

## Research Article

# Design of Low Energy Integrated Membranes Units for Production of Highly Purified Water

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**Abstract:** Some industries like medical, pharmaceuticals, cosmetics, chemical manufacturing need a special quality of treated water which is called Purified water. Integrated membrane system was designed and developed to produce Purified water grades to serve these industries. A simple engineering design for water filtration through membrane systems was scanned; beginning from carbon filters, followed by different kinds of membranes like microfiltration, ultrafiltration, nanofiltration and reverse osmosis membrane. These units were developed according to membranes type and the produced water quality before and after each unit. The produced water and its quality control tests were compared with the World Health Organization water quality standard. The produced water from the integrated membrane system has total dissolved solids (TDS) reached 0.95 mg/L, which matched with the World Health Organization water quality standard.

**Keywords:** purified water, membranes system, quality control, ultrafiltration, microfiltration, nanofiltration, reverse osmosis

## 1. Introduction

There are different kinds of filtration techniques that can be used to produce the different grades of pure and ultrapure water required for advanced and precise industries such as pharmaceutical food industries and for laboratory analysis using [1-5]. Pure water can be defined in terms of various parameters, including resistivity, microorganism content, pyrogen (endotoxins) levels, reactive silica levels and total organic carbon (TOC) levels [1-4]. There are at least five grades of pure water depending on various standards and conventions, which are illustrated in Table 1 [1-3]. Each grade of pure water can be used in a number of various applications such as [1]:

- Deionized water: used for medium pressure boiler feed, renal dialysis make-up, and battery top-up.
- Purified water: used for pharmaceuticals, cosmetics, chemical manufacturing.
- Pyrogenic water: used for vial washing, tissue culture, water for injections.
- High Purity water: used for high-pressure boilers, combined heat and power systems, laboratories.
- Ultrapure water: used for microelectronics, supercritical boilers.

The most commonly used technologies for water treatment to reach different water treatment grade are membranes, ultraviolet (UV) emission technology, ion exchange technologies [3-8].

The use of ultraviolet (UV) emission technology is widespread in pure water production, especially, for application

needs water with low total organic carbon levels, such as in purified, pyrogenic and ultrapure water applications. Research and development over recent years have shown that short wavelengths (190-195 nm) are highly effective at breaking down organic molecules present in pure water, especially low molecular weight contaminants. UV systems are also used for disinfection, dechlorination, and de-ozonation within pure water treatment processes. Several of the process stages in the manufacture of pharmaceutical products can cause downstream microbial contamination, however, UV can be used as an effective barrier to ensure these microbes remove to do not compromise overall quality requirements [1, 9-11]. Ion exchange technologies are needed for producing high purity water. They also offer the possibility of developing noncorrosive processes due to their eco-friendly nature. Regeneration and handling are the main problems of these units [1-3]. Reverse osmosis (RO) membranes systems combined with other technologies is now the preferred main treatment option in Purified Water production. This is due to many reasons including the security of combination, the TOC limit, easy handling of chemicals and effluent, and microbiological quality [12-13].

Activated carbon is used to purify liquids and gases in a variety of applications, including municipal drinking water, food and beverage processing, odor removal, industrial pollution control, and point-of-use filters in the houses. Activated carbon filter contains three regions: Micropore region-less than 100 Angstroms, Mesopore region-between 100 and 1,000 Angstroms and Macropore region-greater than 1,000 Angstroms.

The contaminants in the water are adsorbed onto the surface of carbon from water due to differences in adsorbate concentration in the feed water and in the carbon pores. The dissolved adsorbate transfer from the solution through the pores channels to reach the area where the strongest attractive forces are located. Besides, physical adsorption chemical reactions can occur on a carbon surface. One such reaction is chlorine removal from water involving the chemical reaction of chlorine with carbon to form chloride ions.

Recently, membrane technology is considered to be a significant way to produce different grades of pure water, according to the feeding water. Treating water using membranes can be performed by using integrated membranes unit [14-20].

Membrane-based processes are widely used for desalination and water treatment. Microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) are the most kinds of membrane technologies. Enhancement of permeate flux, rejection percentage, and antifouling properties are necessary to improve the efficiency of these processes. Ultrafiltration (UF) or microfiltration (MF) technology can be effectively used as a pre-treatment for reverse osmosis (RO) depending on the feeding water quality to the water treatment system. Microfiltration can remove materials such as sand, silt, clays, *Giardia lamblia* and *Cryptosporidium* cysts, algae, and some bacterial species. The deionized water can be easily produced using single-pass RO systems as the final process step with using high rejection (HR) membranes. RO is a cross-flow membrane separation process providing a level of filtration down to ionic levels for removal of dissolved salts [9, 12-13, 15-20]. According to the feeding water quality RO membranes can be formed in an array system to give an overall concentrate stream flow as low as 10% of the feeding supply, equating to an overall system recovery of up to 90%. The salts in the water feeding supply will be concentrated in the reject stream and must be treated by subsequent processes onsite or discharged to the sewerage system for further treatment. Individual RO membranes typically reject 95-98% of the total dissolved solids (TDS) in the feeding supply, which will reduce the ionic loading onto downstream processes. Also, UF and MF membrane technology can be used for the final polishing of pure water and removal of bacterial endotoxins, bacteria, particles in pharmaceutical pyrogenic and semiconductor applications [3, 7, 21].

The main goal of this article is the development and design of the integration of membranes filtration systems to produce purified water from different water sources.

In the article we studied production of highly purified water which can be used in labs as alternative of distillatory and deionizer using integrated membranes units, so the heating or requirement of excessive treatment for the traditional apparatuses like distillatory and deionizer , that made our system low energy.

## 2. Experimental work

### 2.1 Determination of water source and analysis

The samples were taken from five places of national research center (NRC), Building of Scientific Excellence,

Engineering Research Division, Textile Industries Research Division, The Main Building, and the Agricultural Research Division. The samples were taken from 1/10/2016 to 1/6/2017. The tap water samples were collected in clean and dry glass bottles. Each sample was filtered using Whatman no.42 filter paper and stored in the refrigerator until the analysis time. The analyses of samples were carried out using Agilent ICP-5100 in NRC labs. The TDS and electrical conductivity of the water samples were measured at room temperature using a conductivity meter called Adwa (AD 310), EC/temp meter made in Romania. The pH of water samples also was measured using a Jenway pH meter made in England. The turbidity of the samples was measured by the turbidity meter model Hanna made of Boland.

## 2.2 Design of different integrated lab system of membrane filtration

Lab filtration systems were designed and installed to use our prepared membranes. First, the commercial filtration system was used and commercial membranes which were purchased from Aqua Chiara Company and studied preliminary experiments from tap water filtration. According to the results we designed five integrated systems to study the purity of water.

### 2.2.1 Filtration experiments using commercial filtration system

Tap water from the Building of Scientific Excellence was filtered using a commercial filtration system which purchased from Aqua Chiara Company to indicate the separation elements after each step in this filter as shown in Figure 1. This filter has a microfiltration unit, two activated carbon filters, reverse osmosis membrane and feeding pump with pressure 150 psi. The tap water firstly flows through the microfiltration unit then passes to the activated carbon units and finally goes to the reverse osmosis unit. Samples of water were collected after 1 h from each unit and analyzed. These experiments were carried out to help in the design and determination of the operating conditions.



Figure 1. Commercial filtration unit

## 3. Results & discussions

### 3.1 Determination of water source and analysis

The analyzed results of the samples which were taken from different five places of NRC, Agricultural Research Division (B1), Building of Scientific Excellence (B2), Engineering Research Division (B3), Textile Industries Research Division (B4), and The main Building (B5), were taken from 1/10/2016 to 1/6/2017 were drawn by Pivot table Using Microsoft Office Excel as shown in Table 1. Table 2 illustrates the physical parameters for average analysis of water samples. Also, the statically analysis of these results was studied as shown in Table 3. Figure 2 illustrates the ions percentage in different water samples, where the di-ions are the highest ions in the samples, that means the nanofiltration

membrane can be used in our design to remove divalent ions before reverse osmosis membrane.

The limit of pH value for drinking water is specified as 6.5 to 8.5. While pH value in the studied tap water from a different place of NRC varied from 7 to 7.18. So, the pH value is in the limit of drinking water. Increasing pH provides a bitter taste to water, and causes corrosion for equipment. According to American Society for Testing and Materials (ASTM) D 1193-06, purified water pH is range 5-8 [2].

The total hardness is mostly high in all samples due to the presence of magnesium, iron, chloride and sodium ions. The high amount of hardness in water that can lead to heart diseases and kidney stone formation. Hardness value in the samples varied between 109-117 mg/L. According to ASTM D 1193-06, purified water hardness must be less than 70 mg/l [2].

**Table 1.** Average results of chemical parameters of water samples from different places of NRC

Values (average) (mg/L)	B1	B2	B3	B4	B5	Accepted limit
Chloride	35.5	36.5	34.5	34.5	35	< 250
Sulphate	31	32	34	32	33	< 250
Total Hardness	109	117	112	110	109	< 500
Potassium	4.305	4.17	7.89	4.535	4.735	< 10
Sodium	29.65	30.6	30.76	28.5	27.58	< 200
Magnesium	8.8	10.25	8.85	7.85	7.65	< 36
Calcium	27.75	29.125	27.25	29.7	30.4	< 140
Boron	0.01	0.085	0.07	0.01	0.01	< 0.5
Strontium	0.055	0.15	0.28	0.045	0.04	< 0.5
Iron	0.0001	1.815	1.175	0.0001	0.0001	< 0.3
Aluminum	0.12	0.28	0.39	0.025	0.14	< 0.2
Manganese	0	0.01	0.02	0	0.01	< 0.4
Nickel	0	0	0.01	0	0	< 0.02
Zinc	0	0.33	2.64	0	0	< 3
Arsenic	0.01	0	0	0	0.01	< 0.01
Barium	0	0	0.06	0	0	< 0.7

**Table 2.** Average results of physical parameters of water samples from different places of NRC

Values (average)	B1	B2	B3	B4	B5	Accepted limit
Turbidity (NTU)	0.33	6.7	7.1	0.34	0.41	< 1
TDS (mg/L)	221.5	211.5	213.5	241	225	< 1,000
TSS (mg/L)	0.3	9	10	0.3	0.2	< 100
Conductivity (μs/cm)	452.5	438	462.5	495.5	459	< 1,200
COD (mg/L)	3	4.5	4	2.75	3	< 250
pH	7.03	7.475	7.525	6.925	6.975	6.5-8.5

Where, Agricultural Research Division (B1), Building of Scientific Excellence (B2), Engineering Research Division (B3), Textile Industries Research Division (B4), and The main Building (B5)

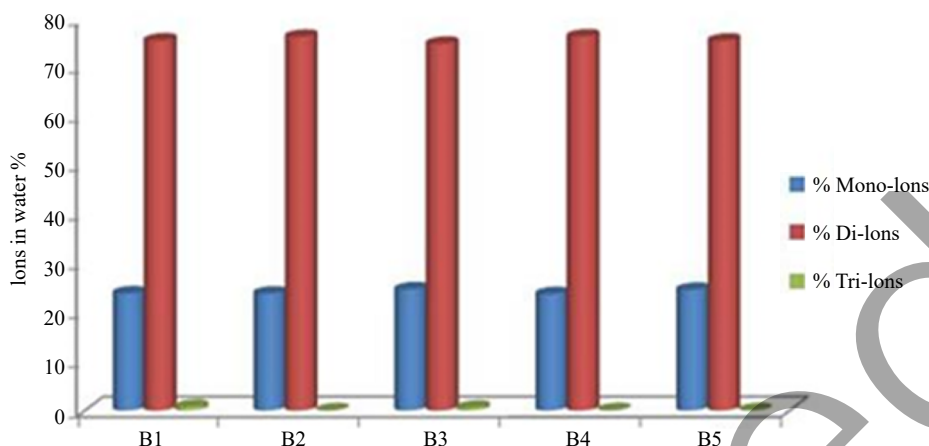


Figure 2. Average percentage of ions on water samples

The iron value in the water samples varied between 0-1.8 mg/L. In European pharmacopeia, iron in purified water must be less than 0.1, while at the US Pharmacopeia iron must be zero [1].

COD in the water samples varied between 3-4.5 mg/L. COD means that there is inadequate oxygen available in the water samples due to the oxidizable inorganic matter. In European pharmacopeia, the COD must be less than 0.5 and for high purity water must be 0%.

Electrical conductivity (EC) of water is a direct function to the total dissolved salts in water and an indication for ions in the water. The conductivity value of the water samples varied between 438 to 462.5  $\mu\text{S}/\text{cm}$ . If water has high conductivity, this means the presence of a high amount of dissolved inorganic substances in the ionized form [1]. EC in European pharmacopeia must be 0.6-4.7  $\mu\text{S}/\text{cm}$ .

High values of TDS in the water samples may affect persons who are suffering from kidney and heart diseases. A high content of dissolved solids leads to the density of water, influences osmoregulation of freshwater organism, reduces the solubility of gases (like oxygen) and decrease the solubility of water for drinking, irrigation, and industrial purposes. TSS and TDS values in the water samples varied between 0.3-10 mg/L, and 221-241 mg/L respectively. In purified water for analyzed purified water, the TDS must be less than 1 mg/L at US Pharmacopeia [1].

### 3.2 Correlation studies

Interrelationship studies between various water quality parameters are very useful in understanding geochemistry of the studied region of water. The regression equations for the parameters contain significant correlation coefficients which can estimate the concentration of other constituents. Table 3a illustrates Correlation coefficient values for total hardness with the influencing elements effect on it. Where, the total hardness indicates significant correlation with chloride, magnesium, sodium, and iron due to the effect of their salts in water. Table 3b indicates that the turbidity significant correlation with sodium, magnesium, iron, boron, and aluminum. Table 3c illustrates that TSS has a significant correlation with sodium, magnesium, boron, iron, aluminum, strontium and manganese, where their salts increase the total suspended solids. Table 3d indicates that COD has a significant correlation with sodium, magnesium, boron, iron, aluminum, strontium and manganese due to the oxidability of these inorganic elements [1, 5].

**Table 3.** Correlation coefficient values of various physico-chemical parameters of water samples from NRC various places

		Chloride	Sodium	Magnesium	Iron	Total hardness			
(a) Total Hardness and their influencing elements	Chloride	1							
	Sodium	0.366614842	1						
	Magnesium	0.794987874	0.845045509	1					
	Iron	0.540622707	0.801383325	0.869738965	1				
	Total Hardness	0.675562228	0.683619915	0.882285967	0.951506988				
(b) Turbidity and their influencing elements		Sodium	Magnesium	Boron	Iron	Aluminum	Turbidity (NTU)		
	Sodium	1							
	Magnesium	0.845046	1						
	Boron	0.828442	0.830080788	1					
	Iron	0.801383	0.869738965	0.991927	1				
	Aluminum	0.765565	0.598753725	0.866444	0.809044	1			
	Turbidity (NTU)	0.839697	0.747606159	0.98346	0.952578	0.925435334			1
(c) TSS and their influencing elements		Sodium	Magnesium	Boron	Iron	Aluminum	Strontium	Manganese	TSS
	Sodium	1							
	Magnesium	0.845045509	1						
	Boron	0.828442262	0.830080788	1					
	Iron	0.801383325	0.869738965	0.991927	1				
	Aluminum	0.76556539	0.598753725	0.866444	0.809044	1			
	Strontium	0.799596865	0.49594833	0.821419	0.742771	0.937879621	1		
	Manganese	0.443348181	0.254859501	0.696022	0.623608	0.905945789	0.851562424	1	
	TSS	0.847261085	0.736556537	0.977524	0.942918	0.929167572	0.922918946	0.787418363	1
(d) COD and their influencing elements		Sodium	Magnesium	Boron	Iron	Aluminum	Strontium	Manganese	COD
	Sodium	1							
	Magnesium	0.845045	1						
	Boron	0.828442	0.830080	1					
	Iron	0.801383	0.869738965	0.991927	1				
	Aluminum	0.765569	0.598753725	0.866444	0.809044	1			
	Strontium	0.7995968	0.49594833	0.821419	0.742771	0.937879621	1		
	Manganese	0.4433481	0.254859501	0.696022	0.623608	0.905945789	0.851562424	1	
	COD	0.8067208	0.873159179	0.986431	0.990389	0.857437397	0.758211693	0.669893845	1

### 3.3 Design of different integrated lab system of membrane filtration

#### 3.3.1 Filtration experiments using the commercial filtration system

Tap water from the Building of Scientific Excellence was filtered using a commercial filtration system to indicate the separation elements after each unit as shown in Table 4. The system consists of microfiltration membrane, two activated carbon filters and Reverse osmosis membrane. The analysis of water was recorded after each step and compared with feeding water from the center of excellence labs.

**Table 4.** Analysis of water after treatment by commercial filtration system

Parameter	Unit	Tap water	After MF	After AC1	After AC2	After RO membrane
Chloride	mg/L	27	27	27	27	20
Nitrate	mg/L	ND	ND	ND	ND	ND
Nitrite	mg/L	ND	ND	ND	ND	ND
Sulphate	mg/L	32	32	32	32	8
Bicarbonate	mg/L	102	100	100	100	28
Carbonate	mg/L	0	0	0	0	0
Total Hardness	mg/L	102	88	66	66	0
Silica	mg/L	ND	ND	ND	ND	ND
Potassium	mg/L	78	75	75	75	15
Sodium	mg/L	55	55	55	55	21
Magnesium	mg/L	7	5	4.8	4.7	0
Calcium	mg/L	26.5	26	18.4	18	0
Turbidity	NTU	6.7	1	1.45	1.15	0.6
pH		7.2	7.1	8.5	9	7.5
EC	ms	426	338	336	335	100
TDS	mg/L	203	183	180	178	51
COD	mgO <sub>2</sub> /L	3	3	3	3	2
TSS	mg/L	9	8	8	8	0.02
Boron	mg/L	0.06	0.05	0.05	0.05	0.03
Strontium	mg/L	0.28	0.27	0.27	0.25	0.25
Fe	mg/L	1.2	1.2	1.1	1.1	0.65
Al	mg/L	0.45	0.45	0.44	0.43	0.1
Mn	mg/L	0.01	0.01	0.01	0.01	0.001

##### 3.3.1.1 Microfiltration step

The first step is Microfiltration where the Microfiltration is a membrane with a pore size of approximately 0.03 to 10 microns; in this case, the pore size of the membrane is 5 µm. It was worked at low feed water operating pressure



of approximately 100 to 400 kPa (15 to 60 psi). Microfiltration can remove materials such as sand, silt, clays, *Giardia lamblia* and *Cryptosporidium* cysts, algae, and some bacterial species. Accordingly, MF can control the microorganisms in water. MF can be used as a pretreatment to RO or NF to reduce fouling potential. Table 4 indicates the analysis of water after the microfiltration step. The results indicated that using commercial microfiltration membrane to treat tap water reduce turbidity from 6.7 NTU to 1 NTU, which means the colloidal materials, bacteria and any suspended materials were separated by 85%. But total suspended solids (TSS) decreased from 9 mg/L to 8 mg/L, (11% separation percentage) which was a very low percentage of separation.

### 3.3.1.2 An activated carbon step

The experiments were carried out, where the water passes through microfiltration firstly and two activated carbon filters secondly. Table 4 indicates the analysis of water after activated carbon filters and compared with feeding water in the center of the excellence lab. The experiments result indicated that all analysis of water elements had a high percentage, where the turbidity decreased than feed (6.7 NTU) to be 1.45 NTU after first activated carbon and 1.15 after second activated carbon.

### 3.3.1.3 Reverse osmosis membrane

Reverse osmosis can effectively remove approximately all inorganic contaminants from water. RO can also effectively remove all contamination from water. But it is more effective when used in series with multiple units [9-10, 13, 19-21].

The experiments were carried out, where the water passes through micro filtration firstly and two activated carbon filters secondly and finally RO unit.

Table 4 indicates that the elements of water decreased after the RO membrane. The hardness as calcium and magnesium were removed completely. But removing sodium was 50% and TDS separation was from 203 to 51 mg/L which means 75% separation percentage. To reach purified water which can be used in research studies TDS must be less than 1 mg/L.

### 3.3.2 Design of integrated lab membranes filtration system

The integrated system of membrane filters was designed, where the designed system has a pressure pump after ultrafiltration unit to increase the pressure for nanofiltration and reverse osmosis units.

Our prepared membranes were fabricated to reach the high quality of purified water. According to preliminary results for water treatment of tap water in the center of excellence labs after commercial filtration system using commercial membranes. We have designed membrane-integrated systems to study the purity of water as shown in Figure 3.

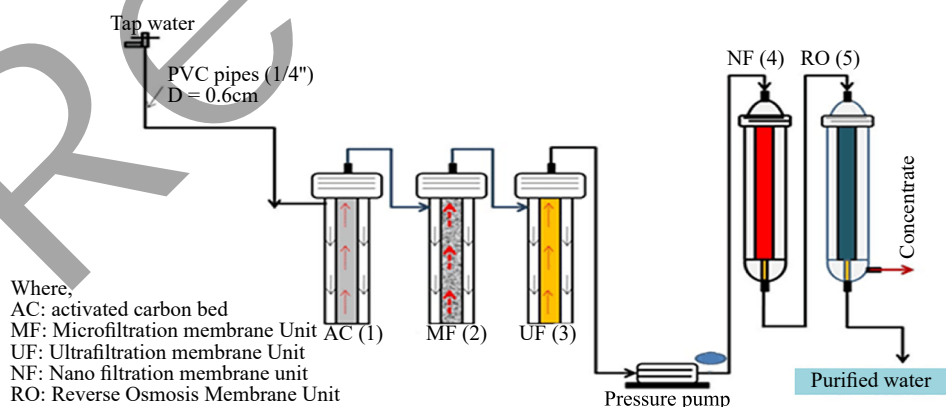


Figure 3. Schematic drawing for integrated membrane filtration system design for water purification



The integrated filtration system design composed of an Activated Carbon unit, Microfiltration unit, Ultrafiltration unit, Nanofiltration Unit and Reverse Osmosis Unit. The Design was built on the commercial applied size of membrane housing in the local market because spiral wound membranes were produced in standard size like commercial and imported spiral wound size, which is considered as international size. So, this can facilitate the application of these standard modules in this work.

### 3.3.2.1 Design concepts of membrane units

There is a number of general concepts that are applicable to all kinds of pressure-driven membrane systems, which serve as the underlying basic principles of system design and operation. These concepts include flux, recovery and flow balance. Membrane filtration system productivity is typically characterized by the system flux, which is defined as the filtrate flow per unit of membrane filtration area, as shown in Equation 1 [11, 22-23]:

$$J = \frac{Q_p}{A_m}. \quad (1)$$

Where:

$J$  = flux ( $\text{L}/\text{m}^2 \cdot \text{h}$ ).

$Q_p$  = filtrate flow ( $\text{L}/\text{h}$ ).

$A_m$  = membrane surface area ( $\text{m}^2$ ).

The recovery of a membrane unit is defined as the amount of feed flow that is converted to filtrate flow, expressed as a decimal percent, as shown in Equation 2:

$$R = \frac{Q_p}{Q_f}. \quad (2)$$

Where:  $R$  = recovery of the membrane unit (%).

$Q_p$  = filtrate flow produced by the membrane unit ( $\text{L}/\text{h}$ ).

$Q_f$  = feed flow to the membrane unit ( $\text{L}/\text{h}$ ).

A general flow balance that can be applied to all membrane filtration systems is shown in Equation 3:

$$Q_f = Q_c + Q_p. \quad (3)$$

Where:  $Q_f$  = feed flow to the membrane unit ( $\text{L}/\text{h}$ ).

$Q_c$  = concentrate flow from the membrane unit ( $\text{L}/\text{h}$ ).

$Q_p$  = filtrate flow from the membrane unit ( $\text{L}/\text{h}$ ).

(a) Microfiltration and Ultrafiltration.

MF and UF are characterized according to the ability to separate suspended or colloidal particles through a sieving mechanism based on the size of the membrane pores relative to that of the particulate matter. However, Membranes have different pore size distribution depending on membrane materials and fabrication processes. MF membranes are generally having a pore size range of 0.1-10  $\mu\text{m}$  (nominally 0.1  $\mu\text{m}$ ). UF membranes pore sizes generally range from 20 nm-0.05  $\mu\text{m}$  [11, 22-23].

The driving force for the water transport across a microporous membrane-like MF and UF is a pressure gradient across the membrane, or TMP, which is mean the pressure on the feed side of the membrane minus the filtrate pressure, generally called the backpressure, as shown in Equation 4:

$$TMP = P_f - P_p. \quad (4)$$

Where:  $TMP$  = transmembrane pressure (psi).

$P_f$  = feed pressure (psi).

$P_p$  = filtrate pressure (i.e., back pressure) (psi).

Using standard area of MF and UF filter was 378.84 cm<sup>2</sup>, feed pressure was 72.5-116 psi, filtrate pressure was approximately 69.6-114.5 psi, TMP was 2.9 psi and flux was 46.4 L/m<sup>2</sup>·h. According to the commercial filtration unit size, the microfiltration unit has a cylindrical shape with a diameter of 10 cm and length 28 cm with screw cap from the top of the housing and the material of construction of housing was reinforced PVC. In this design, UF membrane housing was the same as MF housing.

(b) Nanofiltration and reverse osmosis membranes.

NF/RO membranes were designed to separate dissolved solids through the process of reverse osmosis. The flow of solution continues until the chemical potentials (or concentrations, for practical purposes) on both sides of the membrane are equal. The pressure which must be applied to the more concentrated solution to stop this flow of water is called osmotic pressure [24].

In NF and RO processes driving force for water transport across a semipermeable membrane is a pressure gradient across the membrane. The producing osmotic pressure gradient from NF and RO which acts against the transport of water from the feed to filtrate side of the membrane should be taken into consideration. The net driving pressure (NDP) depending on TDS on the feed and filtrate sides of the membrane can be calculated using Equation 5:

$$NDP = \left[ \left( \frac{P_f + P_c}{2} \right) - (P_p) \right] - \left[ \left\{ \left( \frac{TDS_f + TDS_c}{2} \right) - TDS_p \right\} * 0.01 \right]. \quad (5)$$

Where:  $NDP$  = net driving pressure (psi).

$P_f$  = feed pressure (psi).

$P_c$  = concentrate pressure (psi).

$P_p$  = filtrate pressure (i.e., back pressure) (psi).

$TDS_f$  = feed TDS concentration (mg/L).

$TDS_c$  = concentrate TDS concentration (mg/L).

$TDS_p$  = filtrate TDS concentration (mg/L).

Equation (5) represents the differences between the average pressures on the feed side of the membrane and the filtrate back pressure; the second term represents the average osmotic backpressure. The number 0.01 represents the conversion factor in the osmotic pressure term comes from a widely used rule of thumb for fresh and brackish water indicating that there is approximately 1 psi of osmotic pressure for every 100 mg/L of TDS. However, in many cases, the filtrate TDS concentration ( $TDS_p$ ) is small and can be neglected.

The concentration effect is characterized by the volumetric concentration factor (VCF), a dimensionless parameter representing the ratio of the concentration of suspended solids on the feed side of the membrane relative to that of the influent feed to the membrane filtration process, as shown in Equation 6:

$$VCF = \frac{C_m}{C_f}. \quad (6)$$

Where:  $VCF$  = volumetric concentration factor (dimensionless).

$C_m$  = concentration of suspended solids maintained on the feed side of the membrane (number or mass/volume).

$C_f$  = concentration of suspended solids in the influent feed water to the membrane system (number or mass/volume).

### 3.3.2.2 Plug flow unit model

Assumption of hydraulic configurations of membrane filtration systems.

The term hydraulic configuration is used to explain the manner, where the feed water and suspended solids are processed by a membrane filtration system. The hydraulic configuration of a system is determined from operational

conditions such as backwash, concentrate flow and recycle flow, where applicable. The considered hydraulic configuration mode is suspension mode (crossflow mode) [11, 22-26].

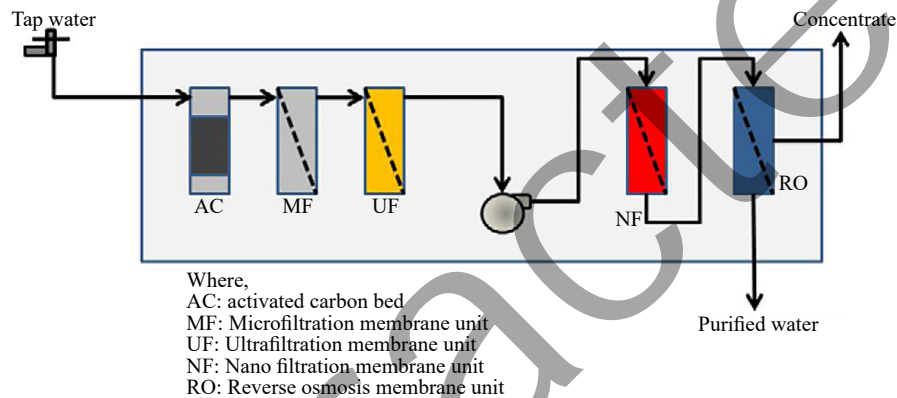
Three basic assumptions for the various hydraulic configurations in which membrane filtration systems can operate and present the associated equations used to determine the respective volumetric concentration factor (VCFs):

If a hydraulic force tangential to the membrane surface is absent, suspended particles in the feed stream are deposited on the membrane and held in place by the TMP.

If a hydraulic force tangential to the membrane surface is found, significant suspended particles remain in suspension, providing in elevated concentrations of suspended particulate matter on the feed side of the membrane. Increasing concentration is characterized by the VCF, which can vary as a function of position and/or time for various hydraulic configurations.

The membrane is a complete barrier to the passage of the particulate contaminants assuming fully integral conditions.

Membrane filtration systems that operate as PFUs have a VCF that varies as a function of position in the system. The designed filtration systems include spiral-wound modules NF/RO systems and MF/UF systems connected in a continuous mode as shown in Figure 4.



**Figure 4.** Flow diagram for plug flow units for filtration systems

The concentration of suspended solids on the feed side of the membrane in a PFU can be expressed as a function of the recovery at any position within the system, as shown in Equation 7:

$$C_m(x) = \frac{C_f}{1 - R(x)}. \quad (7)$$

Where:  $C_m(x)$  = concentration on the feed side of the membrane at position  $x$  in the membrane unit (number or mass/volume).

$x$  = position in the membrane unit in the direction of tangential flow (i.e.,  $x = 0$  at the entrance to the first module).

$C_f$  = feed concentration at the inlet to the membrane unit (number or mass/volume).

$R(x)$  = recovery as a function of position within the membrane unit (decimal percent).

Equations 6 and 7 can be combined to create an expression for the VCF as a function of position in a PFU, as shown in Equation 8:

$$VCF(x) = \frac{1}{1 - R(x)}. \quad (8)$$

Where:  $VCF(x) = VCF$  as a function of position in the membrane unit (dimensionless).

$x$  = position in the membrane unit in the direction of tangential flow (i.e.,  $x = 0$  at the entrance to the first module).  
 $R(x)$  = recovery as a function of position within the membrane unit (decimal percent).  
 A flow-weighted average can be computed using numerical techniques, as shown in Equation 9 [11]:

$$VCF(avg) = \frac{\sum [VCF(x) * Q_p(x)]}{Q_p} \quad (9)$$

Where:  $VCF_{avg}$  = (flow-weighted) average  $VCF$  (dimensionless)  $VCF(x) = VCF$  at discrete position “ $x$ ” within the membrane unit (dimensionless).

$x$  = position in the membrane unit in the direction of tangential flow (i.e.,  $x = 0$  at the entrance to the first module).

$Q_p(x)$  = filtrate flow at position “ $x$ ” within the membrane unit (L/h).

$Q_p$  = total filtrate flow from the membrane unit (L/h).

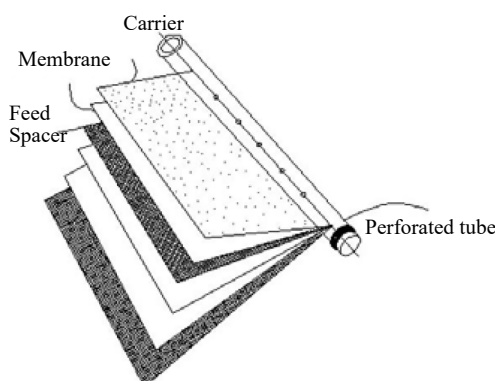
Both the maximum and flow-weighted average VCFs (as calculated using Equations 8 and 9, respectively) for a typical NF/RO system over a range of overall system recoveries from 70 to 99 percent are summarized in Table 5.

**Table 5.** Summary of VCF Values for NF/RO System Modeled as a PFU

Recovery %	Avg	VCF	Max
70	1.73	-	3.33
75	1.86	-	4
80	2.02	-	5
85	2.25	-	6.67
90	2.56	-	10
95	3.16	-	20

Using standard area of NF and RO filter was 378.84 cm<sup>2</sup>, feed pressure was 145-250 psi, filtrate pressure was approximately 138-210 psi, TMP was 7.2 psi and flux was 26.4 L/m<sup>2</sup>·h. According to the commercial filtration unit size, the nanofiltration and Reverse osmosis unit have the same structure of commercial. The material of construction of housing was reinforced PVC.

The flat sheet membranes which were prepared were used in the fabrication of spiral wound membranes in size 29.85 cm length and 4.57 cm diameter to be the same size of commercial membranes in the market.



**Figure 5.** Elements of spiral wound modules



**Figure 6.** Spiral wound machines in NRC

The spiral wound membrane is cylindrical configuration and it is considered essentially a flat-sheet, cross-flow device. The feedwater passes through the module axially, while permeate moves in the spiral, radial direction toward the permeate collection tube. Using spiral wound modules provides cost reduction but more often by the desire to extract the full value of the latest membrane technologies. There are five major non-membrane components of the spiral wound module as shown in Figure 5; Feed Spacer; Permeate Spacer and Permeate Tube. These components with membranes were rolled using machines as shown in Figure 6.

### **3.4 Comparison between commercial filtration system and integrated system**

Tap water from the Building of Scientific Excellence was filtered using new integrated system, where the water flows through the activated carbon filter, microfiltration membrane, ultrafiltration membrane then nanofiltration and reverse osmosis membrane, where these membranes were prepared in our lab as shown in Figure 7. The commercial filter results indicated that TDS reached 51 mg/L, while after an integrated filtration system with using nanofiltration and reverse osmosis membrane the TDS reached 0.95 mg/L, which matched with the World Health Organization water quality standard.



**Figure 7.** Prepared filters in NRC lab

## **4. Conclusion**

Purified water is most important for some applications in industries and scientific application like medical,

pharmaceuticals, cosmetics and chemical manufacturing which needs a special quality of treated water.

In this study, Water samples were collected from five locations of the National Research Centre; and analyzed to detect the most common problems in water and to determine the way for treatment.

Interrelationship studies was carried out between various water quality parameters to understand the geochemistry of the studied region of water.

The commercial filtration system was used to indicate the percentage of the element after each filtration step to facilitate the design of an integrated membrane system.

Design of five membrane systems was occurred to use our prepared membranes in the same standards of commercial membrane size to facilitate comparison between fabricated and commercial membranes.

The design model for system performance was studied assuming the model of the system is a plug flow model, where the calculated recovery reached to 95% using NF/RO membranes system.

Microfiltration polymeric membrane, ultrafiltration polymeric membrane, nanofiltration polymeric membrane and reverse osmosis polymeric membrane were prepared in NRC labs and were used in the designed integrated filtration system.

The integrated filtration system provides very low TDS for produced water reached 0.95mg/L which matched with the World Health Organization water quality standard.

## Conflict of interest

The authors declare no conflict of interest.

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