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Import Substitute for Production of Ultrapure Water by Membrane Integrated Process for Medical and Biotechnological Applications

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Abstract

The present invention discloses an inexpensive import substitute compact design of low-cost membrane process for the production of ultrapure water for dialysis and medical applications in different fields like pathological laboratories, biochemical analysis, sterilization and sanitation, dental and optical lens cleansers. The ultrapure water of demineralization (DM) process is related to the cascaded high- flux and high-selective membrane system for hyper permeation which is operated under the pressure of3-7 kg/cm^2 to generate DM water with total dissolved solids (TDS) of 0−2 ppm. The DM water system is designed for a capacity in the range of 25–60 L/h capacity and its salient features include compact design of the membrane assembly with higher effective membrane area per unit volume to ensure higher DM water recovery at relatively lower pressure compared to the existing reverse osmosis (RO) membrane system. The process pertaining to the present invention is more economical, low maintenance and highly effective compared to the conventional demineralization and more expensive demineralization membrane units currently available in the market. The configuration of the membrane modules adapted in the present invention is simple, easy to operate and useful for several biotechnological, biochemical, medical, and industrial applications shown as graphical sketch figure1.

Keywords: Ultrapure water, demineralized water, cascaded design, membrane system, import substitute

INTRODUCTION

The ultra-pure water generation process is a series of unit operations designed to remove contaminants from water to achieve an ultra-pure level. Ultrapure water treatment technology has progressed and evolved significantly over the years. The major trends include using membrane processes in the use of recycled water. Ultrapure water is treated through multiple stages to meet the quality standards for different market users. The primary end-users of ultrapure water include huge number of industries such as semiconductors, pharmaceuticals, power generation (boilers), medical, biochemistry analysis, biotechnology, battery, and automobile industries Figure 1.

As per the UPDF determination in international guidelines the term “ultrapure” was coined in the early 80’s to underline the fact that dialysis fluid solutions (water and dialysis fluid) were highly purified in comparison to standard procedures (Canaud et al. 1986) [1]. UPDF was defined as containing < 0.1

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colony-forming unit/ml (CFU/ml) using sensitive microbiological methods and < 0.03 endotoxin unit/ml (EU/ml) using the limulus amoebocyte lysate (lAl) assay. A summary of microbiological standards for water and dialysis fluids in HD is given in Table 1.

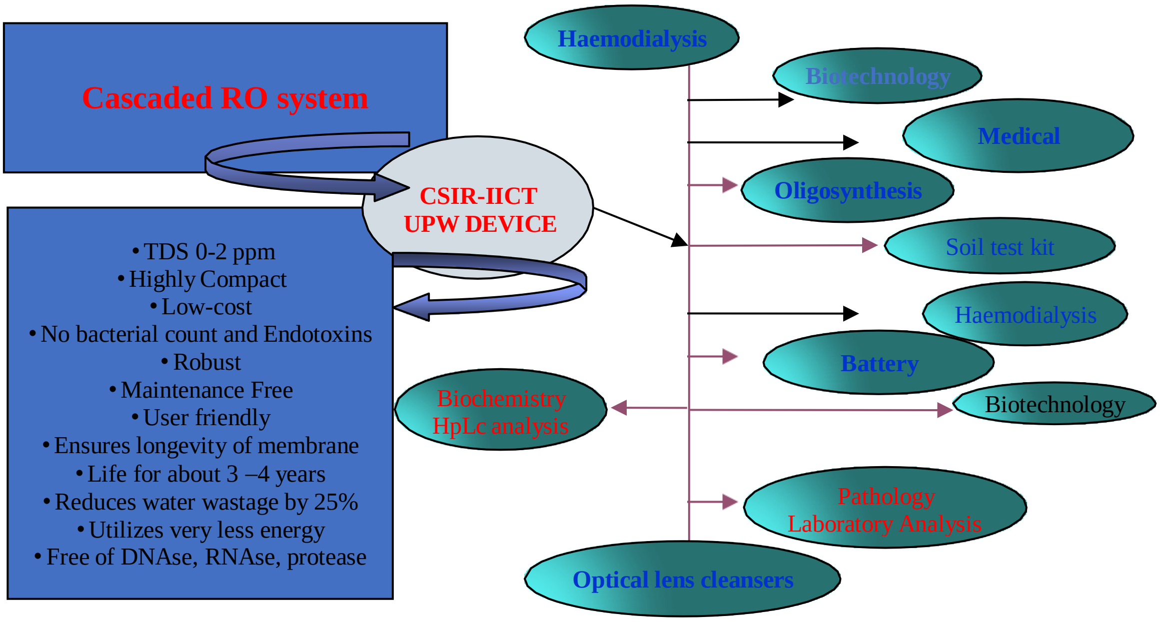

Figure 1. Graphical sketch showing application and other features of CSIR-IICT's ultrapure water (UPW) technology.

Table 1. Summary of microbiological standards for water and dialysis fluids in HD.

Microbiological standards for water and dialysis fluid purity					
	Standard Water	**Standard Water**	**Ultrapure Water**	**Ultrapure Dialysate**	**Sterile Dialysate**
Bacterial limits [a], CFU/mL	< 100-200	< 100-200	< 0.1	< 0.1	< 10-6
Endotoxin limits [b], EU/mL	< 0.25-2	< 0.25	< 0.03	< 0.03	< 0.03

[a]Adequate monitoring and microbiological technique (i.e. UPDF, poor media TGEA, R2A,17-23ºC,7 days); [b]Sensitive LAL assay, threshold detection limit , 0.03 EU/mL; [b]Sensitive LAL assay, threshold detection limit, 0.03 EU/mL
(Source: Canaud B, Lertdumrongluk P, 2012)[2]

Haemodialysis and Water

In hemodialysis, blood flows out of the body and by one side of a semi-permeable membrane. Dialysate, the fluid in a dialysis machine, flows by the opposite side of the membrane. During this process the undesired waste in the blood flows into the dialysate, while bicarbonate (a needed solute that helps in pH balance) flows from the dialysate into the blood. The clean blood is then returned to your body. Removing the harmful waste and extra salt and fluids helps control blood pressure, pH balance, and plasma volume, like the results of a functioning kidney. The cost of maintenance hemodialysis for a single session varies between 10 US dollars to 40 between government-run and private hospitals. It is estimated that only less than 30 percent of patients suffering from end-stage kidney disease manage to receive dialysis in India, where almost 200,000 new patients need dialysis every year [3].

Despite these medical and technical advances, it is disappointing to note that morbidity and mortality remain high in dialysis-dependent chronic kidney disease patients (Goodkin et al. 2003, 2004) [4, 5]. Patients undergoing chronic haemodialysis (HD) three times per week, four hours each, are exposed to a high volume of water between 360 and 576 litres weekly depending on their dialysate blood flow (500

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to 800 mL/min). Therefore, contamination of this water by microorganisms or toxic chemicals could be very harmful to the patient's health, and it becomes mandatory to achieve the highest level of purity of water coming into close contact with a patient's blood and hence worldwide, the nephrology community is witnessing an increased use of high-flux membranes and ultrapure water in haemodialysis (HD) units.

Ultrapure Water in Trade

The ultrapure water market is rising exponentially and is projected to reach $20billion by 2021, at a CAGR of 20% from 2016 to 2021. Moreover, the pharmaceutical industry in India is anticipated to reach US$65 billion by 2024 and US$120 Billion by 2030 (Kenneth Research, 2021) [6]. Though the high-volume consumption of ultrapure water in the semiconductor industry and coal fired power plants is high, its huge demand for dialysis-dependent chronic kidney disease patients is one of the prime factors driving the growth of the ultrapure water market. To cater to these demands, India spends a huge amount as import duty to the tune of 0.8654 USD Million from one of the major ports for Ultrapure Water Purification system import to India [7]. Figure 2 shows a detailed analysis and trend on import data of Ultrapure Water Purification Systems [8].

Figure 2. Import analysis of ultrapure water.
(Source: India's import export data import trends & analysis). [8]

Various national and international companies such as Milli Q, (U.S.), Sartorius, Dow Water & Process Solutions (U.S.), GE Water and Process Technologies Inc. (U.S.), PALL Corporation (U.S.), Dharmanandan Techno Projects Pvt. Ltd, Surat, Gujarat, Adwyn Chemicals Pvt. Ltd, Mayur Vihar, New Delhi and others provide ultrapure water systems to add to their large consumables market. A comparative cost analysis has been made in Table 2.

Table 2. Comparison between market products & CSIR-IICT on UPW water.

Company	Brands	Technology/Capacity	Cost in Rs
Milli Q, USA	Merck Millipore	3–15 L/h	5,00,000/-
Sartorius	Arium Laboratory-grade Water Purification Systems	EDI, RO 50 L/h	3,00,000
Dharmanandan Techno Projects Pvt. Ltd, Surat, Gujarat	FRP RO Plant	RO system, FRP filters	2,50,000
Adwyn Chemicals Pvt. Ltd, Mayur Vihar, New Delhi	Demineralization Plant	RO, mixed bed ion exchanger, 250 L/h	90,000
Elga	Elga Tech.	20–25 L/h	1,000,00
Evoqua	Evoqua Water Tech	5–10 L/h	4,00,000
Rephile	Rephile Bioscience	Not Available	
CSIR-IICT Ultrapure Water System	CSIR-IICT	Two Stage RO, Resin, UV, 25–60 L/h	80,000/-

Besides, sudden outburst of the COVID-19 pandemic has caused stringent lockdown regulations across several nations resulting in disruptions in import and export activities of different sectors including Ultrapure Water Equipment. This has also drastically affected the Indian supply of medical grade ultrapure water and subsequently, the treatment of dialysis-dependent chronic kidney disease patients of the country.

(https://www.marketsandmarkets.com/Market-Reports/ultrapure-water-market-88839327.html) [9].

Keeping in consideration to provide cost-effective, safe and equitable access to dialysis, the present invention on the development of ultrapure demineralized water system is an option towards the need of the hour. The present study investigates the performance of indigenous RO cascaded membrane system for production of ultrapure water for analytical applications and for application in hemodialysis centers for preparation of dialyzing fluid that reduces water wastage by 25% and electricity consumption by 20% compared to existing products that allows to remotely monitor the quality of water as well as health of the unit (chlorine, TDS, flow rate, pressure, etc). Hence this paper presents the design and application of the low cost ultrapure water system made up of two cascaded membranes with higher permeability in general.

Prime Objectives

1. To design the compact demineralization membrane treatment plant with cascaded membrane system in two stages by hosting high flux high selective polyether urea composite membranes.
2. To provide a low-cost compact membrane treatment process for production of demineralized water which obviates the current drawbacks of lower water recovery, high costs (operating, maintenance, and energy) and process complexity.
3. To provide a multi-stage cascaded reverse osmosis system that facilitates complete demineralization of raw water with maximum rejection of impurities.
4. To design the two staged membrane treatment system with no intermediate pressure pumps to ensure the energy-effective demineralization process.
5. To obtain demineralized water by means of robust and compact process at low cost.
6. To provide zero ppm water for biological and biomedical applications.

METHODOLOGY

The process for demineralisation of water involves combination of a pre-treatment stage followed by the membrane treatment and UV disinfection. The pre-treatment system contains polypropylene spun cartridge that removes suspended solids and colloidal matters followed by activated carbon cartridge to remove the turbidity and colour of raw feed water. Two booster pumps of 300 GPD with pressure range of 70 to 80 psi is placed after the pre-treated stages for pressurizing the first stage of cascaded membranes system containing two bigger membrane systems arranged in parallel. The permeate water obtained from the stage I is fed to the second stage II of the membrane system placed in series with stage I.

The specifications of the spiral wound modules are in length 12” x diameter 3” which hosts high-flux and high-selective novel polyether urea composite membrane of about 6 wounds. The effective area of each membrane wound is 0.2 Sq m and the total effective membrane area of the employed spiral wound membrane module is 1.2 Sq m. The module also hosts spacer material in feed and permeate side which is made of polypropylene mesh and polypropylene fabric respectively. The thickness of feed spacer is about 0.017–0.020 inch whereas the thickness of permeate spacer is about 0.010–0.012 inch. The schematic module has been shown in Figure 3.

The feed pressure is maintained to 3-7 kg/cm^2 by means of the flow restrictor wherein a restricting needle valve regulates the flow of concentrate (reject) line. The pressure generated from the pump is sufficient to allow permeate obtained from stage-I membrane system to feed stage-II membrane system directly that is arranged in series with stage-I. The final permeate generated through stage-II is then passed through UV lamp for disinfection where in the TDS of the product water obtained is in the range

0 to 2 ppm. Reject water from stage-I of membrane system is stored and used for the purpose of cleaning, gardening, washing while the reject stream from stage-II that has TDS in the range of raw feed water is recycled back to the feed water stream to improve the water recovery. The reject stream from stage-I and permeate stream from stage-II relate to two glass rotameters with metal floats to monitor flow rate.

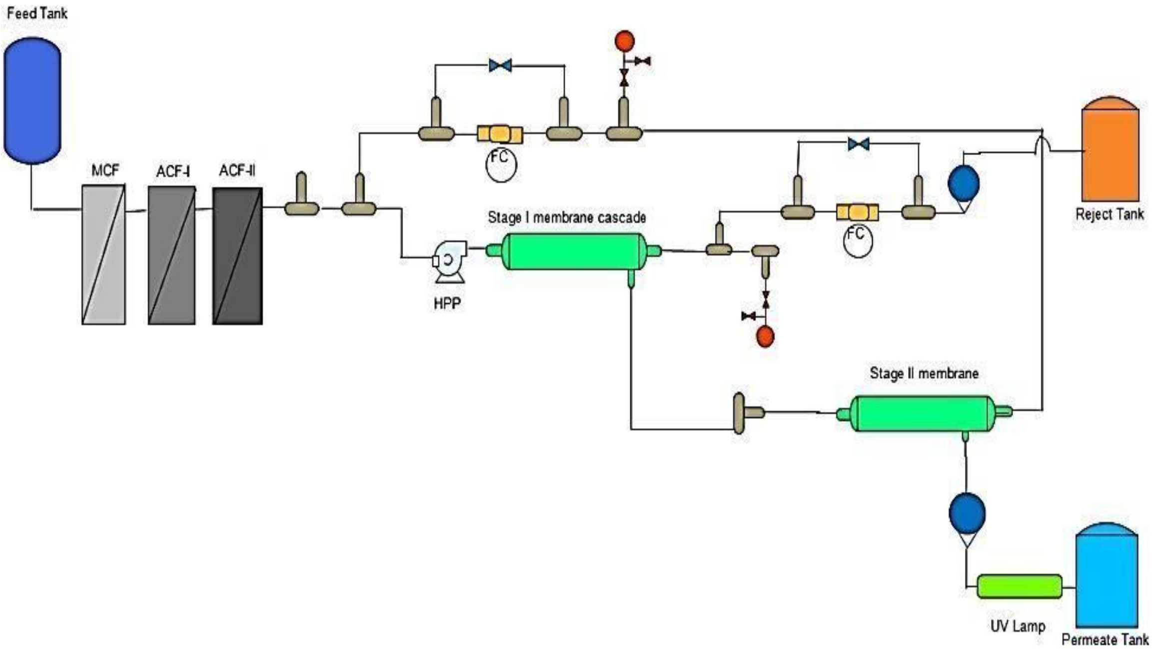

Figure 3. Cascaded RO system for production of type 3 grade water.

The flux (J) is the rate of permeate volume collected per unit membrane area:

$$J = \frac{V_i}{A \times t} \tag{1}$$

Where, V_i is the volume of permeate (L), A is the membrane area (m^2) and t is the time of operation (h).

% Recovery is the % volume of feed that is obtained in permeate which can be calculated as per the relation given below

$$\%\ Recovery = \mathrm{Qp/Qf} \times 100 \tag{2}$$

Where, Q_p and Q_f are the flow rates of permeate and feed (m^3/s).

RESULT AND DISCUSSION

Ultrapure water system technology of CSIR-IICT includes the design of compact low-cost cascaded membrane unit with booster pumps, pre-filter and post-filter cartridges, membrane modules, pressure gauges and mixed bed ion exchange resins. The process for the demineralized water production includes the design of compact low-cost cascaded two-staged membrane systems to achieve hyper permeation at 25-70 LPH capacity is shown in Figure 4. The demineralization membrane process disclosed in this invention is carried out by employing high-flux and high-selective composite membranes.

Permeate of both stages of membrane system were examined for TDS at different pressure conditions and the results shown in Table 3. The effect of pressure on the permeate TDS and % recovery implies that the lowest pressure of 4-6 kg/cm^2 enables the production of demineralized water with TDS of 0 ppm. However, water recovery increases with the increase in pressure to 7 kg/cm^{2}with the quality of demineralized water suitable for applications necessitating 0−2 ppm.

Initial version Update model with cabinet

Figure 4. Photograph of compact cascaded membrane system form production of DM medical-grade water.

Table 3. Effect of pressure on TDS and % water recovery.

Pressure pump-I (kg/cm^2)	Pressure pump-II (kg/cm^2)	Feed Water TDS (mg/L)	First Stage Permeate TDS (mg/L)	Second Stage Permeate TDS (mg/L)	Water Recovery (%)
2	4	280	7	0	76
2	5	281	8	0	78
2.5	6	280	10	0	78
3	7	280	10	2	80

To find the effect of pressure on permeate flow rate the pressure varied from 4 to 7 kg/cm^2 to determine the recovery rate (%) and TDS (ppm) of the demineralized water. The permeate flow rate as determined for the membrane system with 1:1 arrangement of membrane modules is found to be between 25 to 40 LPH (Table 4).

Table 4. Effect of pressure on permeate flow rate.

Pressure (kg/cm^2)	Feed Water TDS (mg/L)	First Stage Permeate TDS (mg/L)	Second Stage Permeate TDS (mg/L)	DM Water Recovery (%)	DM Water Flow Rate (L/h)
4	280	13	0	46	25
5	280	11	1	43	32
6	280	11	1	42	36
7	280	11	2	45	40

COST ESTIMATION

The total cost of the demineralization water plant was found to be in the range of 320 to 450 USD which is several times lesser when compared to the currently available demineralized or deionized water plant available in the market. The estimation of cost pertaining to the items of demineralization water plant of various capacities in the range of 25-70 L/h is given in Table 5.

Table 5. Cost estimation for 25-70 L/h DM water system.

Flow rate of DM water/Capacity (L/h)	Total Cost in INR	Total Cost in USD
25-40	25,119	389
40-60	20,715	321
55-70	28,189	436

The results of the present invention relates to quite economical design of membrane system that employs interfacially polymerized polyether urea composite membranes for facilitating demineralization of raw water with complete rejection of total dissolved solids and impurities. The cascaded compact membrane system of 25–50 L/h capacity costs Rs. 0.8–1.0 lakhs only (Selling price inclusive of 50-60% profit margin), whereas pilot plant of 500 L/h costs Rs. 4.0–5.0 lakhs only (Selling price inclusive of 50-60% profit margin), post treatment by UV lamp/resin to produce ultrapure water for medical applications, dialysis water and washing surgical tools in hospitals, microbial culture preparation in biotech laboratories, soil test kits, automobile batteries & radiators, and lab grade water for colleges/universities. This indigenous system generates Type–III water of resistivity 2–3 mega Ώ cm as per ASTM standards, which can be used to produce pre-treated water (feed) for longer life and easier maintenance of imported systems installed for Type-1 water in laboratories and universities (Table 6). The reject water from both the stages of membrane system is collected in a reject tank for the domestic cleaning and washing purposes. In conclusion the Ultrapure demineralization (UPW-DM) water plant constitutes of cascaded membrane assembly of 25−70 L/h capacity with several salient features like reliability, durability and compactness of the design, minimal operational expenditure, and ease of maintenance.

Table 6. Specification of reagent water.

Parameter (Unit)	Type-I	Type-II	Type-III
Conductivity(µmhos/cm)	<0.056	<1.0	1.0 to 20
Resistivity (M Ώ cm)	>18.0	>1.0	0.05 to 1
Total bacterial count (CFU/100ml)	1	10	1000
Endotoxin (EU/ml)	0.03	0.25	N/A

(Source: ASTM D1193-06 (2011), Standard Specification for Reagent Water, ASTM International, West Conshohocken, PA, 2011, www.astm.org) [10]

DEPLOYMENT

For the present technology innovation, cost and convenience has played a crucial role in setting up the demand and successful deployment. The compact and basic prototype of cascaded RO system (25-60L/h) has been installed at 12 different locations and has been working very well. The key reverse osmosis membrane element is indigenously developed high-flux and highly selective polyether urea

Figure 5. Highly compact cascaded membrane based DM Medical grade water production unit (500 L/h capacity).

membrane and is fabricated locally in India. The prototype of the present invention takes municipal water, pre-filters it through multimedia filter and activated carbon, then the indigenous filter, UV and finally output water of 2-5 ppm TDS (haemodialysis grade). This is membrane based demineralized water technology has been deployed successfully at M/S Plantris Ventures Pvt. Ltd, New Delhi, M/S Care Hospital, NIPER, Hyd., JNTU, Kakinada, Osmania University, Hyderabad and in different divisions in IICT including Chemical Biology, Polymers & Fine Coatings, Bio-Engineering and Environmental Center and Nanomaterials Laboratory. The ultrapure medical grade water ofautomated cascaded membrane pilot plant of 500 L/h (Figure 5) has been successfully utilised for more than 2,00,000 dialysis patients at Kamareddy, Nandyal and Marredpally branches of Nephroplus Chain of Hospitals. IICT has received STEM Impact and CIPET National Awards for this invention which is filed for Indian Patent Application No. 201711037739 in the year 2017.

CONCLUSION

Salient Features of the Process

1. Compact design of demineralization process by including the cascaded membrane system which offer high flow rate of about 25-70 L/h
2. No pressure booster pumps between the two membrane stages of the demineralization process, thus enables cost and energy savings
3. Novel polyether urea / Polyamide RO membrane that provides high TDS rejection. Two staged membrane system is effective in resulting TDS of 0-2 ppm in the permeate water quality and hence useful for applications related to automobile industries (Radiators & Batteries), grade water, soil testing kits, caustic soda & power plant boilers, biomedical (saline solution & dialysisfluids) fields.
4. The demineralized water is also free of DNAse, RNAse, protease which makes them sterile to be used for biotechnological applications, especially for microbial cultures, oligo synthesis and other experiments requiring sterile water. The demineralized water of TDS 0-2 ppm also serves the purpose of academia and research for uses in laboratory experiments.
5. No bacterial count and Endotoxins observed.
6. No additional chemical regeneration is required.
7. Composite cascaded membrane ensures longevity of membrane life for about 3 −4 years.
8. Reduces water wastage by 25% and electricity consumption by 20% compared to existing products i.e., utilizes very less energy.
9. Technology robust, easy to operate and maintenance free.
10. Technology meeting international standards/specifications of Type-II and Type-III grade water used in health sector units.
11. Allows to remotely monitor the quality of water as well as health of the unit (chlorine, TDS, flow rate, pressure, etc).
12. Cost-effective option compared to imported units (about 70% less cost).
13. Ideal feed water for high-capacity imported Type-1 units.
14. Much more affordable compared to imported Type-2 ultra pure water units.
15. Extremely low operating costs

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