

**International Workshop on
Membrane Distillation
and Related Technologies**

October 9 - 12, 2011

***Auditorium Oscar Niemeyer
Ravello (SA) - Italy***

Proceedings



organized by the
Institute on Membrane Technology (ITM-CNR)

in collaboration with the

***Dept. of Chemical Engineering and Materials
University of Calabria***



www.itm.dnr.it/Ravello2011.html

Edited by E. Drioli, G. Di Profio, M.A. Liberti

International Workshop on Membrane Distillation and Related Technologies

Auditorium Oscar Niemeyer, Ravello (SA) – Italy

October 9 - 12, 2011

Organizing Committee

Conference Organizer

Institute on Membrane Technology
(ITM-CNR) at University of Calabria

Chairman

Enrico DRIOLI (ITALY)

Scientific Committee

Vincenzo ARCELLA (Italy)
Tony FANE (Australia)
Kamalesh SIRKAR (USA)
Young Moo LEE (Korea)
Maria TOMASZEWSKA (Poland)
Matthias WESSLING (Germany)

Organizing Committee

Enrico DRIOLI
Alessandra CRISCUOLI
Efrem CURCIO
Romeo DE LUCA
Gianluca DI PROFIO
Maria A. LIBERTI
Francesca MACEDONIO

Secretariat

Maria A. LIBERTI
Institute on Membrane Technology
Tel: +39 0984 492007
Fax: +39 0984 402103
E-mail: m.liberti@itm.cnr.it

Sponsors

Solvay Solexis Spa
www.solvaysolexis.com

Solvay
Solexis



Elsevier
www.elsevier.com



Wiley-VCH
www.wiley-vch.de

 **WILEY-VCH**

AIDIC Sud
www.aidic.it

AIDIC

ITM-CNR
www.itm.cnr.it



University of Calabria
www.unical.it

UNIVERSITÀ DELLA CALABRIA



**Dept. of Chemical Engineering and Materials -
University of Calabria**
dicem.unical.it



INDEX

<i>Introduction</i>	9
<i>Program</i>	10
<i>Oral presentations</i>	15
<i>Fluoromaterials for membrane distillation</i>	16
Vincenzo Arcella, Aldo Sanguineti	16
<i>Membrane distillation: developments in membranes, modules and applications</i>	18
Tony Fane, Rong Wang, Xing Yang, Hui Yu, Filicia Wicaksana, Guangzhi Zuo, Lei Shi, Shuwen Goh, Jinsong Zhang	18
<i>Current advances in membrane distillation</i>	20
M. Khayet	20
<i>Design of novel hydrophobic/hydrophilic composite membranes for desalination by membrane distillation</i>	24
Mohammed Rasool Qtaishat, Mohamad Khayet, Takeshi Matsuura	24
<i>Direct contact membrane distillation: effects of membrane pore size distribution and support layer on mass transfer</i>	27
G.Y. Rao and A.E. Childress	27
<i>The influence of scaling on the MD process performance</i>	31
Marek Gryta	31
<i>Nano-structure of membrane materials: outcomes of the decade</i>	35
Yuri Yampolskii	35
<i>Predictive calculation of the solubility of liquid and vapor solutes in glassy polymers with application to PV membranes</i>	38
Maria Grazia De Angelis and Giulio C. Sarti	38
<i>Membrane condenser for the recovery of evaporated “waste” water from industrial processes</i>	42
E. Drioli, F. Macedonio, A. Brunetti, G. Barbieri	42
<i>On spacers</i>	46
Matthias Wessling	46

<i>Direct contact membrane distillation-based desalination: membranes, modules, scaling, cascades, operating conditions</i>	51
Kamalesh K. Sirkar, Dhananjay Singh	51
<i>Design analysis for membrane-based heat pump devices</i>	53
Jason Woods, John Pellegrino, Jay Burch, and Eric Kozubal	53
<i>Siral wound modules for membrane distillation: modelling, validation and module optimization</i>	58
D. Winter, J. Koschikowski, D. Duever	58
<i>Mathematic model for analysis of evaporation ratio under different conditions in DCMD</i>	62
Stephen R. Gray, Jianhua Zhang, Jun-De Li, Mikel Duke, Noel Dow, Eddy Ostarcevic	62
<i>Vacuum membrane distillation tests for purifying waters containing arsenic</i>	65
Alessandra Criscuoli, Patrizia Bafaro, Enrico Drioli	65
<i>Air gap membrane distillation and applications in water purification and desalination</i>	67
Andrew R. Martin	67
<i>Membrane distillation - an emerging technology for pure water production and draw solution recycle in forward osmosis processes</i>	69
Tai-Shung Chung, May May Teoh, Kai Yu Wang, Felinia Edwie, Peng Wang and Gary Amy	69
<i>Assessment of solar powered membrane distillation desalination systems</i>	72
Rasha Saffarini, Edward Summers, Hassan Arafat, John Lienhard	72
<i>Application of MD/chemical reactor in fertilizer industry</i>	76
Maria Tomaszewska, Agnieszka Łapin	76
<i>Applications of osmotic distillation in food and wine processing: the critical points, their weaknesses and the potentialities</i>	80
Carlo Gostoli and Roberto Ferrarini	80
<i>Seawater desalination with Memstill technology – a sustainable solution for the industry</i>	83
Pieter Nijskens*, Brecht Cools*, Bart Kregersman*	83
<i>Membrane distillation: solar and waste heat driven demonstration plants for desalination</i>	86
A. Cipollina, J. Koschikowski, F. Gross, D. Pfeifle, M. Rolletschek, R. Schwantes	86
<i>Evaluation of different strategies for the integration of VMD in a seawater desalination line</i>	90
Corinne Cabassud, Stéphanie Laborie	90
<i>Membrane contactors in liquid extraction and gas absorption: weddings, funerals and lessons learned</i>	91
João Crespo	91
<i>Membrane distillation in the dairy industry: process integration and membrane performance</i>	93
Angela Hausmann, Peter Sanciuolo, Todor Vasiljevic, Mike Weeks and Mikel Duke	93

<i>Membrane emulsification to implement innovative production systems</i>	97
Emma Piacentini, Rosalinda Mazzei, Enrico Drioli, Lidietta Giorno	97
<i>Design and analysis of membrane based process intensification and hybrid processing options</i>	100
Oscar Andrés Prado-Rubio, Philip Lutze, John Woodley and Rafiqul Gani	100
<i>Membrane distillation - Experience in field applications and potentials</i>	104
Martin Rolletschek, Marcel Wieghaus	104
<i>An integrated Forward Osmosis – Nanofiltration – Membrane Distillation system for seawater desalination</i>	107
E. Curcio, S. Osmane, G. Di Profio, A. Cassano, E.Drioli	107
<i>Industrialized modules for MED Desalination with polymer surfaces</i>	110
Wolfgang Heinzl, Sebastian Büttner, Götz Lange	110
<i>Membrane crystallization for the direct formulation of crystalline bio-active molecules</i>	116
Gianluca Di Profio, Efrem Curcio, Enrico Drioli	116
<i>Approach for a combined Membrane Distillation-Crystallization (MDC) concept</i>	121
Raymond Creusen, Jolanda van Medevoort, Mark Roelands, Alex van Renesse van Duivenbode	121
<i>Vacuum membrane distillation: A new method for permeability measurement of hydrophobic membranes</i>	125
Dao Thanh Duong, Jean-Pierre Mericq, Stéphanie Laborie, Corinne Cabassud*	125
<i>Membrane distillation in zero liquid discharge in desalination</i>	126
E. Drioli	126
<i>Posters</i>	128
<i>Thermodynamic parameters of sorption in amorphous perfluorinated copolymers AFs below and above their glass transition temperature</i>	129
N.A. Belov, A.V. Shashkin, A.P. Safronov, Yu.P. Yampolskii	129
<i>Carbamazepine-saccharin cocrystals formulation from solvent mixtures by means of membrane crystallization technique</i>	131
Antonella Caridi , Gianluca Di Profio , Efrem Curcio , Enrico Drioli	131
<i>Athermal concentration of fruit juices by osmotic distillation: performance and impact on quality</i>	135
Alfredo Cassano, Carmela Conidi, Enrico Drioli	135
<i>A novel TLC based technique for temperature field investigation in MD channel</i>	139
Paolo Pitò, Andrea Cipollina, Giorgio Micale, Michele Ciofalo	139

<i>Concentration of red orange juice by osmotic distillation: effect of operating conditions on water transport</i>	143
Carmela Conidi, Alfredo Cassano, Enrico Drioli	143
<i>Effect of spinning parameters on the morphology and VMD performance of PVDF hollow fibers</i>	147
Alberto Figoli, Silvia Simone, Alessandra Criscuoli, Maria Concetta Carnevale, Soliman Alfadel, Hamad Alromeah, Fahad Alshabonah, Omar A. Al-Harbi, Enrico Drioli⁴	147
<i>Coupling membrane separation and advanced catalysts: A novel process for the oxidative coupling of methane</i>	151
Amit Chaudhari, Tymen Tiemersma, Fausto Gallucci, Martin van Sint Annaland	151
<i>Solubility controlled permeation of hydrocarbons in novel highly permeable polymers</i>	153
Yuri Grinevich, Ludmila Starannikova, Yuri Yampolskii	153
<i>Membrane distillation bioreactor applied for alcohol production</i>	156
Marek Gryta, Justyna Bastrzyk, Wirginia Tomczak	156
<i>Experimental study on process of microwave vacuum membrane distillation</i>	160
Zhongguang Ji, Jun Wang, Deyin Hou, Zhaokun Luan	160
<i>Effects of solvent type on the structural morphology and membrane distillation performance of PVDF-HFP hollow fiber membranes</i>	164
L. García-Fernández, P. Arribas, M.C. García-Payo, M. Khayet *	164
<i>Direct contact membrane distillation of moroccan olive mill wastewater</i>	167
A. El-Abbassi, H. Kiai, A. Hafidi, C. Vélez-Agudelo, M.C. García-Payo, M. Khayet	167
<i>Air gap membrane distillation modelling and optimization: Artificial neural network and response surface methodology</i>	171
M. Khayet, C. Cojocar	171
<i>Modeling and optimization of sweeping gas membrane distillation of sucrose aqueous solutions</i>	175
M. Khayet, A. Baroudi, C. Cojocar, M. Essalhi	175
<i>Polyamide-6 pervaporation membranes for organic-organic separation</i>	178
Wojciech Kujawski, Marta Meller, Radosław Kopeć	178
<i>Preparation and Evaluation of Polypropylene Nano-composite Membrane</i>	182
Shawqui Lahalih, Abeer Rashid, Ebtisam Ghloum, Huda Al-Jabli, Ali Abdul-Jaleel and Mohammad Al-Tabtabaei	182
<i>Poly (ethersulfone) [PES] microspheres encapsulated with imidazolium and pyridinium based ionic liquids using rotating module setup</i>	187
D. Shanthana Lakshmi, A. Figoli*, L. Giorno, E. Drioli	187

<i>Preparation and properties of poly(vinylidene fluoride) membranes with super-hydrophobic surface</i>	189
Xiaolong Lu, Chunrui Wu, Yue Jia, Xuan Wang, Huayan Chen	189
<i>Solar energy assisted direct contact membrane distillation (DCMD) process for sustainable real sea water desalination</i>	192
Il Shik Moon, Ke He, Ho Jung Hwang	192
<i>Preparation and characterization of microporous of PEEK-WC membranes for gases dehydration</i>	198
A. Figoli, S. Santoro, A. Brunetti, F. Macedonio, G. Barbieri, E. Drioli	198
<i>The separation and concentration of whey using UF/MD process</i>	202
Maria Tomaszewska, Lidia Białończyk	202
<i>Novel membrane distillation processes and process strengthen methods</i>	206
Chunrui Wu , Yue Jia, Qijun Gao, Xuan Wang, Xiaolong Lu	206
<i>Effect of oil/surfactant on MD process and performance study of novel modular vacuum-multi-effect-membrane-distillation (V-MEMD) system</i>	210
Kui Zhao, Yogesh Singh, Htut Win, Godart Van Gendt, Wolfgang Heinzl, Rong Wang	210
<i>A tool for modelling spacer-filled MD channels based on open source CFD code</i>	213
Sharaf Al-Sharif1, Mohammad Albeirutty, Andrea Cipollina, and Giorgio Micale	213

Membrane distillation: solar and waste heat driven demonstration plants for desalination

A. Cipollina¹, J. Koschikowski^{2,*}, F. Gross², D. Pfeifle², M. Rolletschek², R. Schwantes²

¹Università degli Studi di Palermo, Dipartimento di Ingegneria Industriale, Viale Delle Scienze (Edificio 6) 90128 Palermo (ITALIA)

²Fraunhofer Institute for Solar Energy Systems (ISE), Heidenhofstr. 2, D 79110 Freiburg, Germany
(joachim.koschikowski@ise.fraunhofer.de)

Introduction

The world's arid and semi-arid zones are already faced with massive water scarcity, which is prospected to increase in the upcoming decades. Therefore the demand for desalination technologies is increasing rapidly. The development of medium size, autonomous and robust desalination units is needed to establish an independent water supply in remote areas. This is the motivation for research on alternative desalination processes. Membrane distillation (MD) seems to meet the specific requirements very well. The robust membrane allows it to follow alternating operation conditions given by e.g. solar energy. The Fraunhofer Institute for Solar Energy Systems (ISE) has been working on the development of energy self-sufficient desalination systems based on solar driven MD technology since 2001. The focus is on module and system development.

This work is focused on experimental studies on full scale demonstration systems, utilizing a parallel multi MD-module setup. The according MD technology background and module set up is presented in this conference in the paper “SPIRAL WOUND MODULES FOR MEMBRANE DISTILLATION: MODELLING, VALIDATION AND MODULE OPTIMIZATION” by D. Winter. From 2004-2008 different autonomous solar driven MD systems, covering a capacity range from 80 to 2000 liters/day, have been developed, installed and monitored. Simulation tools have been developed and validated with the data from pilot plant operation. As shown in figure 1 two different system configurations for different capacity ranges were developed.

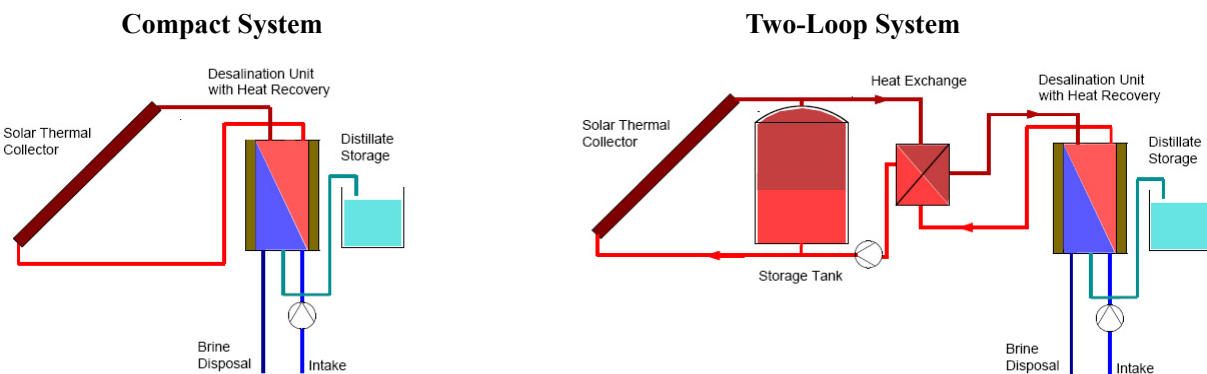


Figure 1: Two different system configurations, the “Compact System” for capacities of 150 up to 1000 l/day and the “Two Loop System” for capacities from 1m³/ day upwards.

The compact system is presented in the paper “MEMBRANE DISTILLATION – EXPERIENCE IN FIELD APPLICATIONS AND POTENTIALS” by M. Rolletschek.

This paper focuses on the two loop system design, which is designed for larger capacities. The main difference compared to the compact system is the use of a separated collector loop consisting of standard flat plate collectors and an integrated heat storage for 24-hour/day operation. The collector

loop and the desalination loop are hydraulically separated by a titanium heat exchanger. The simulation tools were validated with the experimental data from the pilot plant operation. The tools were used to improve the MD-module technology and the overall system design. In the EU FP7 project MEDIRAS two two-loop systems were designed and installed in Pantelleria and Gran Canary between 2010 and 2011. Another two-loop system was installed in the frame of the BMBF funded project CuveWaters in the north of Namibia in 2010. Table 1 provides an overview on the technical specifications of the two loop systems installed between 2010 and 2011.

Location	Date of commissioning	System design capacity	Design capacity desalination unit 24h operation	Raw water source / recovery ratio	Heat supply	Comments
Amarika Namibia Etosha basin (remote inland location)	07/2010	4 m ³ /day at alternating temperatures 65 -80°C, 12 MD modules 168m ² membrane	5m ³ /day at evaporator inlet temperature of 80°C, feed flow rate of 4800 l/h,	Ground water, drilling well 28Tppm R= 10 - 30%	Solar thermal flat plate collectors single glazed 232m ²	-T _{Evaporator-in} was reduced to 70°C to reduce scaling. - Significant problems with collectors
Pantelleria, island of Italy, Power station equipped with Diesel engines	10/2010	5 m ³ /day at constant temperature of 80°C, 12MD modules, 120m ² membrane	5m ³ /day evaporator inlet temperature of 80°C, feed flow rate of 4800 l/h,	Sea water Mediterranean sea, open intake 35Tppm R= 0 -65%	Waste heat from diesel engine + solar thermal flat plate collectors 30m ²	Top brine temperature was lower than designed (70 - 75°C only)
Gran Canaria Spain Test site of ITC	03/2011	3 m ³ /day at alternating temperatures 65 - 80°C, 12MD modules, 120m ² membrane	5m ³ /day at evaporator inlet temperature of 80°C, feed flow rate of 4800 l/h,	Sea water Atlantic ocean, beach well intake 35Tppm R= 0 -50%	Solar thermal flat plate collectors 180m ² (90m ² single glazed, 90 ² double glazed)	Problems with collector performance due to very high wind speeds

Table 1: Specifications of Two Loop Systems installed in 2010 and 2011

Namibia System

The two loop system in Namibia was designed for the fresh water production up to 5m³ in 24 hour operation from raw water of 20 - 28mS/cm conductivity. The location is remote in the land and without any infrastructure or technically trained staff. In order to make transportation and installation more convenient the complete system including desalination unit, controls and heat storage (12m³) were, installed inside a 20' standard container. The set up can be seen in figure 2. The collector field consists of 100 flat plate collectors with a total aperture area of 232 m². All collectors are connected in parallel in order to minimize the pressure drop. The electrical energy is supplied by a PV system including batteries and DC-AC converter. The membrane distillation unit consists of 12 MD-modules, each of 14m² membrane area. All modules are connected in parallel to reduce the pressure drop of the desalination system. The desalination system is operating fully automated never the less the controller and data acquisition systems are connected to a satellite communication system for remote control and daily data transfer. Since raw water is very limited about 75% of brine is recirculated in order to increase the overall recovery ratio of the plant. The recirculated brine is cooled down in a cooling tower by 6 to 8K in order to reach the condenser inlet temperature after mixing with make-up water. Due to the brine recirculation the salinity of feed water is about 35g/kg. The maximum evaporator inlet temperature was reduced from 80°C to 70°C in May 2011 after scaling occurred in the heat exchanger and the hot section of the MD-modules. Accordingly the distillate productivity decreased from 170 l/hour to 150 l/h. Today scaling is controlled by periodic (6 to 12 weeks) flushing with sulphuric acid. The specific thermal energy

demand of the MD system was determined with 150 to 180kWh/m³. The reliability of the system was tested under extreme conditions due to the intensive solar radiation, very high ambient temperatures of more than 45°C, temperatures of more than 65°C inside the container respectively. Low temperatures of less than -5°C and very high temperature gradients between day and night (>30K) occur. Comprehensive experiences were made particularly on the reliability of key components (e.g. pumps, frequency converters, controllers,...). The performance of the collector loop was significantly reduced due to degradation of the solar thermal collectors. The graphs in figure 3 show typical operation parameters as feed flow rate (Vp feed), raw water flow rate (Vp raw), global radiation (I global), evaporator inlet temperature (Tevap in) and the distillate flow rate (Vp dist) for system performance of 15th of October 2010.

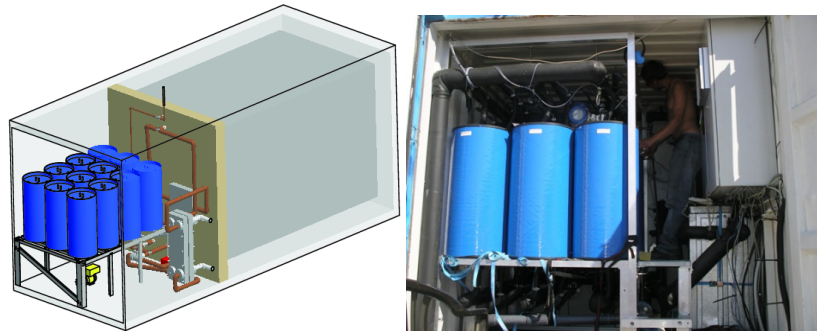


Figure 2: Design of the Namibia system and view into the ready installed container

In general the experience in Namibia show that the predicted performance was not achieved due to different technical problems. On the other hand the ambitious aim to make a stand alone MD system running under extreme remote conditions was achieved and very relevant experiences regarding plant design and component selection were made. The performance is currently improved by different measures.

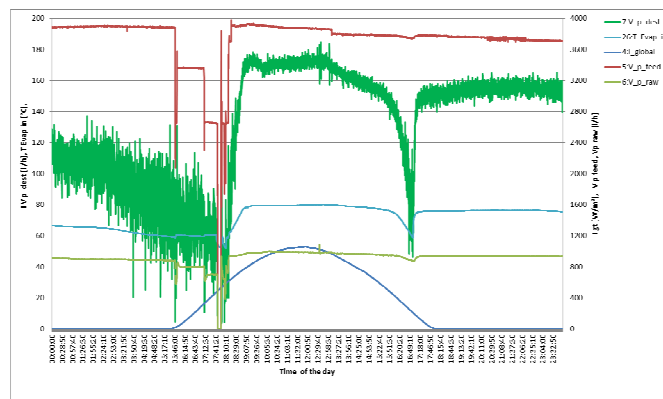


Figure 3: Operation parameters of the MD system in Namibia on October 15th, 2010

Pantelleria System

The Pantelleria system was mainly designed for steady state operation utilizing waste heat from a diesel engine of a power station. Additionally a solar thermal collector field of 30m² was installed in order to investigate the control of a hybrid heat supply. The design capacity of the MD-unit is 5m³/day in a 24h operation mode. The raw water source is the sea water intake of the power plant where sea water is used for cooling. The salinity of the raw water is about 35g/kg. For experimental investigations a brine recirculation is possible. For the cooling a particular brine evaporative cooler (BCC) was developed by the University of Palermo and University of Bremen. The pictures in

figure 4 show the CAD drawing and the ready installed MD system on site. It consists of 12 MD-modules each of 10m² membrane area connected in parallel.

The evaporator inlet temperature is typically between 65 and 75°C depending on the mechanical load of the Diesel engine. The design temperature of 80°C was not achieved with the design feed volume flow rate of 4800 l/h. The graphs in figure 5 show experimental results from plant operation at different evaporator inlet temperatures between 55 and 75°C and different feed salinities of 45, 57 and 100g/kg. The mean condenser inlet temperature was 25°C. The trend lines show, that the average value of the distillate flow rate increases almost linear with an increase of the evaporator inlet temperature. Higher feed salinities lead to a significant decrease in total distillate flow. An increase of feed salinity from 45 to 100g/kg at an evaporator inlet temperature of 75°C induces a reduction of distillate flow rate from about 180 down to 125kg/h.



Figure 5: Construction drawing and ready installed pilot MD system in Pantelleria

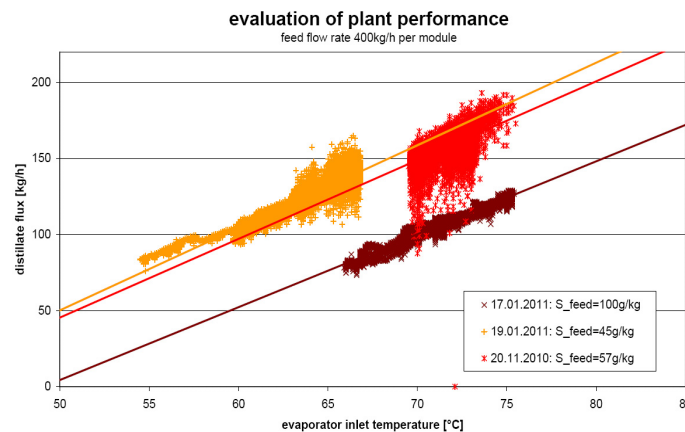


Figure 6: Experimental investigations of the Pantelleria plant demonstrating the effect of feed water salinity and evaporator inlet temperature on the distillate flow rate

Figure 6 shows that the Pantelleria plant could produce about 220 l/h (5280 l/day) distillate if the plant could be operated according the primary design parameters ($T_{\text{evap in}}=80^{\circ}\text{C}$, $S_{\text{feed}}=50\text{g/kg}$).