

# **Polymer film heat transfer elements for multi - effect and vapour compression desalination**

by

**ANTÓNIO JOSÉ LEÃO**

A thesis submitted in partial fulfilment of the requirements  
for the degree of

**PHILOSOPHIAE DOCTOR**

in the

FACULTY OF NATURAL AND AGRICULTURAL SCIENCES

UNIVERSITY OF PRETORIA

April 2004

# Polymer film heat transfer elements for multi-effect and vapour compression desalination

by

António José Leão

**Supervisor:** Dr TB Scheffler  
**Faculty:** Natural and Agricultural Sciences  
**Department:** Physics  
**Degree:** Philosophiae Doctor

## ABSTRACT

The continuing improvement of existing desalination processes – both distillation and membrane – is contributing significantly to reducing the cost of desalted water, and to the rapid growth of the desalination industry. Thus the world capacity has more than *doubled* during the two years 2000 - 2001, and desalination of seawater is at present the major source of potable water in arid coastal regions such as the Arabian Gulf region.

Conventional multi-effect distillation (MED) and multi-stage flash (MSF) desalinators use cupro-nickel and/or titanium heat transfer surfaces. Polyolefins such as high density polyethylene (HDPE) and polypropylene (PP) have better corrosion resistance than these, which permits much thinner walls. Depending on the internal & external convection coefficients, 20-50 $\mu$  thick HDPE and PP film heat transfer elements have from 60-105% of the U value of 1mm cupro-nickel tubes. Experience has shown them to last as well as – and in some high-scaling water re-use applications better than – titanium elements. But per unit area they cost only about 1% as much.

In chapter 2 we show how the low cost permits the installation of much more thermal conductance (UA) than is economically feasible with metal heat transfer surfaces. This leads to a lower temperature difference  $\Delta T_1$  between the condensing and evaporating sides, and a *lower specific energy consumption*.

This thesis further describes the design, building and testing of a simple falling saline film

mechanical vapour compression (MVC) desalinators. With air mattress-shaped polyolefin film heat transfer elements. Designed for operation (under vacuum) at various temperatures in the range 50-65°C, with a *small* temperature difference  $\Delta T_i$  between the condensing and evaporating sides.

In chapter 3 we determine the pressure drop of the condensing vapour for laminar flow inside a film tube, to obtain the relation between film tube diameter, length, U value, temperature and the ratio  $R_T = \Delta T_i / \Delta T_f$  of temperature difference  $\Delta T_i$  to frictional temperature drop  $\Delta T_f$ .

We also determine, for  $\Delta T_i = 1\text{K}$  and  $R_T = 8$ , the relation between tensile stress and temperature for the HDPE and PP films that we have used to fabricate HTE's. For 39 $\mu$  HDPE film elements up to 60 - 65°C, and for 50 $\mu$  PP ones up to 90 - 95°C, the stress is below 0.4 MPa – and in most cases well below the creep strength of the materials for a 10 year design life.

In chapter 4 we discuss the welding of thin HDPE and PP films on specially developed apparatuses to produce air mattress-like heat transfer elements (HTE's). Some of these were pressure tested (up to several bars at room temperature) to determine the strength of the weld lines.

Chapter 5 discusses the successful vapour inlet manifolding of the heat transfer elements into heat transfer units. Also the design, construction and testing of a vacuum vessel and a turbo vapour compressor. And of the other auxiliaries (feed water heater, vacuum pump with protecting pre-condenser, water pumps, instrumentation . . .).

It also discusses problems encountered, and the merits of various possible remedies.

Chapter 6 discusses suitable surface treatments to increase their surface tension and wettability of the air mattress-like heat transfer elements (HTE's). As these are of a non-polar hydrophobic material, such treatment – aimed at creating charged, polar or polarizable sites – is essential for film evaporation. As our original process – oxyfluorination – was only partially successful after several year's work, we have started another surface treatment – sulfonation – which is in the early stages of evaluation.



## Polimeerfilm hitte-oordrag elemente vir multi-effek en dampsaampersingsontsouting

deur

António José Leão

**Studieleier:** Dr TB Scheffler  
**Fakulteit:** Natuur- en Landbouwetenskappe  
**Departement:** Fisika  
**Graad:** Philosophiae Doctor

### SAMEVATTING

Die voortgesette verbetering van bestaande ontsoutingsprosesse – beide distillasie- en membraan- – dra beduidend by tot die vermindering van die koste van ontsoute water, en tot die snelle groei van die ontsoutingbedryf. So het die wêreld-ontsoutingsvermoë meer as verdubbel gedurende die jare 2000-2001, en is ontsouting reeds die vernaamste bron van drinkbare water in droë kusstreke soos die Arabiese golfgebied.

Konvensionele multi-effek distillasie (MED) en multi-stadium flits (MSF) distilleerders gebruik kupro-nikkel en titaan hitte-oordrag-oppervlakke. Poli-olefiene soos hoë-digtheid polietileen (HDPE) en polipropileen (PP) is meer bestand teen korrosie as hierdie materiale, en maak dit moontlik om veel dunner wande te gebruik. Vir redelike aannames oor die interne en eksterne konveksie-koëffisiënte, sal 20-50 $\mu$  HDPE en PP film hitte-oordrag-elemente 60-105% van die U-waarde hê van 1 mm wand kupro-nikkel buise. Die ervaring wys dat hulle netso goed soos – en in sommige skaalvormende hergebruik toepassings beter as – titaan elemente hou. Maar per m<sup>2</sup> kos hulle slegs 1% soveel.

In hoofstuk 2 toon ons hoe die lae koste die installering van veel meer hitte-oordrag oppervlak toelaat as wat ekonomies is met metaal oppervlakke. Dit lei tot 'n kleiner temperatuurverskil  $\Delta T$ , tussen die kondenseer- en verdampingskante, en tot 'n laer energie-verbruik per m<sup>3</sup> distillaat.

Die proefskrif beskryf ook die ontwerp, bou en evaluering van 'n eenvoudige vallende

soutwater film meganiese dampsaampersings-distilleerder – met parallele buis poli-olefien film hitte-oordrag elemente (HOE) in 'n lugmatras-tipe konfigurasie. Ontwerp vir bedryf (onder vakuüm) by temperature tussen 50 en 65°C, met 'n klein temperatuurverskil  $\Delta T_1$  tussen die kondensasie- en verdampingskante van die HOE.

In hoofstuk 3 bepaal ons die drukval van die damp vir laminêre vloei binne 'n filmbuis – om die verband te bepaal tussen filmbuis deursnee, lengte, U-waarde, temperatuur en die verhouding  $R_T = \Delta T_1 / \Delta T_f$  van  $\Delta T_1$  tot die vloeiweerstand-geïnduseerde temperatuurval  $\Delta T_f$ .

Ons bepaal ook, vir  $\Delta T_1 = 1\text{K}$  en  $R_T = 8$ , die verband tussen trekspanning en temperatuur vir die HDPE en PP films wat ons gebruik het om HOE te fabriseer. Vir 39 $\mu$  HDPE film-elemente tot 60-65°C, en vir 50 $\mu$  PP film tot 90-95°C, is die spanning minder as 0.4 MPa – en in die meeste gevalle minder as die kruip-sterkte van die materiale vir 'n 10 jaar ontwerpleeftyd.

In hoofstuk 4 bespreek ons die sweis van dun HDPE en PP films met spesiaal ontwikkelde aparate om lugmatras-vormige hitte-oordrag elemente (HOE) te vervaardig. Sommige hiervan is met druklug getoets (tot verskeie bar by kamertemperatuur) om die sterkte van die lyn-sweislasse te bepaal.

Hoofstuk 5 bespreek die suksesvolle ontwerp en konstruksie van die damp-inlate tot die HOE, en die saamvoeg van HOE tot hitte-oordrag eenhede. Ook die ontwerp, konstruksie en toets van 'n vakuüm-houer, en van 'n turbo dampsaamperser. Ook van die ander toebehore (toevoerwater verwarmers, vakuümpomp met beskermende kondenseerder, waterpompe, instrumentasie . . ).

Dit bespreek ook probleme met die bestaande apparaat en bedryfsmetode, en die meriete van verskillende potensieële oplossings.

Hoofstuk 6 bespreek geskikte oppervlak-behandelings om die oppervlak-spanning en benatbaarheid van die HOE te verhoog. Aangesien hulle van 'n nie-polêre hidrofobiese materiaal is, is sodanige behandeling – daarop gemik om polêre of polariseerbare plekke op die polimeer-oppervlakte te skep – essensieel vir film-verdamping. Aangesien ons

eerste proses – oksifluorinerig – slegs gedeeltelik geslaagd was na jare se werk, het ons begin met ‘n tweede proses – sulfonering – wat tans in ‘n vroeë stadium van evaluering is.

*To my family:*

*“My mother would have been proud of me!!”*



## ACKNOWLEDGEMENTS

I am greatly indebted to

- my supervisor Dr. T. B. Scheffler for his able and valued assistance and guidance,
- C. Thompson for valued support and cooperation,
- the technicians G. Pretorius, J. Taljaard and R. Van Weele for their assistance and fruitful support,
- my family, for support and encouragement,
- my friend Q. Odendaal for valuable help
- the Nuclear Energy Corporation of South Africa for the opportunity to use their facilities, and
- finally to SAREC for funding my studies.



# TABLE OF CONTENTS

	<b>Page No.</b>
<b>ABSTRACT</b>	ii
<b>ACKNOWLEDGMENTS</b>	viii
<b>1. INTRODUCTION</b>	1-1
1.1 Background	1-2
1.2 Thesis Objectives	1-3
1.3 Desalination Technologies	1-4
1.3.1 Multi-Effect Distillation	1-5
1.3.2 Multi Stage Flash Distillation	1-6
1.3.3 Vapor Compression Distillation	1-7
1.3.3.1 Historical Perspective	1-7
1.3.3.2 Basic Functioning Principle of a MVC	1-8
1.3.3.3 Temperature - Entropy Chart	1-9
1.4 Implementation of Results	1-12
1.5 Summary	1-12
1.6 References	1-13
List of Symbols	1-14
<b>2. REDUCING THE COST OF DESALINATED WATER: POLYMER FILM HEAT TRANSFER ELEMENTS</b>	
2.1 Introduction	2-1
2.2 Polymer Heat Transfer Elements	2-5
2.3 Coaxial Helical Polymer Tube Condenser for Multi-stage Flash Distillation - an early project	2-6
2.4 Summary	2-7
2.5 References	2-8

### **3. FLOW IN A THIN-WALLED POLYMER TUBE**

3.1	Introduction	3-1
3.2	Polyolefins ( HDPE and PP)	3-1
3.2.1	Polypropylene (PP)	3-1
3.2.2	High Density Polyethylene (HDPE)	3-2
3.3	Optimal Tube Diameter	3-3
3.4	Tensile Stress in Polymer Film Tubes. Creep	3-9
3.5	Summary	3-11
3.6	References	3-11
	List of Symbols	3-12

### **4. FABRICATION OF POLYMER FILM HEAT TRANSFER ELEMENTS**

4.1	Introduction	4-1
4.2	Welding Apparatus (Design)	4-1
4.2.1	Heating Elements	4-3
4.2.2	Welding Pressure	4-6
4.3	Fabrication of “Air Mattresses”	4-8
4.4	Pressure and Leakage Tests	4-9
4.5	Summary	4-10
4.6	References	4-11

### **5. ASSEMBLY**

5.1	Introduction	5-1
5.2	Heat Transfer Unit	5-1
5.3	Vacuum Vessel	5-5
5.4	System Auxiliaries	5-8
5.4.1	Vacuum Pump	5-8
5.4.2	Water Pumps	5-9
5.4.3	Centrifugal Vapour Compressor	5-9

5.4.4	Measuring Devices	5-11
5.5	Experimental Procedure	5-11
5.6	Recommendations	5-13
5.7	Summary	5-15
5.8	References	5-15
<b>6.</b>	<b>WETTABILITY AND WETTING</b>	
6.1	Introduction	6-1
6.1.1	Efficient Evaporation	6-1
6.1.2	Surface Modification	6-1
6.1.3	Unwanted Capillary Action	6-2
6.2	Wettability Test	6-4
6.3	Test Results	6-7
6.3.1	Tests without Surfactants	6-8
6.3.2	Test with Surfactants	6-8
6.4	Surface Tension Measurements	6-13
6.4.1	Experimental Setup	6-16
6.5	Liquid Distributor	6-19
6.6	Summary	6-24
6.7	References	6-25
	List of Symbols	6-27



## LIST OF FIGURES

Number	Description	Page No.
1.1	Principle of multi-effect distillation.	1-6
1.2	Simplified flow diagram of multistage flash distillation	1-7
1.3	Basic principle of vapour compression.	1-9
1.4	Temperature - entropy chart of vapour compression process.	1-10
2.1	Variation of the capita, energy and total cost of desalinated water with the total installed thermal conductance UA.	2-2
2.2	Overall heat transfer coefficient U in MED or VCD as function of wall thickness for some metallic and polymeric materials.	2-6
3.1	Tube diameter as a function temperature for a given ratios $R_T$ . For 2 m long tubes of 50 $\mu$ thick PP film (U value 2500 W/m <sup>2</sup> K). The dashed horizontal lines indicate tube diameters that can be readily produced by our film welding apparatus.	3-6
3.2	Tube diameter as a function temperature for a given ratios $R_T$ . For 2 m long tubes of 39 $\mu$ thick PP film (U value 3200 W/m <sup>2</sup> K).	3-6
3.3	Tube diameter as a function temperature for a given ratios $R_T$ . For 4 m long tubes of 50 $\mu$ thick PP film (U value 2500 W/m <sup>2</sup> K).	3-7
3.4	Tube diameter as a function temperature for a given ratios $R_T$ . For 4 m long tubes of 39 $\mu$ thick PP film (U value 3200 W/m <sup>2</sup> K).	3-7
3.5	Tube diameter as a function temperature for a given ratios $R_T$ . For 8 m long tubes of 50 $\mu$ thick PP film (U value 2500 W/m <sup>2</sup> K).	3-8
3.6	Tube diameter as a function temperature for a given ratios $R_T$ . For 8 m long tubes of 39 $\mu$ thick PP film (U value 3200 W/m <sup>2</sup> K).	3-8
3.7	Tensile stress as function of vapour temperature for PP and HDPE with $R_T$ .	3-10
4.1	Side view of the welding apparatus.	4-2
4.2	Schematic overview of the first configuration of the welding apparatus with 40 electric ribbons. In a later version, only every 4 <sup>th</sup> ribbon was retained.	4-2
4.3	Dependence of thermal ribbon's expansion to the electrical power per unit length.	4-4



Number	Description	Page No.
4.4	Total thermal expansion of iron-nickel alloys showing the effect of third elements.	4-5
4.5	Schematic setup using springs to offset the thermal expansion of the used ribbons.	4-6
4.6	Drawing visualizing the application of weld pressure with pneumatically inflated thin-walled silicone rubber.	4-7
4.7	Diagram of the electrical circuit used in the final version of the welding apparatus.	4-9
4.8	Device used to repair “air mattresses” with discontinuities in the weld lines.	4-11
5.1	(a) Top view of part of a manifold, showing air mattress shaped film elements (thin blue lines) to be clamped between manifold pieces. (b) Side view of entry ports into adjacent film tube like A and B.	5-2
5.2	Initial design for vapour manifold piece - intended for use with 4mm diameter polymer film tubes:- (a) isomeric view; (b) side view; (c) close-up top view; close-up bottom view, showing the small holes for distributing saline water to each individual film tube on each side of this part, which was also intended to serve as saline water distributor.	5-3
5.3	(a)Vapour manifold for 35 film tubes of 18.4mm diameter, with rounded (anti-vena contracta) inlets as shown in fig. 5.1b; (b) Front view of a manifold with some relevant dimensions.	5-4; 5-5
5.4	The uninsulated 2.35m tall vacuum vessel showing 200mm windows, stand and scaffolding.	5-6
5.5	Schematic bottom view of the separator plate with the water inlet and the liquid distributors tubes. Two manifolds used to join the air mattresses (five each) are presented. The evaporating vapour reaches the compressor through the orifice (circle) at the centre of the plate.	5-8
5.6	Upper part of the vacuum vessel with the motor for the compressor.	5-10
5.7	Schematic diagram of the desalinator with auxiliaries.	5-12
6.1	(a) Capillary action between adjacent film tubes, in the region of the weld lines, between adjacent film tubes (b) a close-up view of the capillary zone. In our test setup, each “air mattress” has seven film tubes. Water is drawn into the region between adjacent tubes - that is, into the film region nearest to the weld lines.	6-2



Number	Description	Page No.
6.2	Spacers used to keep the “air mattress” tubes in a constant staggered spacing relative to the tubes of the next “air mattress”. The lower spacer is upside down.	6-3
6.3	Experimental setup for wettability test.	6-5
6.4	Closed-up view of the setup for separation of fluid streams.	6-5
6-5	(a) Drawing of the separation unit with the white holders H and test tubes TT (dashed lines), (b) close-up view of the separation region (A= aperture, W= weld line, F= plastic film, and P= Putty).	6-6
6.6	Improved experimental setup for wettability test.	6-7
6.7	Visualization of the streams flowing downwards.	6-9
6.8	View of the flow on a non-masked oxyfluorinated plastic film.	6-11
6.9	Flow dripping through the weld lines of an oxyfluorinated film.	6-13
6.10	Sulfonated film with water flowing on its surface.	6-14
6.11	Another sulfonated film.	6-14
6.12	A DCA series 322 Analyzer.	6-16
6.13	Dynamic contact angle hysteresis curve for untreated uniaxially stretched PP film.	6-18
6.14	Dynamic contact angle hysteresis curve for a 400s oxyfluorinated PP film.	6-18
6.15	Dynamic contact angle hysteresis curve for a 800s oxyfluorinated PP film.	6-19
6.16	Cross sectional view of the liquid distributor with the inserted micro-tubes.	6-20
6.17	Setup for liquid distributor testing.	6-21

## LIST OF TABLES

Number	Description	Page No.
4.1	Welding pressure for polypropylene used in different technologies.	4-7
6.1	The surface tension values of some polymeric materials for comparison with that of water.	6-15
6.2	Dynamic contact angles for PP sample.	6-17
6.3	Water head $h$ for configuration A, B, and C in the transitions jet-mixed, mixed-drop, and vice versa.	6-22
6.4	Calculated Reynolds numbers for the three configurations with the flow in jet mode.	6-24