Membrane Distillation for the Removal of Fluoride and Pesticides in Remote Areas in India

by

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Certificate of original authorship

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of Student: (Julia Plattner)

Date: 11.5.2017
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Table of contents

Certificate of original authorship.......................................................................................... II
Acknowledgements................................................................................................................ III
Journal articles published ................................................................................................ IV
Conference Papers and Presentations ................................................................................. IV
Table of contents .................................................................................................................. V
List of abbreviations............................................................................................................. IX
List of symbols.................................................................................................................. XI
List of illustrations ............................................................................................................. XII
Abstract ................................................................................................................................. XIV

1. Introduction ..................................................................................................................... 2
1.1. Background of research .......................................................................................... 2
  1.1.1. Global fresh water demand ........................................................................... 2
  1.1.2. Fresh water supply for remote areas ........................................................... 2
  1.1.3. Membrane distillation ................................................................................. 2
1.2. Objective of this research ....................................................................................... 3
1.3. Outline of this study ............................................................................................... 4

2. Literature review .......................................................................................................... 6
2.1. Introduction ............................................................................................................. 6
2.2. Microbial and chemical contaminants in groundwater in India .................................. 6
  2.2.1. Microbial contamination ............................................................................. 6
  2.2.2. Pesticide contamination ............................................................................. 7
  2.2.3. Nitrate contamination ............................................................................... 12
  2.2.4. Fluoride contamination ............................................................................. 13
  2.2.5. Arsenic contamination .............................................................................. 15
  2.2.6. Iron contamination ................................................................................... 15
  2.2.7. Salinization of groundwater ................................................................... 16
2.3. Small scale water treatment technologies .................................................................. 17
Chapter 1 - Introduction

2.4. Membrane Distillation ................................................................. 19
  2.4.1. MD configuration ................................................................. 20
  2.4.2. Transfer mechanisms ........................................................... 22
  2.4.3. MD in Drinking Water Production ............................................ 23
  2.4.4. Challenges in MD application ................................................ 25
  2.4.5. Scaling and fouling phenomena in drinking water production ... 26

2.5. Conclusions ................................................................................. 28

3. Material and Methods ................................................................. 30
  3.1. Chemicals and solutions ............................................................ 30
    3.1.1. Feed solutions fluoride experiments ...................................... 30
    3.1.2. Feed solutions pesticide experiments ..................................... 31
    3.1.3. Selected pesticides ............................................................. 32
  3.2. Experimental setup ................................................................. 36
    3.2.1. Bench scale DCMD unit ...................................................... 36
    3.2.2. Pilot DCMD unit ............................................................... 37
    3.2.3. Rapid small scale column test ............................................ 38
  3.3. Experimental protocols ........................................................... 42
    3.3.1. Optimum operation conditions for MD .............................. 42
    3.3.2. Performance measurement methods .................................... 42
    3.3.3. Membrane cleaning .......................................................... 43
    3.3.4. Calculation of volume concentration factor (VCF) and water recovery ... 43
    3.3.5. Calculation of saturation index ......................................... 44
  3.4. Analyses .................................................................................. 45
    3.4.1. Organic analysis .............................................................. 45
    3.4.2. Inorganic analysis ............................................................ 47
    3.4.3. Membrane characterisation ............................................... 48

4. Results and discussions ............................................................ 51
  4.1. Optimum operating parameters for MD .................................... 51
    4.1.1. Effect of feed flow .......................................................... 52
Chapter 1 - Introduction

4.1.2. Effect of feed temperature ..............................................................53
4.1.3. Effect of vacuum incorporation ......................................................54
4.1.4. Summary of results ........................................................................55
4.2. Removal of fluoride and nitrate in MD ...............................................56
4.2.1. Permeate flux ................................................................................57
4.2.2. Permeate quality and fluoride rejection ...........................................58
4.2.3. Influence of nitrate .........................................................................58
4.2.4. Membrane morphology and element characteristics (SEM-EDX) ......59
4.2.5. Fluorite precipitation ......................................................................60
4.2.6. Contact angle measurement ............................................................63
4.2.7. Organic analysis ..............................................................................64
4.2.8. Restoring hydrophobicity of used MD membrane ............................65
4.2.9. Conclusions ..................................................................................66
4.3. Impact of vacuum application .............................................................67
4.3.1. Flux pattern and fluoride rejection by VEDCMD .............................67
4.3.2. Continuous VEDCMD operation with groundwater solution ..........68
4.3.3. Conclusions ..................................................................................70
4.4. Removal of pesticides in MD ..............................................................70
4.4.1. Preparatory pesticide removal experiments ......................................71
4.4.2. System pre-conditioning .................................................................72
4.4.3. Permeate flux ................................................................................74
4.4.4. Contact angle measurement ............................................................75
4.4.5. Permeate quality and pesticide rejection ...........................................76
4.4.6. Permeate quality and pesticide rejection at 40°C and 70°C ...............81
4.4.7. Rapid small scale column test ..........................................................82
4.4.8. Conclusions ..................................................................................84
5. Conclusions and recommendations .......................................................86
5.1. Conclusions .......................................................................................86
5.1.1. Fluoride removal ...........................................................................86
5.1.2. Pesticide removal ..................................................................................86
5.1.3. Application of a GAC post treatment.................................................86
5.1.4. Application of vacuum for performance enhancement .....................86
5.2. Recommendations....................................................................................87
Appendix ........................................................................................................88
A1 Speciation and log D of selected ionic micropollutants........................88
A2 Mass distribution pesticide experiments at different temperatures discussed in Chapter 4.4.6.................................................................89
A3 Chemviron Carbon Activated Carbon Datasheet .................................90
References ....................................................................................................93
List of abbreviations

AGMD  Air gap membrane distillation
BB    Building blocks
BP    Biopolymers
BV    Bed volumes
CCD   Charge coupled device
CDI   Capacitive deionisation
CF    Concentration factor
CP    Concentration polarisation
DCMD  Direct contact membrane distillation
DOC   Dissolved organic carbon
DOM   Dissolved organic matter
EBCT  Empty bed contact time
ED    Electrodialysis
EDC   Endocrine disrupting chemicals
EDR   Reverse electrodialysis
EDX   Energy-dispersive x-ray spectroscopy
FE-SEM Field emission scanning electron microscope
FO    Forward osmosis
GAC   Granulated activated carbon
GC-MS Gas chromatography-mass spectrometry
HA    Humid acid
HPLC  High pressure liquid chromatography
IAP   Ion activity product
IC    Ion chromatography
LC-OCD Liquid chromatography-organic carbon detection
MD    Membrane distillation
MED   Multiple-effect distillation
MEMD  Multi-effect membrane distillation
MGMD  Material gap membrane distillation
MP-AES Microwave plasma-atomic emission spectrometry
MSF   Multi-stage flash
NF    Nanofiltration
NMI   National measurement institute
PAC   Powdered activated carbon
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>PEDCMD</td>
<td>Pressure enhanced direct contact membrane distillation</td>
</tr>
<tr>
<td>POE</td>
<td>Point-of-entry</td>
</tr>
<tr>
<td>POU</td>
<td>Point-of-use</td>
</tr>
<tr>
<td>PTFE</td>
<td>Polytetrafluorethylene</td>
</tr>
<tr>
<td>PVDF</td>
<td>Polyvinylidene fluoride</td>
</tr>
<tr>
<td>RO</td>
<td>Reverse osmosis</td>
</tr>
<tr>
<td>RR</td>
<td>Recovery ratio</td>
</tr>
<tr>
<td>RSSCT</td>
<td>Rapid small scale column test</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning electron microscope</td>
</tr>
<tr>
<td>SGMD</td>
<td>Sweep gas membrane distillation</td>
</tr>
<tr>
<td>SI</td>
<td>Saturation index</td>
</tr>
<tr>
<td>SIM</td>
<td>Selective ion mode</td>
</tr>
<tr>
<td>SPE</td>
<td>Solid phase extraction</td>
</tr>
<tr>
<td>SSS</td>
<td>Small-scale system</td>
</tr>
<tr>
<td>TDS</td>
<td>Total dissolved solids</td>
</tr>
<tr>
<td>TOC</td>
<td>Total organic carbon</td>
</tr>
<tr>
<td>TP</td>
<td>Temperature polarisation</td>
</tr>
<tr>
<td>TROCs</td>
<td>Trace organic compounds</td>
</tr>
<tr>
<td>TZW</td>
<td>Technologie Zentrum Wasser</td>
</tr>
<tr>
<td>UF</td>
<td>Ultrafiltration</td>
</tr>
<tr>
<td>VCF</td>
<td>Volume concentration factor</td>
</tr>
<tr>
<td>VE-DCMD</td>
<td>Vacuum enhanced direct contact membrane distillation</td>
</tr>
<tr>
<td>VMD</td>
<td>Vacuum membrane distillation</td>
</tr>
<tr>
<td>V-MEMD</td>
<td>Vacuum multi effect membrane distillation</td>
</tr>
<tr>
<td>WTP</td>
<td>Water treatment plant</td>
</tr>
</tbody>
</table>
List of symbols

- **A**: Area
- **B**<sub>m</sub>: Membrane coefficient
- c<sub>inf</sub>: Concentration of the compound in the influent to the column
- c<sub>f0</sub>: Concentration in the feed solution at the beginning of the experiment
- c<sub>fe</sub>: Concentration in the feed solution at the end of the experiment
- c<sub>eff</sub>: Concentration in the effluent to the column
- c<sub>p</sub>: Concentration in the permeate at the end of the experiment
- ΔH<sub>v,i</sub>: Latent heat of vaporization
- ΔP: Delta P, partial pressure difference
- Δt: Delta t, temperature difference
- E<sup>0</sup>: Oxidizing character
- H: Global Heat Transfer Coefficient
- h<sub>w,f</sub>: Heat Transfer Coefficient in the Feed Boundary Layers
- h<sub>w,p</sub>: Heat Transfer Coefficient in the Permeate Boundary Layers
- J: Flux [L/(m²·h)]
- k<sub>m</sub>: Thermal Conductivity of the Membrane
- K<sub>OC</sub>: Carbon-water partitioning coefficient
- K<sub>SP</sub>: Ion activity product
- L<sub>c</sub>: Concentrate Feed Volume
- L<sub>f0</sub>: Initial Feed Volume
- LogD: Distribution coefficient
- LogP: Partition coefficient (octanol water partition coefficient)
- m<sub>f</sub>: Flow rate [L/min]
- Nu: Nusselt number
- Pr: Prandtl number
- R<sub>ads</sub>: Adsorptive removal
- T<sub>f</sub>: Feed temperature
- T<sub>fb</sub>: Fluid bulk temperature on the feed side
- T<sub>filtered</sub>: Filtration time
- T<sub>fm</sub>: Membrane surface temperature on the feed side
- T<sub>pb</sub>: Fluid bulk temperature on the permeate side
- T<sub>pm</sub>: Membrane surface temperature on the permeate side
- T<sub>p</sub>: Permeate temperature
- v: velocity
- v<sub>f0</sub>: Volume of the feed at the beginning of the experiment
- v<sub>fe</sub>: Volume of the feed at the end of the experiment
- v<sub>p</sub>: Volume of the permeate at the end of the experiment
List of illustrations

Figure 2.1 Illustration of the MD process displaying heat and mass transfer (Naidu 2014) .......................................................................................................................... 20
Figure 2.2 Membrane distillation configurations (Naidu 2014) .......................................................... 21
Figure 3.1 DCMD bench scale setup ........................................................................................................ 36
Figure 3.2 Schematic setup of bench scale VE-DCMD/DCMD.................................................................... 37
Figure 3.3 Schematic setup of the pilot DCMD ........................................................................................ 37
Figure 3.4 Pilot DCMD unit .......................................................................................................................... 38
Figure 3.5 Membrane test cell viewed from the permeate side .................................................................. 38
Figure 3.6 Small scale column with activated carbon and glass beads.................................................... 40
Figure 3.7 Feed tanks (20L each) ............................................................................................................... 40
Figure 3.8 Setup of rapid small-scale column test .................................................................................... 41
Figure 4.1 Flux and RR at different flow rates ($T_f = 55\degree C$, $T_p = 25 \degree C$) ........................................... 53
Figure 4.2 Flux at different feed temperatures, ($T_p = 25 \pm 0.5 \degree C$, $m_f = 0.8$ L/min, cross flow velocity $= 0.04 \text{ m/s}$) ............................................................................................................... 54
Figure 4.3 Average flux at different system pressures, ($T_f = 55 \pm 0.5 \degree C$, $T_p = 25 \pm 0.5 \degree C$, $m_f = 0.8$ L/min, cross flow velocity $= 0.04 \text{ m/s}$) ............................................................... 55
Figure 4.2.1 Membrane SEM images and EDX inorganic element spectra of used MD membranes with (a) Solution A (CaF$_2$) and (b) Solution B (groundwater) .......................................................... 60
Figure 4.2.2 Model simulation of SI variation of CaF$_2$ as a function of CF with Solutions A and B (Solution A: - - - - and Solution B: ---) at different solution temperatures and constant pH 7 ................................................................................................. 62
Figure 4.2.3 Model simulation of SI variation of CaF$_2$ as a function of CF with Solution B at different solution pH values and constant temperature of 55 °C .............................................. 62
Figure 4.2.4 Model simulation of SI variation of CaF$_2$ and CaSO$_4$ as a function of CF with Solution B at different solution pH values and constant temperature of 55 °C ...... 63
Figure 4.2.5 LC-OCD chromatograms of initial and final feed and permeate in treating Solution C with DCMD ($BP=$biopolymer, $HS=$humic substance, $BB=$building blocks, $LMW=$low molecular weight organics) ........................................................................................................... 65
Figure 4.2.6 Permeate flux pattern with continuous VEDCMD operation for 3 runs with intermediate membrane cleaning with water at the end of each run (Solution B, $T_f = 55 \pm 0.5 \degree C$, and $T_p = 25 \pm 0.5 \degree C$, permeate vacuum $= 300$ mbar) .......................................................... 69
Figure 4.2.7 SEM image of the used VEDCMD membrane upon cleaning with Milli Q water .......................................................................................................................... 69
Figure 4.2.8 Rejection rates and LogD of investigated pesticide .................................................................. 72
Figure 4.2.9 Mass distribution and logD of investigated pesticides .......................................................... 72
Figure 4.2.10 System pre-conditioning with 200 μg/L of each pesticide in Milli Q water. .................................................................................................................................73
Figure 4.2.11 Adsorption of tested substances in the MD and membrane system in comparison to LogD after 48h of circulation ..........................................................73
Figure 4.2.12 Permeate Flux of solution A to D, at 55 ± 0.5 °C feed temperature and 25 ± 0.5 °C permeate temperature .................................................................75
Figure 4.2.13 Fouled membrane with solution D containing 5 mg/L humic acid, 200 μg/L of each pesticide and the synthetic groundwater model solution ..............75
Figure 4.2.14 Rejection rates for solution A to D (error bars represent the standard deviation) ........................................................................................................77
Figure 4.2.15 Rejection rates for each compound (error bars represent the standard deviation) .........................................................................................................78
Figure 4.2.16 Mass distribution of pesticides in solution A ........................................79
Figure 4.2.17 Mass distribution of pesticides in solution B ......................................80
Figure 4.2.18 Mass distribution of pesticides in solution C .....................................80
Figure 4.2.19 Mass distribution of pesticides in solution D .....................................81
Figure 4.2.20 Removal of selected pesticides in RSSCT (F400, Chemviron Carbon, EBCT = 10 min equivalent in full scale) .........................................................83
Abstract
The world’s increasing population, economic development and climate change are driving the demand for more drinking water. In India, more than 100 million people live in areas of poor water quality. It has been reported that more than 33% of India’s groundwater resources are unsuitable for consumption. Anthropogenic contaminants, such as microbial contaminants, nitrate, pesticides and industrial discharge, together with geogenic contaminants, such as fluoride, arsenic, iron and saline water, pose a threat to human health. In many rural areas neither a centralized system for drinking water production nor stable electric power supply exists. Decentralized small-scale water treatment systems with independent power supply could be implemented to produce safe drinking water for the communities. Recently, Membrane Distillation (MD) has been identified as a promising technology for drinking water production in situations with off-grid power supply. The objective of this research was to evaluate the application of MD for the production of drinking water in small-scale communities.

It was shown in this study that bulk salinity, as well as fluoride, nitrate and non-volatile pesticides were well removed from a synthetic brackish groundwater solution using a bench scale and a pilot scale MD unit. The application of a vacuum at the permeate side enhanced the permeate production up to 40%. An elevated scaling potential was identified in the presence of fluoride together with calcium. However, only minor traces of loosely deposited solids were observed in this study. The membrane was efficiently cleaned with flushing of Milli Q water.

Fluoride and nitrate were removed at rejection rates higher than 98-99% and 99% respectively in all experiments. The removal of pesticides was shown to be strongly depending on the vapour pressure and the LogD of the target compounds. A low vapour pressure and a low LogD were found to be favourable for a good rejection in MD.

Post-treatment with granulated activated carbon filtration after the MD was tested for removal of any remaining traces of pesticides to safeguard full compliance with drinking water standards. A 2 log unit removal for all selected pesticides was achieved up to 67,600 bed volumes.

The study demonstrates that membrane distillation is a promising alternative for small-scale water supply from brackish groundwater.