g.* humic acid, fulvic acid) as THM precursors and prevent the formation of substances posing hazards to human health [Konieczny & Klomfas, 2002].

In cases where the feed water contains high turbidity levels or high fouling tendencies, combination with conventional pre-treatment (adsorption, coagulation, oxidation) is required to allow the membranes to operate efficiently [Thompson, 2001]. UF alone also is not very effective for removing DBPs and dissolved substances in general, and have limited capability in removing organic matter. The use of powdered activated carbon (AC) in combination with UF membrane is attracting increasing interest for the removal of organic compounds in drinking water treatment [Campos, *et. al.* 2001]. This hybrid process utilizes the capabilities of activated carbon to adsorption of impurities and the microorganisms and particles removal ability of the membranes [Konieczny & Klomfas, 2002]. Coupled with PAC, UF can be used to treat groundwater contaminated by micropollutants such as pesticides or surface water with high organic matter load [Laine, *et. al.* 2000]. Effect of filtration time, membrane reactor volume, carbon dosing procedure, carbon dose and carbon particle size on the adsorption removal of selected micro pollutants and dissolved organic matter has also been studied [Campos, *et. al.* 2001; Brasquet, *et.al.*, 1996; Matsui, *et.al.*, 2001]. Yuasa (1998) found that combination of UF with PAC/GAC could improve the removal of organics and other micropollutants such as agrochemicals. Currently there are already several installations of water treatment plant that has been applied using hybrid of AC/UF with the capacity range from 200-65.000 m^3/day [Laine, *et. al.* 2000].

Combination of coagulation/UF can also be considered for surface waters containing fairly high level of organics and also to minimize membrane fouling potential [Laîné, *et. al.* 2000]. Coagulation pre-treatment may enhance permeate flux by reducing foulant penetration into membrane pores, conditioning the layer of materials deposited on the membrane, and improving particle transport characteristics [Wiesner & Laîné, 1996]. Guigui, *et.al.* (2001) reported that the addition of coagulant before UF unit with or without settling may increase NOM removal for a better reduction of DBP. Determination of optimum coagulation condition, removal efficiency, effect of configuration and module design of combination UF/coagulation has also been studied [Park, *et.al.,* 2000; Galjaard, *et.al.*, 2001; Park, *et.al.,* 2002].

Other potential application of UF is the production of ultrapure water. Usually, UF is act as pre-treatment of RO unit to produce ultrapure water. However, Oosterom, *et. al.* (2000) proposed an innovative alternative process to use rainwater followed by low-pressure MF/UF to produce demineralised water.

Recently, membrane technology has been considered as an alternative water treatment in aquaculture [Wenten, 2004]. A sufficient supply of good quality water is essential to any aquaculture operation. Water quality affects reproduction, growth, and survival of aquatic organism. The criteria for good quality water established by safe level of physical, chemical and biological properties of water, which have significant adverse effects on aquatic organism growth and survival. To increase the quality of water input, the use of UF will surely retain the pathogen and generate highly free pathogenic water. As the UF pore size still allowed ions to pass the membrane pore, the use of UF to treat seawater for example in shrimp culture is perfect. A study showed that growth rate, survival rate and production of Black Tiger Shrimp *Penaeus monodon* postlarve is directly influenced by water quality and hygienic condition in culture system [Fast & Wang, 1992; Wanichpongpan, 2003]. Therefore, in aquaculture system, UF is needed to reject suspended solid and pathogenic microorganism from the culture water [Wenten, 2004].

VI. THE REVERSE OSMOSIS SYSTEM

One of the first membrane applications for the utilization of membrane technology was the conversion of seawater into drinking water by reverse osmosis (RO). RO system separate dissolved solutes (includes single charged ions, such as Na^+, Cl^-) from water via a semipermeable membrane that passes water in preference to the solute. RO can be described as diffusion-controlled process in which mass transfer of ions through RO membranes is controlled by diffusion. Physical holes may not exist in an RO membrane, which distinguishes RO membrane with other filtration system. RO membrane is very hydrophilic; therefore water will be able to readily diffuse into and out of the polymer structure of the membrane. RO membrane is capable of rejecting contaminants as small as 0.001 μm [Taylor & Jacobs, 1996].

Four types of modules are used for RO membrane, *i.e*., plate and frame, tubular, hollow fiber, and spiral wound. However, the spiral-wound element is the most common by far for the production of drinking water. RO configurations include single stage, two stages, and two-pass systems. The selection among these configurations depends on the desired quality of the product water. The pass system gives the highest purity product and it is suitable for preparation of make-up boiler water. The single stage system is the simplest layout and quite common for use on various desalination applications. Meanwhile, the two-stage system is common for brackish water use where it is necessary to increase the overall recovery ratio [Fawzi & Al-Enezi, 2002].

Nowadays, RO system has become a popular water treatment technology in industry requiring separation of dissolved solute from its solvent (water) including desalination and also, residentially, to improve the taste of water as well as to remove potentially unhealthy contaminants. RO has increased the water supply by making possible the use of brackish waters for potable water supply. Desalination using RO has become a major source to produce fresh water in many arid regions including remote area where the fresh water is hardly found. Recent advances particularly in improvements of the membrane materials and pre-treatment have meant that RO desalination has now become economically attractive even at seawater concentrations [Buckley & Hurt, 1996]. The scale of membrane applications is now very large, plants with capacity in excess of 19,000 m^3/d are common [Buckley & Hurt, 1996].

The success of RO technology has been due mostly to the economics of its operation and to its simplicity. Rapid developments in RO membrane are addressed to new membrane working at lower pressure and increasing salt rejection from the original cellulose acetate membrane requiring 28 bar to modern polyamide thin-film membranes requiring only 7 bar net driving pressure. The increase of salt rejection of RO membrane from 97 to 99.5% with some special membrane types exhibiting even higher separation efficiency [Nicolaisen, 2002]. Bryne (1995) also noted that newer membranes, because of its ability to reject more salts and pass more water at a particular pressure, is having greater energy efficiency. The simplicity of RO desalination process layout compare with the large-scale thermal desalination process is also one of the main attractive feature of RO system. Its modular design allows for simple expansion and increase of the production capacity. Specific power consumption of RO is low, around 5 kWh/m^3. This amount is almost equivalent to the pumping power for the major thermal desalination process, which include MSF and ME [Fawzi & Al-Enezi, 2002].

Yet, available RO membranes are generally not robust enough to operate directly on surface feed seawater [Ebrahim, *et.al.*, 2001]. RO membranes are more sensitive than thermal desalination processes to scaling, fouling, chemical and biological attack. The susceptibility to fouling is one major shortcoming of RO membrane. Hence, RO has developed into an energy efficient alternative to thermal processes but it still continues to face competition due to the requirements of pre-treatment as shown in Figure 6.

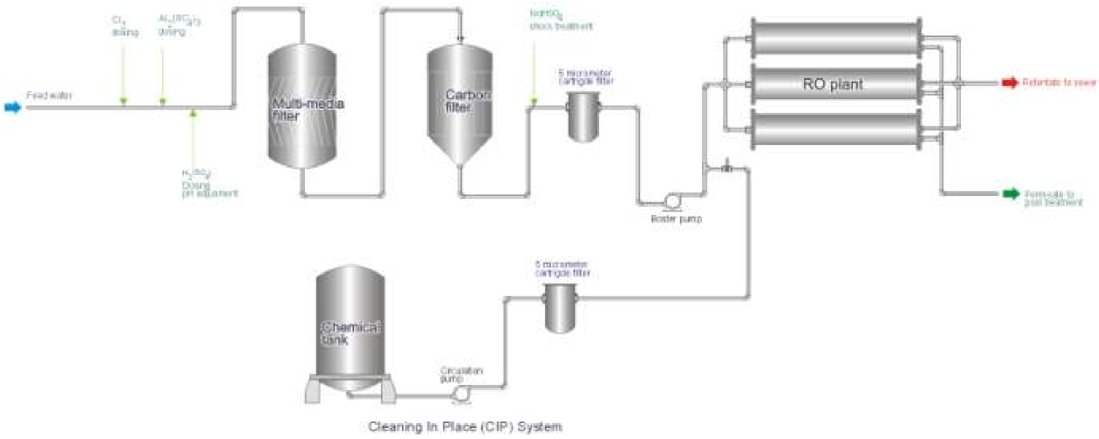

Fig. 6. Extensive pre-treatment of RO system

VII. IMS, INTEGRATED MEMBRANE SYSTEM

The successful long-term performance of RO seawater desalination plant is highly depend on proper pre-treatment. Pre-treatment of RO system is designed to prevent fouling of the membrane, maintain performance of the system, and extend the lifetime of the membranes [Ebrahim, *et.al.*, 2001]. The selection of pre-treatment RO system is based on the raw water quality, the reliability, the investment cost, and the RO membrane type [Glucina, *et.al.*, 2000].

Where potential fouling waters are the only available source for processing into high purity water as in marginal waters, the conventional pre-treatment process methods may not be adequate. Marginal waters are difficult to treat due to the fouling problems that can occur with insufficient pre-treatment in a membrane plant [Redondo, 2001]. High fouling surface water and low fouling beach well water sources need different complexity of pre-treatment. As in the case of direct seawater intake or municipal wastewater reuse, extensive pre-treatment is required up-stream the RO process compare with beach well water.

As mentioned before, pre-treatment of process water before RO is very important for membrane life and the economical operation of the RO plant [Anselme & Jacobs, 1996]. Pre-treatment by conventional means (*i.e.*, coagulation, flocculation, and media-filtration) is known to be complex, labour intensive and space consuming. Many SWRO (sea water RO) plants operate successfully for many years with conventional pre-treatment [Prato, *et.al.,* 2000]. However, if conventional pre-treatment is not designed and operated carefully, RO plants can have problems with membrane fouling [Hasim, *et.al.,* 1999].

Primarily, the development of UF technology in water application is focused in producing filtrate for drinking water [Bates, 1999]. Recently, UF has become an efficient pre-treatment for reverse osmosis (RO) system [Clever, *et.al.,* 2000]. It is important to re-evaluate the cost and operating benefits of UF as pre-treatment particularly for high fouling feed water source such as surface water, a wastewater, or an open-intake seawater [Bates, 1999]. A system designed with a MF/UF membrane system as pre-treatment prior to RO system has been referred to as an Integrated Membrane System (IMS) [Bates, 1999; Nederlof *et.al.*, 2000]. IMS combines the advantages of UF for particle removal with the selectivity of RO [Glucina, *et.al.*, 2000]. IMS to achieve the water quality objectives is considered very seriously, and several studies are currently on going to evaluate the feasibility of such dual membrane system [Laîné, *et. al.*2000]. A major reason for the re-emergence of UF technology has been improvements in the control of fouling during the service operation by the use of short-duration periodic backwashing. Periodic backwashing is designed to minimize the need for chemical cleaning to once every month to six months [Bates, 1999]. The IMS design approach to water treatment systems has some significant advantages over RO systems designed with conventional pre-treatment. The important features of UF pre-treatment are continuous and easily automated operation, no breakthrough as occurs in granular media filtration, good downstream protection of RO membranes, no addition of chemicals, simple chemical shock disinfections treatment and compact design of pre-treatment equipment [Heyden, 1985].

The pre-treatment of feed water prior to RO is intended to lower the silt density index (SDI), remove excessive turbidity or suspended solids, and adjust and control the pH [Ebrahim, *et.al.*, 2001]. The SDI is the most widely used fouling index. The SDI of feedwater of an RO plant should be less than 2 to minimize the rate of colloidal fouling [Taylor & Jacobs, 1996]. The significantly lower SDI filtrate produce by UF membrane as RO pre-treatment have also been proven by several researchers. The quality of feed water produced by the UF system, operating parallel with the conventional system, was very little affected by the fluctuation of the seawater quality [Glueckstern, *et.al.*, 2002]. The surface seawater SDI of 13-25 was reduced to below 1 whereas the conventional pre-treatment failed to reduce it below 2.5 [Brehant, *et.al.*, 2002]. A pilot plant conducted by Van Hoof (2001) showed that UF membranes used for RO pre-treatment produced water with SDI_{15} values as low as 0.4 and showed stable operation. Glucina, *et.al.* (2000) also found that UF could produce filtrate with the average SDI of 1.2, a reasonably low value when compared to the maximum advised by the RO membrane manufacturer. Good quality of RO feed make it possible to reduce RO cleaning frequencies due to colloidal fouling.

The dead-end UF mode coupled with operation at low pressure allowing very low power consumption, approximately 0,1 kWh per m^3 of permeate [Teuler, *et.al.*, 1999]. UF system also require less time and is easier to operate than some conventional filtration processes, particularly those prone to system upsets. UF concentrated waste streams are easier to dispose of relative to chemically enhanced conventional pre-treatment processes [Bates, 1999]. Drioli, *et.al.*, (2000) also mentioned that an interesting way for further reducing fouling phenomena and extending the life time of RO membranes is related to the use of UF for pre-treatment. The field test results of UF membrane pre-treatment, tested at two different sites confirm that the membrane pre-treatment is reliable technology capable of providing consistently good quality feed water for RO seawater system independently of the raw water quality fluctuation [Glueckstern, *et.al.*, 2002]. Meanwhile, the specific flux of the UF membrane also remained stable as found by Teuler, *et.al.* (1999). Truby (2000) pointed out that UF pre-treatment increases the RO flux of 20% with respect to conventional pre-treatment.

The IMS system choice depends on the fouling properties of the feed water, which may necessitate additional (pre) treatment and the local circumstances. Additional pre-treatment inevitably leads to extra investment costs. However operating and maintenance costs may be lower due to a more stable system performance with lower cleaning frequencies and longer life time of the membranes [Nederlof, *et.al.*, 2000]. Typically the only pre-treatment requirement to UF system is course filtration by the use of strainers rated at 100 to 150 micron. Occasionally the use of a coagulant aid like a ferrous salt is considered [Bates, 1999]. The combination of UF with a pre-coagulation at low dose helped in controlling the UF membrane fouling and providing filtered water in steady state condition [Brehant, *et.al.*, 2002]. The seawater system operating with UF membrane pre-treatment can be designed to operate at the higher limit of the permeate flux range due to the very low concentration of suspended solids in the UF filtrate [Glueckstern, *et.al.*, 2002]. Ability to operate RO seawater unit at higher flux and recovery rate enables optimisation of the RO process and reduction of water cost [Glueckstern, *et.al.*, 2002].

The reason why the trend of pre-treatment RO system goes for integrated membrane system are mainly feasibility, process reliability, plant availability, modularity, relative insensitivity in cases of raw water changes and lower operating costs. UF allows the membrane inventory of an RO plant to be reduced by some 20% and have simplified the RO pre-treatment process resulting in lowering the operating costs of the plants [Redondo, 2001]. Leslie, *et.al.*(1998) reported a reduction of operating and maintenance costs of water treatment for providing potable water of 39% when MF or UF replaces conventional RO pre-treatment. Truby (2000) reported UF as pre-treatment RO leads to a significant reduction of RO capital costs (from US $ 2-4/gal of capacity to US $ 1.75-3.25/gal of capacity). Bates (1999) reported that operating costs and chemical costs are competitive and in some scheme less. The demand of UF system as pre-treatment for RO will be accentuated by the increasing scarcity of low-fouling feed water sources (well water) and the need to treat more difficult feed water sources (surface waters, industrial wastewater, and municipal sewer waters). In future the coagulation-sedimentation-filtration (CSF)-UF-RO scheme will compete with the CSF-SSF (slow sand filtration) scheme as estimated by Nederlof, *et.al.* (2000).

Although UF provides high quality feed water for RO, the UF design was generally dismissed as commercial alternative to conventional pre-treatment for a number of reasons, *i.e.*, capital costs were too high for treatment of surface waters. Glueckstern, *et.al.* (2002) reported that the cost of membrane as pre-treatment is more expensive than the conventional pre-treatment. As cited by Redondo (2001) from several authors, the application of IMS is currently not frequently used to lower costs although this may change. However, since the energy requirement is very low, consequently the cost is mainly directed to the membrane price. Nowadays, the UF membrane price has gone far down, even below conventional treatment system with the new coming Asian membrane industries. Therefore, there is no doubt, UF is now becoming a competitive pretreatment system for RO in a wide range of raw water quality, from excellent to poor quality of raw water.

VIII. CONCLUSION

Ultrafiltration is proven to be a competitive treatment compare with conventional ones. It is the preferred alternative to remove water-borne pathogens in the preparation of drinking water and nowadays, it is commonly used to replace clarification step in conventional water treatment plant. In some cases, the combination of ultrafiltration with conventional process is also feasible particularly for high fouling tendency feed water or for removal of specific contaminants. Recently, ultrafiltration has been recognized as competitive pre-treatment for reverse osmosis system. A system designed with an ultrafiltration as pre-treatment prior to reverse osmosis system has been referred to as an Integrated Membrane System (IMS). The application of IMS is a must for sites require very extensive conventional pre-treatment or where wide fluctuation of raw water quality is expected. Several studies have showed that UF pre-treatment could produce consistently good quality of feed water independently of the raw water quality fluctuation and also increases the RO flux. However, the UF design was generally dismissed as commercial alternative to conventional filtration due to its high membrane cost. Nevertheless, today the UF membrane price has gone far down, even below conventional treatment system with the new coming Asian membrane industries. Therefore, there is no doubt, UF is now becoming a competitive pretreatment system for RO in a wide range of raw water quality.

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