Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2014.933623

53 (2015) 3170–3178
March

Taylor & Francis
Taylor & Francis Group

Experimental investigation of the performance of a reverse osmosis desalination unit under full- and part-load operation

Evangelos Dimitriou*, Essam Sh. Mohamed, George Kyriakarakos, George Papadakis

Department of Natural Resources and Agricultural Engineering, Agricultural University of Athens, 75 Iera Odos Street, Athens 11855, Greece, Tel. +30 210 5294046; Fax: +30 210 5294032; email: vdimt@aua.gr (E. Dimitriou)

Received 19 October 2013; Accepted 29 January 2014

ABSTRACT

Sea water reverse osmosis (SWRO) desalination constitutes a successful technology for covering the potable water needs of islands and coastal regions. SWRO units can be combined with renewable energy technologies such as photovoltaic and wind generators. Conventional small scale SWRO units are not often combined with energy recovery devices; however, these devices can decrease drastically the energy consumption of the SWRO units. Furthermore, in the literature there are references which prove that the operation of a desalination unit in part-load conditions can result in lower specific energy consumption compared to full-load operation. This paper presents the simulation and the experimental investigation under full- and part-load conditions of an existing SWRO desalination unit (50 mS/cm feed water) in order for the desalination unit to be optimally utilized in a polygeneration microgrid topology which uses advanced energy management algorithms. The experimental operation of the SWRO Unit in part-load conditions is achieved by varying the speed of the motor—pump assembly, the pressure and the flow rate of the feed water. During the evaluation of the measurements result, an optimum operating window in the range of 40–57 bar was drawn regarding the operation of the SWRO desalination unit in part- and full-load conditions. More specifically, in this pressure range the average value of fresh water production was 60 L/h with an acceptable fresh water electrical conductivity of 550 μS/cm, and with a specific energy consumption range from 6.1 to 7.7 kWh/m^3. With these results the operational parameters of the polygeneration microgrid energy management system can be optimized.

Keywords: Sea water reverse osmosis desalination; Variable operating conditions; Polygeneration; Microgrid

1. Introduction

Many areas of the world today are characterized by lack of access to both electrical electricity and high quality potable water. Most of the times, these areas are located in remote parts of the world. Reverse osmosis (RO) desalination units, which are powered by photovoltaics and/or wind turbines, are thought to be a viable solution for the water production in these remote areas.

*Corresponding author.

Presented at the International Conference WIN4Life, 19–21 September 2013, Tinos Island, Greece

In order for a community to be able to flourish economically and socially, specific needs ought to be covered; needs like access to electrical energy, potable water, fuel for transportation, heating, cooling etc. One of the approaches that aim to holistically cover these needs is the autonomous polygeneration microgrid topology [1]. In this topology all needs are covered by a single system, which is based on a distributed generation microgrid, dominated by renewable energy technologies [1].

Desalination plays a very important role in this topology. From its conception the utilization of a RO desalination system was chosen since it presents specific advantages, namely low energy consumption, minimal maintenance requirements, and can be used in cases of brackish water [2]. Previous studies have shown that there are advantages when operating the system at part-load conditions [3], such as lower specific energy consumption and hence the possibility of interconnection with renewable energy technologies. Sea water reverse osmosis (SWRO) units powered by photovoltaics and/or wind turbines and equipped with energy recovery devices deliver excellent energy efficiency over a wide operating range [4–6]. Another experimental study showed that a battery-less photovoltaic seawater RO desalination system, equipped with a DC motor and an energy recovery device, consumed only 4.6 kWh/m^3 with a product conductivity of 309 μS/cm [7].

Extensive theoretical investigation of the autonomous polygeneration microgrid topology has taken place and as a result two advanced energy management systems were developed and validated under simulation conditions; one is based on fuzzy logic [8] and one on a combined approach of petri nets and fuzzy cognitive maps [9]. Moreover an advanced demand side management system has also been designed and implemented in software [10]. All these advanced control and management algorithms fully utilize the advantages of part-load operation of the desalination unit.

The next step in the research path is the extensive testing under real world conditions of these computational intelligence approaches. A polygeneration microgrid has been installed at the grounds of the Agricultural University of Athens [11]. This polygeneration microgrid initially operated all the devices at their nominal point of operation and the energy management system gave only ON/OFF signals to these devices. In order to optimize the operation variables of the advanced energy management systems that allow part-load operation, in depth knowledge of the operational characteristics of all the controlled devices is needed. This paper presents a developed simulation model, based on ROSA v.9.1 software [12] as well as an experimental investigation of the SWRO desalination unit installed in the Agricultural University of Athens and equipped with energy recovery with focus on its part-load operation characteristics. The knowledge gained through this experimental work will allow the future optimal parameterization of the energy management system of the polygeneration microgrid. Finally a comparison between the theoretical and the experimental results is presented in order to evaluate the reliability of the simulation results.

2. Simulation model

Prior to the experimental investigation, a simulation of the system operation parameters was conducted using ROSA v.9.1 software [12] for an inlet seawater temperature of 15˚C and an electrical conductivity of 50 mS/cm, simulating the real conditions of the seawater used by existing RO desalination unit. The membranes selected are SW30-2540 type [13] (two in-series membranes in each vessel, two vessels in total). Simulating the RO desalination unit, in different operating modes, it was possible to calculate several parameters of the unit such as the permeate flow and the electrical conductivity of the desalinated water, under part-load conditions. The theoretical data used in the simulation of the system are shown in Table 1.

3. Description of the experimental setup

3.1. Overview

The RO desalination unit consists of an AC motor, equipped with a frequency converter for the control of the motor's rotational speed. A data logging system was implemented in order to collect all operating data of the desalination unit. The configuration of the system is presented in Fig. 1. The system works in a closed water loop circuit to avoid continuous solution preparation (Fig. 2).

Table 1
Simulation data

Parameter	Value
Feed water concentration	32,000 ppm TDS
Sodium (Na)	12,588 mg/L
Chlorine (Cl)	19,412.02 mg/L
Membrane inlet pressure	30–60 bar
Feed flow rate	150–850 L/h

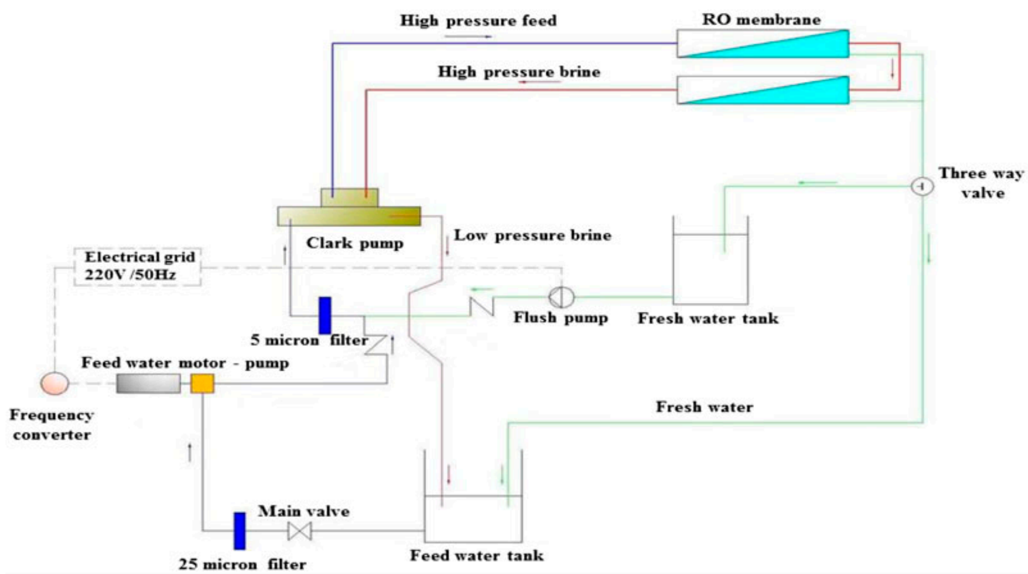

Fig. 1. Schematic diagram of the experimental desalination system.

Fig. 2. RO desalination unit.

3.2. Feed water tank

The feed water tank is a black polyethylene tank with a capacity of 1 m^3. The electrical conductivity of the NaCl solution, which is prepared by the de-chlorinated tap water, was adjusted to 50 mS/cm, simulating the seawater.

3.3. Feed water motor pump assembly

The feed water motor pump assembly consists of an AC motor and a water rotary vane pump which drives the feed water from the mixing tank to the system through the pretreatment system and also provides the positive pressure required at the inlet of the Clark pump. The technical specifications of the motor pump assembly are shown in Table 2.

3.4. Pretreatment system

To increase the efficiency and life—time of RO systems, effective pretreatment of the feed water is required. The pretreatment system of the RO desalination unit consists of three filters, described in detail in [14].

3.5. Clark pump

The Clark pump replaces the high pressure pump in a conventional RO desalination unit. The Clark

Table 2
Technical characteristics of the feed water motor pump assembly

Feed water pump	
Pump type	Rotary
Model	Fluid—o—tech PO700
Maximum pressure	16 bar
Rated flow rate at 1,450 RPM	0.8 m^3/h
Motor specifications	
Motor type	CEG 80b—4
Rated Power	0.75 kW
Voltage	3-phase, 220 V

pump is a piston pump which increases the seawater pressure at an appropriate value to enter the membranes. The feed water motor pump assembly pressurizes the NaCl solution, from the main mixing tank to one of the two cylinders of the Clark pump. The high pressure brine enters the second Clark pump cylinder and exchanges its hydraulic energy with the medium feed water pressure; the result of these actions is the intensification of the feed water pressure to the required membrane pressure (around 50–60 bar). The technical characteristics of the Clark pump are presented in Table 3.

3.6. Membranes

The RO desalination unit consists of two spiral wound seawater Filmtec membrane elements connected in series in order to increase the recovery rate of desalinated water. The membrane is the "heart" of the desalination unit and separates the feed water stream into two output streams: low-salinity product water and high pressure brine. The RO membrane technical characteristics are shown in Table 4.

3.7. Fresh water tank

The flushing tank, constructed of a white polyethylene sheet, has a capacity of 100 L. The product water, produced by the desalination unit, is used for the wash-out of the Clark pump and the membranes' modules [15].

3.8. Flush pump

The flush pump is a centrifugal pump, which drives the fresh water from the flushing tank to the desalination system, for the wash-out of the system. The technical characteristics of the motor pump assembly are shown in Table 5.

Table 3
Technical specifications of the Clark pump

Parameter	Value
Type	Eco systems Clark pump
Model	E—25/590
Rated feed flow rate	760 L/h
Product water flow rate	90 L/h
Rated operating pressure	50 bar
Rated operating feed pressure	12 bar

Table 4
RO membrane specifications [13]

Parameter	Value
Housing	Code line
Membrane type	Filmtec SW 30-2540
Maximum operating pressure	69 bar
Maximum operating temperature	45°C
Maximum feed flow rate	1.4 m^3/h
Product water flow rate	83 L/h
Salt rejection	99.2%
Single element recovery	8%

Table 5
Technical characteristics of the flush pump motor assembly

Flush pump	
Pump type	Centrifugal
Model	ECOJET 120
Maximum suction lift	7.6 m
Maximum flow rate	3.6 m^3/h
Maximum pressure	5 bar
Motor specifications	
Motor type	Totally enclosed fan cooled
Rated power	1 kW
Voltage	Single phase, 220 V

Table 6
Technical specification of the frequency converter

Parameter	Value
Type	HYUNDAI
Model	N50-015SF
Applicable motor capacity	1.5 kW
Rated output current	7 A
Rated output voltage	3-phase, 230 V

3.9. Frequency converter

The frequency converter is a low voltage converter, responsible for the variable speeding conditions of the feed water pump. The AC driver is connected in parallel with the feed water motor pump assembly in order for the required frequency level to be achieved. The technical specifications of the frequency converter are shown in Table 6.

4. Experimental investigation

4.1. General description

The aim of the experimental investigation was to monitor and evaluate the operation of the RO desalination unit in part-load conditions. Thus, several parameters were measured and recorded such as feed/concentrate flow rate, feed/concentrate electrical conductivity, membrane inlet and outlet pressure, and the active power consumption of the feed water motor pump assembly at different frequencies of the motor. At the beginning of the system operation the feed water pump operated at full speed with the frequency converter's set frequency at 60 Hz and was decreased gradually by 5 Hz until the frequency of 10 Hz.

4.2. Feed water and membrane inlet/outlet pressure

The controlled variable through the frequency converter is the motor operation frequency, which is the means of controlling the operation point of the desalination unit. The regression analysis of the experimental data showed a nearly linear relationship between the frequency of the feed water motor and the membrane inlet pressure, the membrane outlet pressure (brine pressure), and the feed water pressure with a correlation coefficient value of 99% (see Fig. 3). As it can be also seen in Fig. 3, the feed water pressure, combined with the brine pressure, raises the membrane inlet pressure due to the intensification of pressure by the Clark pump.

4.3. Fresh water production

As can be seen in Fig. 4, the product water production starts approximately at 33 bar and continues with a linear relationship till the pressure of 57 bar. When the frequency of the feed water motor is increased, the membrane inlet pressure is increased and as a result, the product water flow rate is also increased (Fig. 4).

4.4. Fresh water quality

Increasing membrane inlet pressure increases the rejection of salts and therefore reduces the electrical conductivity of the desalinated water. Thus, the fresh water quality, shown in Fig. 5, is lower than 700 μS/cm at 40 bar and it drops even more as the speed of the feed water motor and the membrane inlet pressure are increased. The water is considered drinkable at the inlet pressure higher than about 35 bar since it is lower than the limits set by the World Health Organization (WHO) [16]. Since the water is stored in a tank after desalination and before consumption mixing of desalinated water of different salinity takes place. As the lowest electrical conductivity is above the set health limits, the salinity of the tank will always be acceptable by WHO standards and moreover the electrical conductivity will always be equal or most probably higher than the instantaneous lowest value. In order to evaluate the quality of the desalinated water the average salinity of the potable water storage tank ought to be considered, rather than instantaneous values. Thus, allowing the SWRO unit to operate at low pressures and feed flow rates will not affect drastically the overall electrical conductivity of the product water at the product water tank.

4.5. Specific energy consumption

The specific energy consumption was calculated with equation Eq. (1).

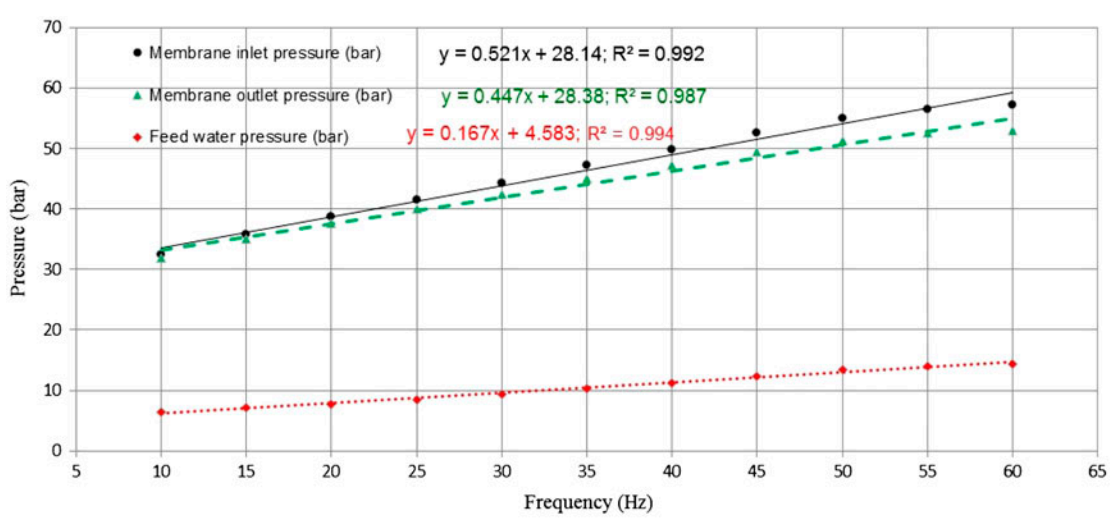

Fig. 3. Membrane inlet and outlet pressures and feed water pressure as a function of the frequency.

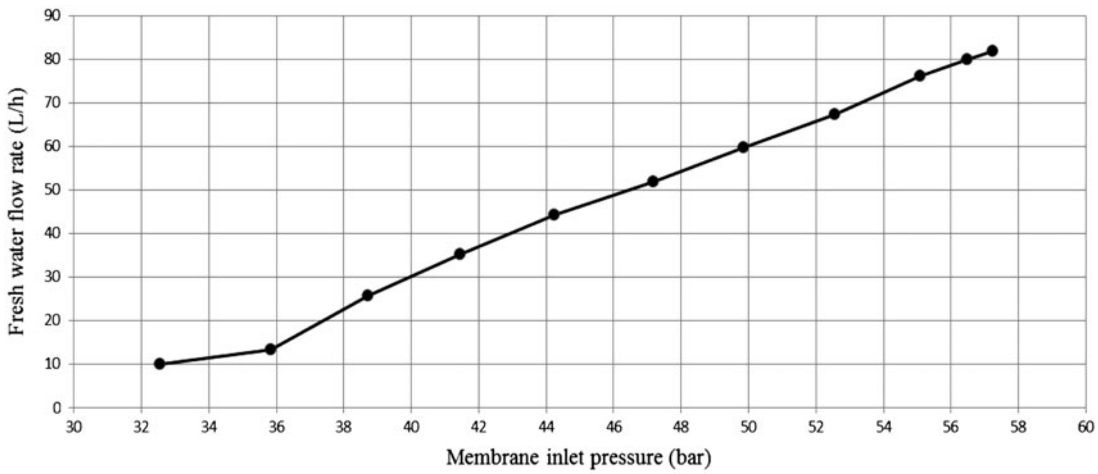

Fig. 4. Fresh water flow rate as a function of membrane inlet pressure.

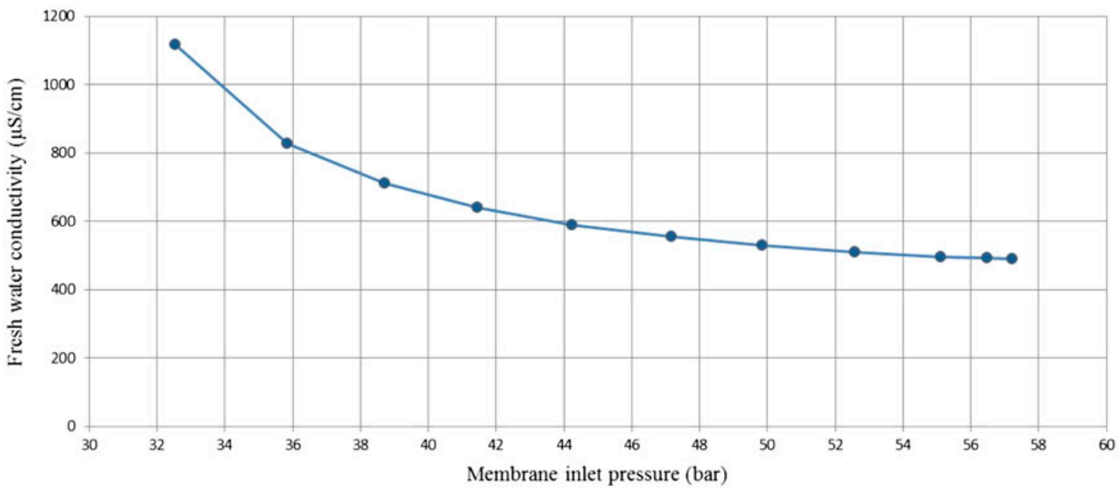

Fig. 5. Fresh water quality as a function of membrane inlet pressure.

$$S_{\mathrm{EC}} = \frac{E_m}{Q_p} \quad (1)$$

where S_{EC} is the specific energy consumption (kWh/m^3), E_m is the energy consumed by the feed water motor (kWh), and Q_p is the fresh water production (m^3).

Fig. 6 shows the calculated values of the specific energy consumption at variable operating conditions (operating pressure and frequency ranges). It can be noticed in Fig. 6 that the specific energy consumption is indeed lower when the desalination unit is operating in part load. As a result the operation window ranges from approximately 40 to 57 bar, which correspond to set frequencies from 25 up to 60 Hz at the frequency converter. For this operating window the specific energy consumption ranges from 6.1 to 7.7 kWh/m^3 and the quality of fresh water is acceptable (<700 μS/cm) (see Fig. 5). In this operating window the energy consumption of the feed water motor is low (see Fig. 6) while the fresh water production is relatively high (see Fig. 4). It is worth mentioning that these specific energy consumption values are higher, comparing them to previous similar studies that was found to be in the range of 3–4.5 kWh/m^3 with a unit powered by DC motor [3,7,14], due to the fact that the seawater temperature is low (15℃) and the power factor of the feed water motor is also low (~0.58). These two factors (low temperature and low power factor) result in increased operating pressure and increased energy consumption respectively.

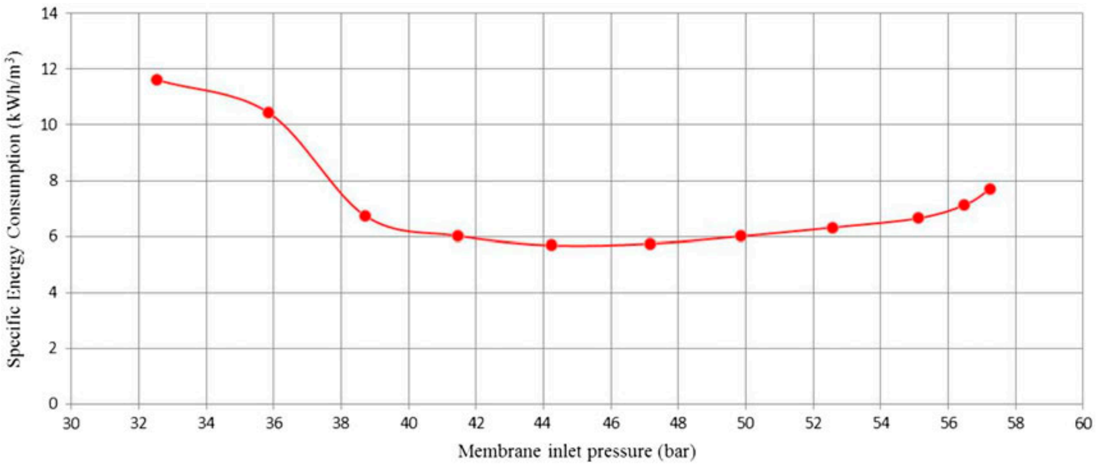

Fig. 6. Specific energy consumption.

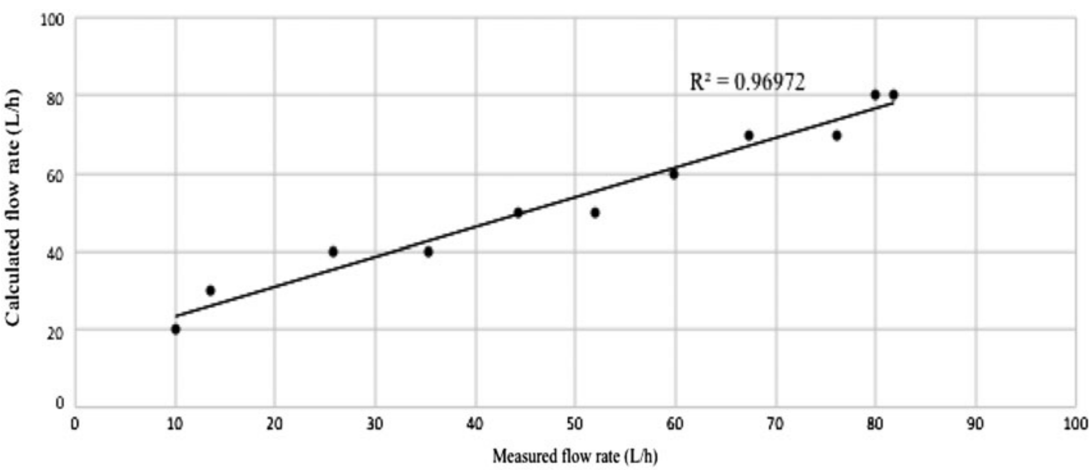

Fig. 7. Correlation of measured and calculated permeate flow rate.

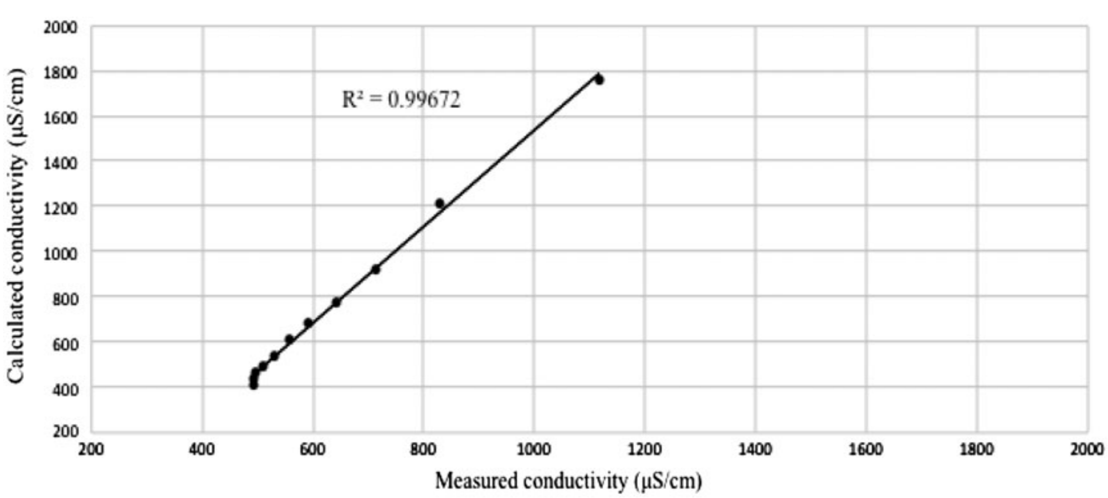

Fig. 8. Correlation of measured and calculated electrical conductivity of the desalinated water.

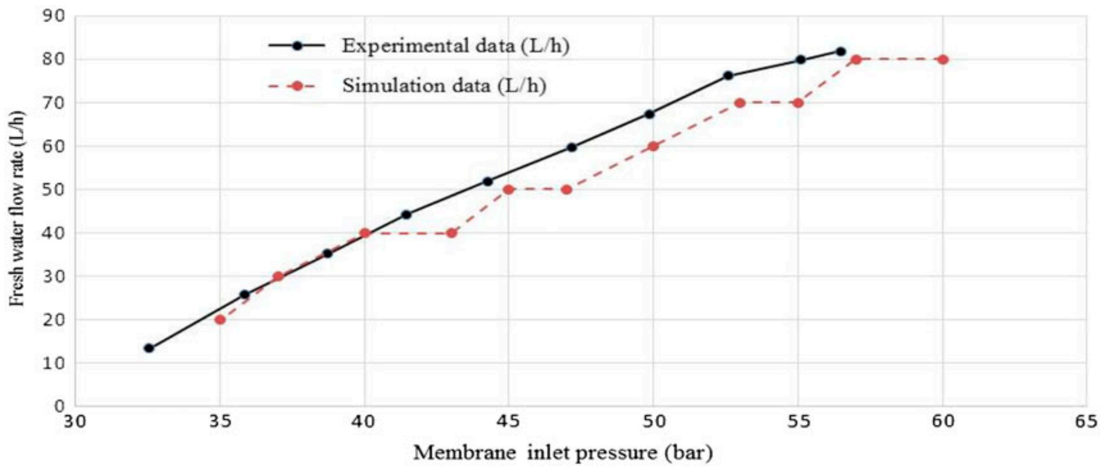

Fig. 9. The fresh water flow rate as a function of the membrane inlet pressure.

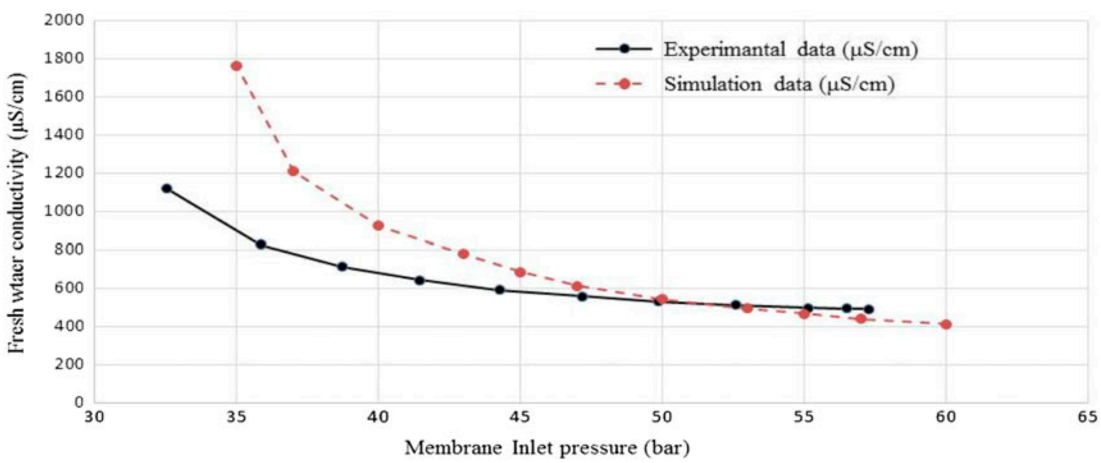

Fig. 10. The fresh water conductivity as a function of the membrane inlet pressure.

4.6. *Theoretical and experimental data comparison*

The simulation results were compared to the experimental operation data, such as the flow rate and the electrical conductivity of the desalinated water, in order to evaluate the reliability of the simulation results. The correlation between calculated results and measured results can be observed in Figs. 7 and 8. As it can be seen in Figs. 7 and 8 the regression analyses of the data showed nearly linear relationships with a correlation coefficient value of 97% for the flow rate and more than 99% for the conductivity.

The comparison between theoretical and experimental results of the permeate flow rate and the electrical conductivity of the desalinated water is presented in Figs. 9 and 10, where in Fig. 9 the permeate flow as a function of the membrane inlet pressure is shown and in Fig. 10 the fresh water conductivity as a function of the membrane inlet pressure can be seen. In Fig. 10, it can be noticed that the disagreement between simulation and experimental conductivity data is increasing for inlet pressures lower than about 45 bar. Obviously the simulation model cannot perform well at low inlet pressures and low feed flow rates.

5. Conclusions

The conclusions arising from this work could be evaluated with regard to the fresh water quality and the operating efficiency of an RO desalination unit for its integration in a polygeneration microgrid.

During the operation of the desalination unit in part-load conditions, an optimum operational window is identified approximately 40–57 bar (which corresponds to a set frequency of 25–60 Hz). In this window the average quality of fresh water is within the limits of WHO and also the specific energy consumption ranges from 6.1 to 7.7 kWh/m^3. Comparing this operational window to previous similar studies, it is concluded that the specific energy consumption values are higher in the current study due to the lower seawater temperature and the lower power factor of the feed water motor.

Furthermore, the comparison between simulation and experimental results of the permeate flow rate and the electrical conductivity of the desalinated water showed high correlation coefficient values. However the model could not predict with an adequate accuracy the fresh water electrical conductivity at lower membrane inlet pressures.

Last but not least, in remote areas, where the needs of electrical energy and potable water are to be satisfied with polygeneration microgrids, a RO desalination unit could operate periodically under a suitable planning and management program in full-load but also in part-load conditions.

Using these real world experimental results, the microgrid advanced energy management system can be optimized in order to fully utilize the desalination unit at all operating conditions of the polygeneration microgrid.

Future work includes the experimental testing of the polygeneration microgrid under an advanced energy management system and the evaluation of its subsystems in that topology including the desalination system.

Acknowledgment

Part of the present work was conducted within the framework of the research project ARISTEIA—Smart Desalination—529, co-funded by EU and the Greek General Secretary of Research and Technology (GSRT).

Symbols

S_{EC} — specific energy consumption (kWh/m^3)
E_m — energy consumed by the feed water motor (kWh)
Q_p — fresh water production (m^3)

References

[1] G. Kyriakarakos, A.I. Dounis, S. Rozakis, K.G. Arvanitis, G. Papadakis, Polygeneration microgrids: A viable solution in remote areas for supplying power, potable water and hydrogen as transportation fuel, Appl. Energy 88(12) (2011) 4517–4526.

[2] E.S. Mohamed, G. Papadakis, Design, simulation and economic analysis of a stand-alone reverse osmosis desalination unit powered by wind turbines and photovoltaics, Desalination 164(1) (2004) 87–97.

[3] E.S. Mohamed, G. Papadakis, E. Mathioulakis, V. Belessiotis, The effect of hydraulic energy recovery in a small sea water reverse osmosis desalination system; experimental and economical evaluation, Desalination 184(1–3) (2005) 241–246.

[4] M.S. Miranda, D. Infield, A wind-powered seawater reverse-osmosis system without batteries, Desalination 153(1–3) (2003) 9–16.

[5] M. Thomson, D. Infield, Laboratory demonstration of a photovoltaic-powered seawater reverse-osmosis system without batteries, Desalination 183(1–3) (2005) 105–111.

[6] M. Thomson, M.S. Miranda, D. Infield, A small-scale seawater reverse-osmosis system with excellent energy efficiency over a wide operating range, Desalination 153(1–3) (2003) 229–236.

[7] E.S. Mohamed, G. Papadakis, E. Mathioulakis, V. Belessiotis, A direct coupled photovoltaic seawater reverse osmosis desalination system toward battery based systems—a technical and economical experimental comparative study, Desalination 221(1–3) (2008) 17–22.

[8] G. Kyriakarakos, A.I. Dounis, K.G. Arvanitis, G. Papadakis, A fuzzy logic energy management system for polygeneration microgrids, Renewable Energy 41 (2012) 315–327.

[9] G. Kyriakarakos, A.I. Dounis, K.G. Arvanitis, G. Papadakis, A fuzzy cognitive maps–petri nets energy management system for autonomous polygeneration microgrids, Appl. Soft Comput. 12(12) (2012) 3785–3797.

[10] G. Kyriakarakos, D.D. Piromalis, A.I. Dounis, K.G. Arvanitis, G. Papadakis, Intelligent demand side energy management system for autonomous polygeneration microgrids, Appl. Energy 103 (2013) 39–51.

[11] G. Kyriakarakos, E. Mohamed, G. Papadakis, Experimental operation of a hybrid renewable energy polygeneration system, in: Agricultural and Biosystems Engineering for a Sustainable World. International Conference on Agricultural Engineering, Hersonissos, Crete, Greece, June 23–25, 2008, European Society of Agricultural Engineers (AgEng), 2008.

[12] Available from: http://www.dowwaterandprocess.com/Resources/ROSA_System_Design_Software (Accessed on June 10, 2013).

[13] Available from: http://www.dowwaterandprocess.com/en/products/f/filmtec_sw30_2540 (Accessed on June 10, 2013).

[14] E.S. Mohamed, G. Papadakis, E. Mathioulakis, V. Belessiotis, An experimental comparative study of the technical and economic performance of a small reverse osmosis desalination system equipped with an hydraulic energy recovery unit, Desalination 194(1–3) (2006) 239–250.

[15] E.S. Mohamed, Investigation of Power Technologies from Renewable Energy Sources for seawater Reverse Osmosis Desalination, in Natural Resources and Agricultural Engineering, in: Natural Recources and Agricultural Engineering, Agricultural University of Athens, Athens, 2009.

[16] World Health Organization (WHO), Guidelines for Drinking-water Quality, fourth ed., World Health Organization, Geneva, 2011.