Doctoral School on Engineering Sciences
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Extended summary

Design of an Onboard Auxiliary Power and Desalination Unit Powered by a Stirling Engine

Curriculum: Energy

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Date: 15-02-2014

Abstract

Starting from the increasingly demand of performance and comforts on pleasure boats, this work refers to an innovative integrated system for the simultaneous production of fresh water and electricity onboard. It is widely recognized indeed that high energy efficiency technologies would play a fundamental role to both support and innovate many manufacturing sectors in great difficulties, such as the nautical.

In particular, a 1 kWe Stirling engine coupled with a thermal desalination plant has been considered for the purpose. The prototype, which refers to the distributed micro cogeneration field, has the final aim of building and testing a single effect distillation plant with a fresh water production of about 150 l/day.

Firstly, the technical and economic feasibility has been evaluated together with the potential plant performance. Then, thermodynamic theories and numerical analysis have been adopted to define the final prototype configuration. Later on, a field test phase has been carried out to evaluate the actual plant performance. Hence, a comparative analysis with a compact reverse osmosis desalination plant has been performed.

In general, the experimental analysis has been in good agreement with the predicted results. In particular, at nominal operating conditions (@50°C) the maximum heat transfer rate was higher

than the designed condition (5 kWt). Despite the non-ideal plant thermal insulation, fresh water production reached about 7 l/h at best operating conditions, proving a good process efficiency.

Definitively, the experimental phase has provided a significant contribution to confirm and understand most of the mutual interconnections between the different key process parameters. According to the predicted behavior, fresh water production has been strongly dependent on salt content of the treated water and on temperature difference between the heating fluid and the salt water in the evaporator tank. However, even at the most severe operating conditions the thermal desalination plant has shown very interesting performance. Moreover, the apparatus exhibited a very good response to varying in time thermal power input thus confirming the opportunity to operate also powered by different forms of waste heat. Nevertheless, additional tests are necessary to fully understand the whole thermodynamic process before system industrialization.

Eventually, even though the objective of this research project was to design and test an integrated micro-chp unit for onboard, other potential applications of the system have been considered, ranging from distributed power production in remote areas to fresh water production by means of different forms of waste heat.

Keywords: m-chp, cogeneration, thermal desalination, reverse osmosis, waste heat

1 Introduction

Fresh water is essential for life, health and human dignity. According to the World Health Organization [1] basic access to the water service consists of about 20 l/day per person whilst higher quantities, about 50 l/day per person, assure personal hygiene and further significant health gains. Despite the unlimited salt water availability, fresh water is usually limited and desalination technologies adopted to satisfy the fresh water demand.

Desalination first began as distillation process for ocean-bound ships [2]. Later on, advanced desalination technologies began to be developed for commercial use onshore.

Today, four major commercial desalination technologies exist:

Multi Stage Flash;

Multiple Effect Distillation;

Vapor Compression;

Reverse Osmosis.

In general, thermal methods are more expensive because of the large quantities of fuel required to vaporize salt water [3-4]. However, they possess the advantage of requiring thermal energy not at a very high temperature and can make use of thermal energy extracted from other sources. For these reasons, thermal desalination is usually arranged in dual-purpose plant using back pressure or extraction steam from steam turbines [5]. A proper design of this coupling ensures both plants running at their optimum operating conditions, minimizing energy consumptions and reducing power and water costs. On the contrary, membrane methods require small amount of electrical energy to desalt water thanks to pressures higher than the osmotic. More precisely, salt water is pumped through a series of semi-permeable membranes to obtain a low salinity permeate as a product.

Despite the high number of large scale thermal desalination plants, small scale desalination plant is limited to RO systems thanks to their compactness and low energy consumption.

2 Small scale thermal desalination plants

Most of the ongoing desalination researches concentrate on large-scale plants which are suitable for mass production of fresh water. Only few researches have been conducted on small scale water thermal desalination even though clean water supply has become a necessary for domestic, small factories, laboratories, and emergency use in remote areas.

In [6,7] authors designed and built a cylindrical evaporator-condenser unit which operates at 0.1 atm. Two heat exchangers inside the element play the role of the condenser and evaporator sensibly reducing plant overall dimensions. In particular, the evaporator is welded to the bottom while the condenser has a greater diameter and it is attached to the inner wall of the unit. During plant operation, vapor rises up from the bottom and condenses on the surface of the cold water coil. However, results have shown very low performance and fresh water production limited to less than 300 g/h.

In [8] performance of a submerged vertical tube evaporator has been extensively investigated. In particular, 175 single fluted aluminum tubes have been used with an inner diameter of 13 mm and a length of 0.5 m to evaporate the salt water making use of waste heat.

The thermal behaviors of the desalination plant have been evaluated for different temperatures and flow rates of heating medium and feed water, and chamber pressures. For the considered conditions, a vapor production rate of 3.3 tons/day and an average overall heat transfer coefficient of about 1000 W/mK have been performance.

Nevertheless, the overall plant dimensions and operation sensibly limited its potential application to few extent.

In this work, a single stage distillation plant has been designed and tested for 150 l/day of fresh water production recovering 5 kWt of waste heat from Stirling engine. Firstly, the technical and economic feasibility has been evaluated together with the potential plant performance. Then, thermodynamic theories and numerical analysis have been adopted to define the final prototype configuration. Later on, a field test phase has been carried out to evaluate the actual plant performance. Hence, a comparative analysis with a compact reverse osmosis desalination plant has been performed.

3 The thermal desalination plant prototype

A m-chp system is able to satisfy the electric energy demand and simultaneously produced thermal energy for heating or hot water demands. However, in warmer locations m-chp annual running operation is limited to hundreds hours and its profitability considerably reduced. On the contrary, m-chp operation can be substantially extended using the thermal power output for different purposes such as seawater evaporation.

In this study, a 1 kWe Stirling engine coupled with a thermal desalination plant has been considered for the simultaneous production of fresh water and electricity onboard pleasure boats [9-10]. Despite the lower efficiencies compared to multiple effects distillation plants, a simple single stage distillation system has been preferred due to the limited Stirling engine thermal output. The system indeed presents reduced overall dimensions and easy operation which are fundamental for the purpose.

The desalination plant has been designed according to the Stirling engine operating conditions. In particular, since lower coolant temperatures entail higher electrical efficiencies, the nominal coolant temperature has been set to 65°C. Therefore, to assure an adequate temperature difference between the coolant and the seawater, evaporation occurs at about 50°C in the evaporator tank. Vapors from the evaporator tank are conveyed to the condenser where distilled water is produced. Fresh water is then collected in a depressurized collection tank and periodically extracted.

At the beginning, a vacuum pump connected to the condensate storage tank draws air from the system until a set-point pressure is reached. On the contrary, during plant operation the vacuum pump runs intermittently to extract the non-condensable gases produced in the evaporation process.

The evaporator consists of a helical tube heat exchanger made of titanium and co-axial to the evaporator tank in order to reduce the salt water column inside. A lower salt water content indeed entails lower energy losses for preheating all the seawater to the saturation temperature and in turn lower energy losses due to concentrate discharge. The corresponding evaporator tank has been designed with the objective of maximizing the fresh water production rate. In particular, higher the diameter lower the salt water column needed to completely submerge the evaporator. According to practical constraints and heat exchanger design a maximum diameter of 500 mm has been set. At the same time, the height has been limited to 550 mm.

The condenser, instead, thanks to a less corrosive atmosphere consist of compact brazed plate heat exchanger made of AISI316 stainless steel.

Table 1: evaporator dimensions

Helical tube heat exchanger		Evaporator tank	
Helical radius	165 mm	Evaporator diameter	500 mm
Helical pitch	16 mm	Evaporator height	550 mm
Number of helical turns	9	Water volume to submerge the coil	30 l
Radial dimension	343 mm	Water volume over the coil	60 l
Axial dimension	160 mm	Fresh water production ratio	2

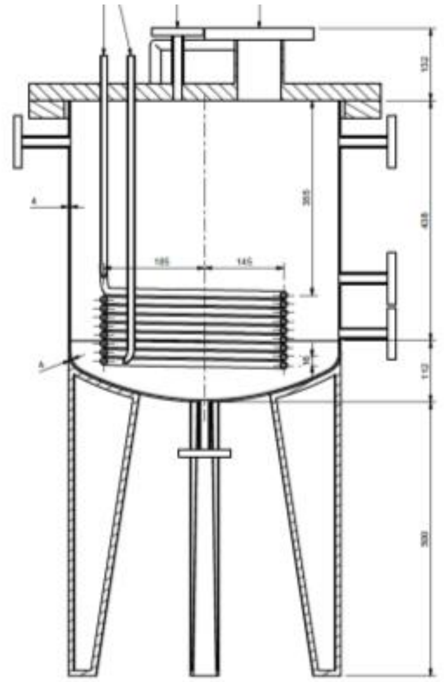

Figure 1: section of the evaporator tank

In the prototype configuration, Stirling engine has been replaced by an electric boiler to test better the evaporation process and the overall thermal desalination plant performance.

Measurements and controls have been included to make plant operation semi-automatic. In particular, according to the operation mode, heating input and pumps operation are automatically controlled. In addition, rounds per minute of the peristaltic pump is remotely controlled by mean of a 0.75 kWe inverter. On the contrary, due to prototype location cooling fluid flow rate is adjusted manually acting on a ball valve.

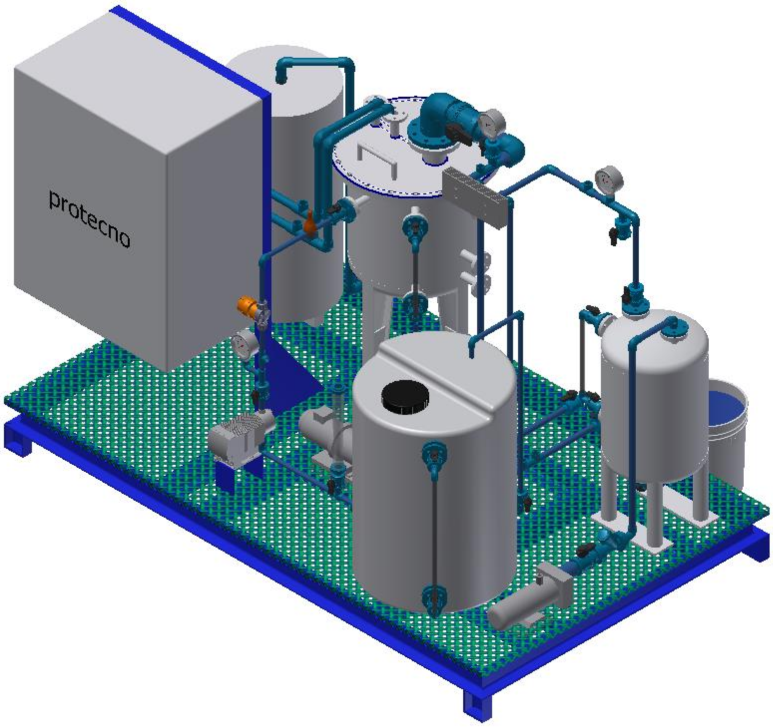

Figure 2: prototype layout

Figure 3: the thermal desalination plant prototype

4 Analysis and discussion of the main results

Plant performance and efficiency in terms of fresh water production/thermal energy input have been evaluated according to the design of the experiments analysis [11]. In particular, plant performance has been monitored both in batch and in continuous operation.

In the former, the evaporator tank is initially filled with the salt water up to its maximum. The evaporation process ends as the free surface of the salt water reaches the top of the coil. In this way, brine salt content is sensibly higher at the end of the process. In the latter, concentrate is continuously extracted and salt water is feed inside again so that brine salinity remains almost constant. More precisely, it depends on the flow rate of the feed water and concentrate respectively.

Batch operation strictly depends on the following three parameters: the heating fluid input temperature, the heating fluid flow rate and the evaporator tank saturation temperature. Compared to batch operation, continuous running needs to control an additional process parameter: the brine concentration.

In batch operation mode, 15 experiments have been performed according to the Central Composite Design (CCD) theory. Initial operating conditions have been usually different for each test. Therefore, transient state effects have been neglected and plant performance evaluated and compared at regime. Experimental data are then fitted according to the least square method and a second order analysis has been carried out in Matlab to predict plant performance at different operating conditions. Anyway, most of variables have a linear dependence with the key process parameters as reported in figures 4-5.

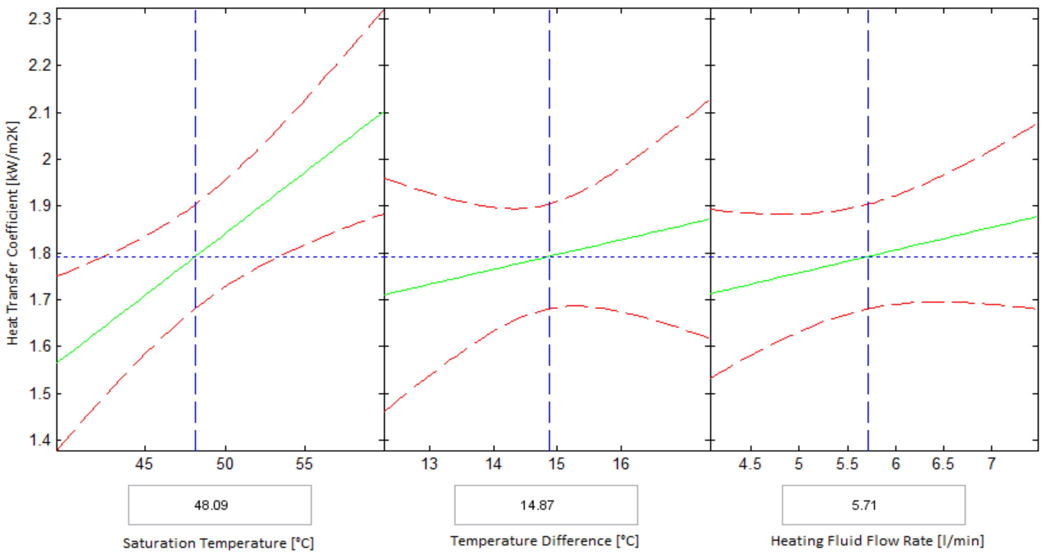

Figure 4: heat transfer coefficient with key process parameters (batch operation)

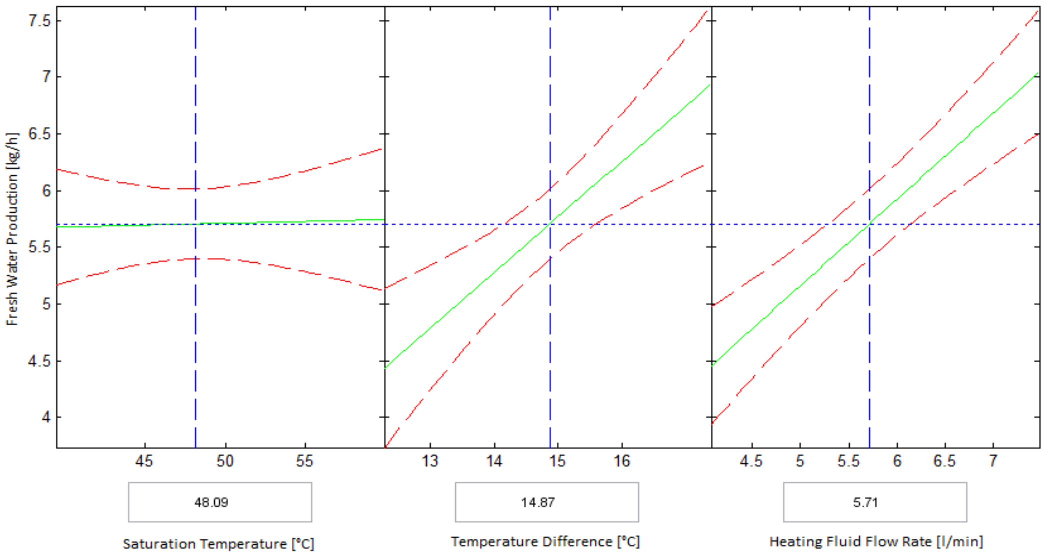

Figure 5: fresh water production with key process parameters (batch operation)

In continuous operation, seawater evaporation depends also on its salt content. Therefore, 25 experiments have been carried out based on the CCD theory. Also in continuous operation mode transient state effects have been neglected and plant performance evaluated and compared at regime. Although the operation time has usually been fixed to 4 hrs for each test, discrepancy in terms of fresh water production exists between the experiments because of different initial operating conditions and transient state effects. Moreover, due to influence of four process parameters at the same time it is difficult to understand plant performance as in batch operation mode.

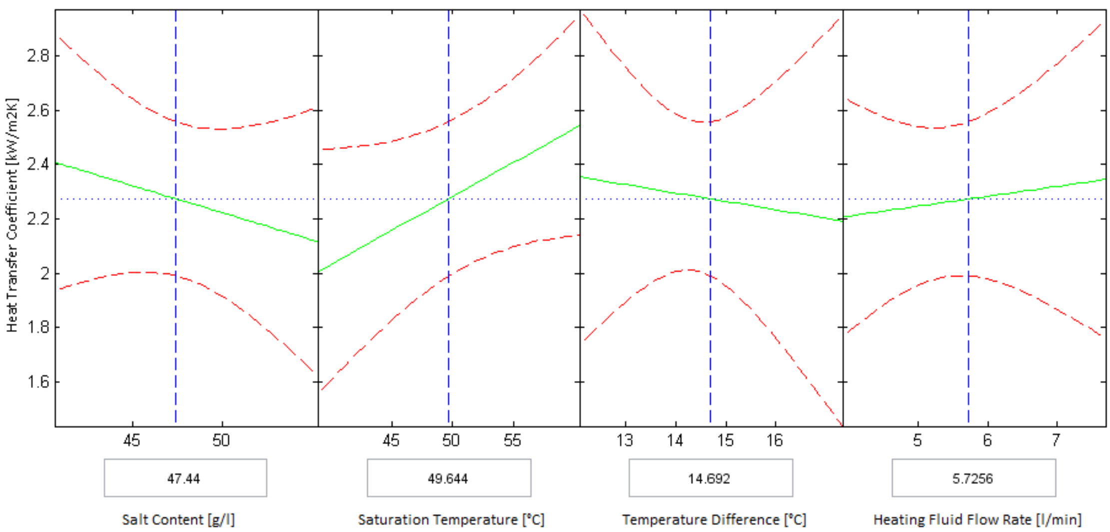

Figure 6: heat transfer coefficient with key process parameters (continuous operation)

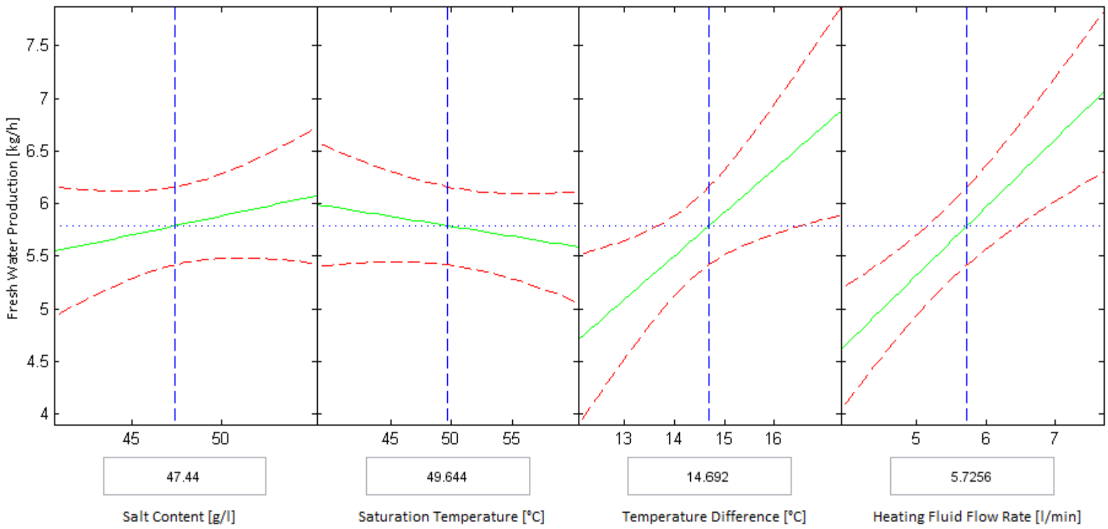

Figure 7: fresh water production with key process parameters (continuous operation)

In general, it is possible to affirm that the response variables can be well predicted in batch operation mode. Despite the higher number of tests results are not satisfactory in continuous operation mode and further experiments are necessary to fully understand the influence of all process parameters. To better appreciate salt content influence on the fresh water production rate salinity should be varied indeed in a wider range (e.g. up to double the seawater salt content).

Several factors have contributed to this discrepancy. For example, the peristaltic pump works inefficiently at low saturation temperatures. Because of the related high pressures and brine conditions (nearly its saturation) actual flow rates are lower than expected thus increasing the salt content in the evaporator tank. In addition, the brine flow rate influenced the conductivity measure causing erroneous fluctuations of the salinity control.

Both in batch and continuous mode vacuum pump operation has been critical at low temperatures. In particular, at 40°C saturation temperature and higher cooling fluid inlet temperatures vapor is partially drawn out prior to its condensation. Besides a reduced fresh water production this has required a higher maintenance of the pump.

Eventually, a comparative analysis with a compact reverse osmosis desalination plant has been performed. In this case, Stirling engine thermal output can be usefully recovered to heat the feedwater thus increasing the desalination plant performance. In the experimental apparatus Stirling engine and the related plate heat exchanger have been replaced by a 1.5 kWe electric heater to better test the desalination plant performance at different inlet temperatures. Experiments shows that despite the higher fresh water production, heat recovery for seawater preheating is unprofitable. In particular, for each kilowatt of thermal power input the consequent electrical power saving is limited to 2.62 We. Moreover, this entails lower water quality and membranes lifetime. Definitively, although small scale RO desalination plants are considerably more efficient than thermal desalination plants these are preferable whenever waste heat can be easily recovered.

4 Conclusions

Most of the ongoing combined power and desalination applications concentrate on large-scale plants which are suitable for mass production of fresh water. Only few studies have been conducted on small scale water thermal desalination systems, and their performance are usually very low. However, there are interesting opportunities for these systems, especially for the needs of isolated users during peak periods.

A simple distillation plant has been built following several design constraints, and its performance experimentally tested. During the experiments several parameters have been adjusted and the performance of the plant was reported under different operating conditions (thermal power input, salt content, saturation pressure and operating temperatures). Since efficiency in terms of fresh water production/thermal energy input was the most interesting result, the performance of the prototype has been evaluated based on the Central Composite Design (CCD) theory. In particular, plant performance has been monitored both in batch and in continuous operation.

In terms of results, the tests campaign has been certainly satisfactory and the target performance largely achieved. The maximum heat transfer was about 6.1 kWt indeed, which is higher than the nominal design condition (5 kWt). Despite the non-ideal plant thermal insulation, fresh water production reached about 7 l/h at best operating conditions, proving good process efficiency. According to the predicted behavior, fresh water production has been strongly dependent on salt content of the treated water and on temperature differences between the heating fluid and the salt water in the evaporator tank. The thermal desalination plant has shown very interesting performance even at the most severe operating conditions. Moreover, the apparatus showed a very good response to the varying in time of thermal power input, thus confirming the opportunity to operate also powered by different forms of waste heat.

In general, the experimental phase has provided significant contribution to confirm and understand most of the mutual interconnections between the different key process parameters. Nevertheless, additional tests are necessary to understand the whole thermodynamic process in further detail before industrializing such a system.

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