

# Optimization of Reverse Osmosis Performance

Angelica Persson  
Pontus Lundberg



**LUND**  
UNIVERSITY

Department of Automatic Control

MSc Thesis TFRT-9999  
ISSN 0280-5316

Department of Automatic Control  
Lund University  
Box 118  
SE-221 00 LUND  
Sweden

© 2018 by Angelica Persson  
Pontus Lundberg. All rights reserved.  
Printed in Sweden by Media-Tryck.  
Lund 2018

# Abstract

A condensed description of my work.



# Acknowledgements

These people helped me a lot with my work.



# Contents

<b>1. Introduction</b>	<b>9</b>
1.1 Background . . . . .	10
1.2 Motivation . . . . .	10
1.3 Goal . . . . .	10
1.4 Method . . . . .	11
<b>2. Theory</b>	<b>12</b>
2.1 Semi-permeable membrane . . . . .	13
2.2 Osmosis . . . . .	13
2.3 Reverse osmosis . . . . .	13
2.4 Mathematical modeling of reverse osmosis . . . . .	14
2.5 Control theory . . . . .	16
<b>3. Equipment</b>	<b>17</b>
3.1 Reverse osmosis membrane . . . . .	18
3.2 Pumps . . . . .	18
3.3 Simscape/Simulink . . . . .	18
3.4 Speedgoat Real-Time Target Machine . . . . .	18
3.5 Measurement instruments . . . . .	18
<b>4. Method/Implementation</b>	<b>20</b>
4.1 Tests on current system . . . . .	21
4.2 Flowchart investigation . . . . .	21
4.3 Modeling . . . . .	21
4.4 Design of control algorithms . . . . .	21
4.5 Control simulations . . . . .	21
4.6 Implementation test rig . . . . .	21
4.7 Improvements . . . . .	21
<b>5. Results</b>	<b>22</b>
5.1 Test on current system . . . . .	23
5.2 Flowchart investigation . . . . .	23
5.3 Modeling . . . . .	23
5.4 Design of control algorithms . . . . .	23

## *Contents*

5.5	Control simulations . . . . .	23
5.6	Implementation test rig . . . . .	23
5.7	Improvements . . . . .	23
<b>6.</b>	<b>Discussion</b>	<b>24</b>
<b>7.</b>	<b>Conclusion</b>	<b>26</b>
	<b>Bibliography</b>	<b>27</b>
<b>A.</b>	<b>Appendix A</b>	<b>28</b>



# 1

## Introduction

## **1.1 Background**

The Water Technologies department at Baxter develops water systems for use in mixing fluid for dialysis treatments. The water quality is important in order to not harm to the patients when using the final product. The water systems used for water purification are using the reverse osmosis (RO) method as the finest level of filtration. It remove impurities, as salt and inorganic molecules from the water[Company, 2018].

In a RO-system the feed water is pressurized by a pump and forced through the RO-membrane to overcome the osmotic pressure. The RO-membrane is a semi-permeable membrane and let water passes freely true the membrane creating a purified product stream.

The pump in the current system has two purposes, creating a pressure to overcome the osmotic pressure and creating a flow on the reject side of the RO-membrane to prevent aggregation of impurities on the membrane surface.

## **1.2 Motivation**

By using two pumps instead of one in the RO-system it will be possible to control the pressure on the module and the flow on the reject side independently and thus get better possibility to optimize the performance of the RO-system, focusing on reducing impurities and water consumption.

As the current model does not take temperature dependencies in concern, the model will be redesigned in order to handle temperature dependencies.

## **1.3 Goal**

The purpose of this masters thesis is to evaluate the feasibility of replacing the main RO-pump with two pumps, one for controlling the flow through the membrane and one for controlling the pressure.

To achieve good performance it will be necessary to design a realistic model of the system, once the model has been designed and tested a control algorithm is to be developed. This algorithm, should be able to control the flow and pressure over the RO-membrane to maximize the efficiency of the filter while minimizing the amount of waste water that is produced.

The temperature dependencies will be taken in concern in the new model.

### **Framing of questions**

- Is it possible to upgrade the RO-membrane model to include temperature dependencies?
- Is it possible to control the system with two pumps instead of one, which is used today?
- Is it possible to control the two pumps in order to gain better efficiency in reducing water waste, noise or performance? (In comparison with the current system)

## **1.4 Method**

In order to investigate the performance of the current system and to compare it with the new model following steps will be evaluated:

- Research on the RO-membrane that is implemented in the system
- Research on previous work on the field
- Modelling of the system to identify suitable component properties and design of the flow path
- Design of control algorithms
- Control simulations
- Implementation in a test rig to verify the performance of the system
- Run tests to determine the performance
- Improve if possible

# 2

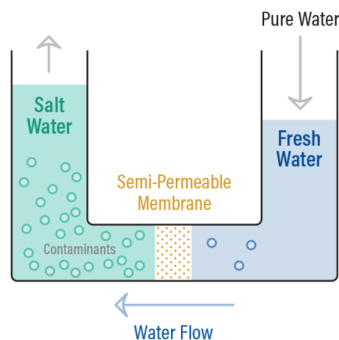
## Theory

## 2.1 Semi-permeable membrane

A membrane is defined as a barrier between two homogeneous phases. The process is a continuous steady-state operation consisting three streams: feed, permeate and reject. Main concern in the process boundary is the semipermeable barrier that selectively allows the passage of some components but not others. [R, 2015]

## 2.2 Osmosis

The osmosis process occurs when two solutions of different chemical concentration are separated by a semi-permeable membrane. The two different solutions will try to reach equilibrium. The solution with less concentration will have a natural tendency to migrate through the membrane over to the side with higher concentration. Osmosis is a naturally occurring phenomenon and one of the most important processes in nature. The pressure that occurs is called the osmotic pressure. The phenomenon can be seen in Figure 2.1

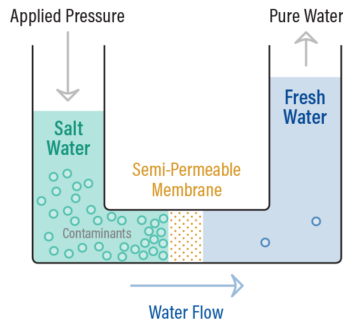


**Figure 2.1** Osmosis

## 2.3 Reverse osmosis

The reverse osmosis(RO) process is the reverse process of the osmosis. When pressure is applied to a semipermeable membrane, the water molecules are forced through the semipermeable membrane and the contaminants are not allowed true. The amount of pressure required depends on the salt concentration of the water. In order to gain reverse osmosis the pressure applied must be greater than the osmosis pressure. The membrane employs cross filtration rather than standard filtration. With cross filtration, the solution passes through the filter with two outlets. One solution passes true the membrane and is called permeate and is the filtered solution.

The other solution can be drained or be fed back into the filtering system. The contaminants build up at the surface area and it is of great importance to try to sweep them away and hold the surface clean. If the contaminants build up the performance of the membrane will decrease, and cleaning with chemicals or heat water might be necessary[*What is reverse osmosis*]. The phenomenon of reverse osmosis can be seen in 2.2. In order to obtain good performance over the RO membrane there



**Figure 2.2** Reverse Osmosis

are some parameters that should be taken in consideration when designing a RO system. These are:

Pressure: feed ( $P_f$ ), permeate ( $P_p$ ), reject, ( $P_r$ )

Conductivity: feed,  $C_f$ , permeate ( $C_p$ ), reject ( $C_r$ )

Flow: feed ( $Q_f$ ), permeate ( $Q_p$ ), reject( $Q_r$ )

Temperature: feed ( $T_f$ ), permeate ( $T_p$ ), reject ( $T_r$ )

## Fouling

Fouling occurs when contaminants accumulate on the surface of the membrane. The fouling contributes to a pressure drop that will decrease the performance of the membrane and cause less permeate flow. Fouling will happen eventually to some extent given the fine pore size of the membrane. A high reject flow and proper pretreatment will extend the operational time between cleaning procedures of the membrane[*What is reverse osmosis*].

## 2.4 Mathematical modeling of reverse osmosis

There are different models to describe the flow of solutes and solvents in the reverse osmosis process. The mass balance equations are central in modeling the process.

Figure ?? shows the main process.

A hydraulic pressure is applied to the feed stream of concentration,  $C_f$  and results in a flow rate  $Q_f$ . Some of the solvent, pure water, passes through the RO-membrane characterized by solvent permeability, solute permeability and surface area. The product water (purified water), is called permeate and has the concentration  $C_p$  and flow  $Q_p$ . The concentration, called reject has the concentration  $C_r$  with flow  $Q_r$ . The study objective of this basic RO-modeling is to calculate output concentrations and flow rates in terms of input and operation conditions. Parameters used to evaluate the performance of the RO-membrane is rejection ratio:

$$R = 1 - \frac{C_p}{C_f} \quad (2.1)$$

and recovery ratio:

$$Y = \frac{Q_p}{Q_f} \quad (2.2)$$

which express the quality and quantity of the solvent product respectively. Mass balance in the system gives:

$$Q_f = Q_p + Q_r \quad (2.3)$$

and:

$$C_f Q_f = C_p Q_p + C_r Q_r \quad (2.4)$$

Solvent flux per unit time per unit membrane surface area is described by:

$$J_w = \frac{Q_p}{A_m} = A(\Delta P - \Delta \pi) \quad (2.5)$$

where  $\Delta \pi = \pi_f - \pi_p$  is the osmotic pressure difference between feed and permeate side and  $A_m$  is membrane surface area. Solute flux is given by:

$$J_s = B(C_f - C_p) \quad (2.6)$$

where B is the solute permeability.

The permeate concentration can be described by:

$$C_p = \frac{C_f}{1 + \frac{A}{B}(\Delta P - \Delta \pi)} \quad (2.7)$$

where A is solvent permeability. Permeate flow is described by:

$$Q_p = Q_f Y \quad (2.8)$$

The four mass balance equations (2.3 - 2.6) make the RO process mathematically solvable.

In order to model the osmotic pressure the van't Hoff principle can be used. It gives the osmotic pressure:

$$\Delta\pi = b(C_f - C_p) \quad (2.9)$$

where  $b$  is a proportionality. In van't Hoff's equation  $b=RT$ , where  $R$  is the gas constant and  $T$  is the absolute temperature on the membrane system.

## **2.5 Control theory**



# 3

## Equipment

### 3.1 Reverse osmosis membrane

The membrane used is a reverse osmosis membrane manufactured by the DOW chemicals company. It is a custom made membrane for Baxter AB.

### 3.2 Pumps

The pumps used in the system are magnet drive rotary vane pump TSSS401 from Fluid-o-Tech. They are designed to deliver a smooth flow reliably and optimized to reduce noise and power consumption. They are made for a maximum static pressure of 20 bar and has a speed limit of 1725 rpm. The nominal flow rate is 400 l/h.

### 3.3 Simscape/Simulink

Simscape is a graphical programming tool within the Matlab simulink environment designed to model and simulate physical systems. A model of the RO-membrane and the flow path is designed using simscape and the simulated system could then be controlled using a control algorithm running in Simulink, a Matlab software too. The RO-membrane model incorporate separate mathematical models of the most important system dependencies, such as temperature , flow, pressure and conductivity.

The system control is implemented in Simulink.

### 3.4 Speedgoat Real-Time Target Machine

Speedgoat is a realtime target machine used for development. It is an FPGA I/O module with Simulink driver blocks. It is capable of simultaneous sampling and is used to drive the system rig. It contains an Intel 2.0 GHz quad core CPU. More technical information can be seen in Appendix

### 3.5 Measurement instruments

Different instruments used to measure pressure, flow, temperature and conductivity in the physical rig.

#### Conductivity sensor block

A conductivity sensor block built by Gambro Lundia AB, called C3 is used to measure the water conductivity. In order to measure the required range two of the blocks where adjusted and calibrated. Two of the blocks, implemented in feed and recirculation path measures in range 0-3000  $\mu$ S. The sensors cell implemented on permeate side measures up to 1500  $\mu$ S.

### **Temperature sensor**

The C3 cell described in section 3.5 contains sensors for temperature measurements and are used for the temperature measurements in the system.

### **Pressure sensor**

Pressure sensors were implemented in the C3 block, described in section 3.5, and calibrated in order to achieve the pressure at feed, recirculation and permeate side of the membrane. The pressure sensors range is between 0-20 bar.

### **Flow sensor**

A flow sensor from Bronkhorst High-Tech B.V is used to measure the flow on permeate side. The flowmeter works in 4-1500 ml/min range and 0-100 bar with water as liquid flowing through. It has an accuracy of  $\pm 1$  ml/min.

# 4

## Method/Implementation

## 4.1 Tests on current system

In order to compare results of the current system and the updated system some test will be done on the current setup. Reasonable values for the test cases were set to:

Temperature 5-45 °C

Conductivity 70-2000  $\mu\text{S}$

## 4.2 Flowchart investigation

To obtain a system to run tests on some different flowcharts will be considered. The current pump will be replaced by two pumps. Following requirements will be desirable when obtaining a updated model of the flowchart:

- Pressure drop over the membrane is high
- Flow through membrane is high

The model shall contribute with the following:

- Permeate conductivity is minimized
- Fouling on the membrane is minimized
- Temperature dependencies will be taken in concern
- Waste water going through drain is minimized

## 4.3 Modeling

Simscape software tool described in section 3.3 is used to do a physical modeling in order to achieve the characteristics of the membrane. Mathematical equations from the manufacturer of the membrane and physics of the solution-diffusion model described in section ??SD) is used and implemented.

## 4.4 Design of control algorithms

## 4.5 Control simulations

## 4.6 Implementation test rig

## 4.7 Improvements

# 5

## Results

## 5.1 Test on current system

Using WAVE program following test cases were evaluated:

Testcases					
Case	Temp °C	Feed ( $\mu$ S)	Feed (P)	Perm ( $\mu$ S)	Drain
1	5	AFG	004		
2	5	ALA	248		
3	5	ALB	008		
4	10	DZA	012		
5	10	ASM	016		
6	10	AND	020		
7	15	AGO	024		
8	15				
9	15				
10	20				
11					
12					
13					
14					
15					
16					
17					

## 5.2 Flowchart investigation

## 5.3 Modeling

## 5.4 Design of control algorithms

## 5.5 Control simulations

## 5.6 Implementation test rig

## 5.7 Improvements

# 6

## Discussion



discussion

# 7

## Conclusion

# Bibliography

- Company, T. D. C. (2018). "Dow water and process solutions - levels of separation of ix, ro, nf, uf". **2**, p. 1.
- R, S. (2015). *"Membrane Technology and Engineering for Water Purification(Second edition)"*. Vol. 435, pp. 1–80.
- water, P. industrial. *What is reverse osmosis*. URL: <https://puretecwater.com/reverse-osmosis/what-is-reverse-osmosis1>. accessed: 09.02.2018.

# A

## Appendix A