Cogeneration Power – Desalination Mobile Floating Plant applied on Supply Vessel

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Abstract. The main objective of this research is to study the supply of both electrical power and potable water through a proposed desalination plant applied on the supply vessels. Fresh water produced will be used for drinking, cleaning and washing purposes contributing to the high demand consumption particularly on board ships. The main idea for proposed plant is to use the renewable energy to produce both power and fresh water which are the main problems in coastal desert. The fresh water generator incorporated in the ship propulsion plant will result in better exploiting the waste heat carried out by cooling water or scavenging air and hence the plant overall thermal efficiency increased by 20%.

Keywords: Hybrid systems, Fuel cell; Cogeneration; Dual purpose facility

Introduction

The fuels history in the marine field started in the 1780s where a number of ships were powered by coal fired boilers feeding reciprocating steam engines (Poil, 1995). Until 1903, when the first diesel powered ship was built, the coal was dominating all kinds and aspects of transportation and power generation all over the world (Elgohary, 2009). Since then the diesel fuel started to gain ground against the coal, this situation continued until the world discovered that coal and diesel were considered as a curse instead of a blessing as was thought before. The environmental effects of
coal and hydrocarbons started to be of a specific importance when the world noticed that the earth's climate is changing to the worse. Global warming, acidic rains, increased hurricanes and tornados, these are the major effects happening due to the uncontrolled use of polluting fuels for about 200 years (Yossef et al., 1995 and Elgohary, 2006). Due to the continuous increase in the worldwide energy demand and therefore consumption, Desalination found to be the most suitable solution for supplying the Egyptian desert with fresh water due to the increasing demand for the Nile water in the Nile valley, the areas suitable for development being those along the Red and Mediterranean Sea shores (Seraq El-din et al., 1978). The standard techniques like multi-stage flash (MSF), multi-effect (ME), vapor compression (VC) and reverse osmosis (RO) are only reliable for large capacity ranges of 100–50,000 m$^3$/day of fresh water production (Fath, 2000). These technologies are expensive for small amounts of fresh water, and they cannot be used in locations where there are limited maintenance facilities and energy supply. Development and use of new technologies for small capacity plants is highly desirable. Solar energy is the most important renewable source of energy in Egypt, which receives more than 5.0 kW/m$^2$ per day (Abdelrassoul, 1998). Solar desalination is a suitable solution to supply some remote regions in Egypt with fresh water. Solar desalination processes are a future promising technology because solar energy is environmentally friendly (Fath, 1998). The solar desalination can be either direct or indirect (Abdel-Monem et al., 1998). One of the well known indirect solar desalination systems is the humidification–dehumidification (HD) process. The humidification dehumidification desalination process is viewed as a promising technique for small capacity production plants. The process has several attractive features, which include operation at low temperature, ability to utilize sustainable energy sources, i.e. solar and geothermal, and requirements of low technology level.

There are a quite number of configurations for HD desalinating processes that have been developed (A1-Hallaj, 1998) using humidification and dehumidification, where the air was circulated in a closed loop using a blower. The humid air was partially condensed in a large surface condenser where most of the latent heat from water condensation was used to preheat the saline water. The circulated air by natural or forced convection was heated and humidified by the hot water
obtained either from a flat-plate solar collector or from an electrical heater. Nawayseh et al. (1997), developed a simulation program to optimize the unit performance. They found that in natural draft operation, the air circulation rate is increased with the rate of water flow.

**Fresh Water Generators on Board Ships**

Much has been published about reducing exhaust gas emissions from marine diesel engine with attention being on either controlling the generation of the emissions inside engine cylinders, removing the emissions after treatment of the exhaust gases, or in the case of SO\textsubscript{x} emissions restricting the fuel specification. There is very little margin left in the large marine diesel engine for reducing CO\textsubscript{2} emissions through improving engine thermal efficiency. After the 1973 oil crisis, considerable investment was put into reducing engine fuel consumption with the result that for some years the largest-bore engines have had an overall thermal efficiency of almost 50%.

Improving the thermal efficiency includes recovering of waste heat like using exhaust gases in a combined power plant or in fresh water generation. There are different methods used for fresh water generation on boardships can be summarized as: Simple vertical evaporator; low pressure evaporator and multistage evaporators (Youssef et al., 1995).

**Mobile Floating Seawater Desalination Plant**

The vast increase in world population and urbanization over the past two decades has resulted in sever potable water and energy shortages. Recent potable water shortages in many parts of the world have cast a spotlight on the problem and led to significant interests in new techniques for water desalination. In addition, environmental concerns over pollutant emissions from conventional power plants using fossil fuel have stimulated research and development in energy technologies that focus on efficient utilization of available energy sources combined with an aggressive search for alternative sources of energy (Lampe et al., 1997). Currently, researchers worldwide are focusing on improving overall energy efficiency of power plants through energy conservation such as cogeneration and by using highly efficient energy conversion systems such as fuel cell. Cogeneration in power plants is a mean for energy
conservation involving the simultaneous production of electric power and useful heat from the burning of fuels in a single steam generation. The utilization of the waste heat from power plant, either as an alternative source of thermal heat or by increasing power generation via a gas turbine, can significantly improve the overall energy efficiency of conventional power plants (Yossef et al., 1995; and Al-Hallaj et al., 2004). In both cases (i.e. cogeneration or fuel cells) considerable emission reduction from power plants can be achieved due to the use of the high efficiency fuel cells or by minimization of waste heat in exhaust streams through cogeneration.

In the Arab Gulf countries, most power plants are cogeneration plants producing electric power and process heat for water desalination. For a given fuel input, the production of water in a cogeneration system is associated with a reduction in electrical power. Although, desalination costs have decreased markedly in the last two decades, cost remains a primary factor in selecting a particular desalination technique for drinking water production. Some reduction in desalination costs may be realized from improvement in plant design, fabrication technique, heat exchange material, plant automation, and scale control techniques. Energy cost for distillation plants (steam and electricity) represents at least 40-50% of the cost of water (Yossef et al., 1995). The minimum cost of water from seawater desalination occurs when power and desalination are combined in one "dual purpose facility" that simultaneously produces electricity and water.

**Seawater Desalination by the Reverse Osmosis Process**

The RO process includes the following three main stages: pretreatment, reverse osmosis and post-treatment (Fig. 1).

**Pretreatment**

The seawater is taken in through sea chests at the bow of the ship and passes through a specially designed metal screen. The seawater supply pumps elevate the pressure of the seawater sufficiently to pass it through the pretreatment process. Here the suspended solids, which cause fouling of the RO membranes, are removed by inline coagulation and filtration. A coagulant is added to the acidified seawater, effectively mixing, and then immediately passing through a dual-media filter to remove the micro flocks which have formed. Polyelectrolyte’s can be
used in addition to coagulants to support the formation of stable, filterable flocks.

A disinfectant is injected into the seawater to prevent microbiological activities in the pipes and filters. Acid is required to prevent carbonate scaling on the RO membranes and is also added upstream of the dual-media filter. The dual-media filters have to be regularly backwashed with filtrate or brine and scour air from the bottom to the top, the effluent being discharged into the sea. The filtrate is polished by means of fine filters for the final protection of the RO membranes from suspended particles.
Reverse Osmosis
The feed water is pumped through the membranes with sufficient pressure, 35-45% of the feed water being converted into permeates and the concentrate being passed through an energy recovery turbine and then partially transferred to the backwash tank and mainly discharged overboard. By passing the concentrate through the energy recovery turbine, the consumption of electric energy is cut by 35%. Chemical cleaning of the RO membranes will be performed regularly in order to reestablish the initial plant performance.

Post-Treatment
Disinfectant and lime are added downstream of the permeate tank for disinfection, pH adjustment and passivation. After lime and disinfectant have been added, permeate becomes potable water.

Power/Desalination Cogeneration
Substantial work has been carried out to date on utilizing waste heat from various processes for desalination; numerous systems involving the utilization of waste heat for desalination of seawater have been proposed and implemented during the last two decades. Defining and mentioning the various sources of waste heat could lead to a better understanding of the utilization of waste heat.

Dual-Purpose Plants Fuel Cell (FC) / Multistage Flash (MSF) Unit / Reverse Osmosis (RO)
One of the waste streams in fuel cells systems is the waste heat contained in the flue gases stream. Depending on the type of fuel cell the heat flow has different qualities. Those fuel cell plants considered suitable for cogeneration can also be coupled with MSF or RO plants to produce distilled water.

The proposal is studying a dual-purpose power/water hybrid plant where power is generated by a high temperature fuel cell system instead of using conventional power generation devices, and water is produced in a MSF plant and a RO system. MCFC and SOFC are the most suitable technologies for cogeneration due to their significantly high operating temperatures, 650 °C and 900 °C, respectively. The rest of fuel cells configurations operate at less than 250 °C. The block diagram of the FC
plant coupled with two desalination technologies representing the main input and output flows is presented in Fig. (2). The fuel cell anode side is fed with natural gas or any other source of hydrogen. Fresh air and recycled CO$_2$ from the auxiliary boiler within the fuel cell system are fed in the fuel cell cathode side. The cooling system inside the fuel cell is a cycle, so there are not input or output flows related to it. The water generated during the operation of the fuel cell stack is reused in steam reforming reaction so this flow is shown as a recycle. The two other outputs of the FC system are AC electricity and exhaust gases stream. Power is directly fed to a RO unit to produce pure water and waste heat is used to produce low pressure steam in a Heat Recovery Steam Generator (HRSG).

Then, low pressure steam is introduced in a MSF desalination unit to produce additional desalted water. Water steam is condensed in the brine heater after MSF and reused in the HRSG unit. Both desalination units are fed with seawater stream which will become two different products: pure water and rejected brine.

![Fig. 2. Block diagram of a fuel cell coupled with a RO and a MSF units.](image_url)

The performance data of the cogeneration power-desalination plant can be summarized in Table 1.
Table 1. Key performance data.

<table>
<thead>
<tr>
<th>Specific electricity consumption kW/m³</th>
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<tr>
<td>Recovery rate</td>
<td>0.33</td>
</tr>
<tr>
<td>Salt rejection</td>
<td>0.99</td>
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<tr>
<td>Electrical output kW</td>
<td>250</td>
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<tr>
<td>Electrical efficiency</td>
<td>0.47</td>
</tr>
<tr>
<td>Exhaust temperature °C</td>
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<tr>
<td>Heat exchanger efficiency</td>
<td>0.85</td>
</tr>
<tr>
<td>Inlet water temperature °C</td>
<td>25</td>
</tr>
<tr>
<td>Steam temperature °C</td>
<td>128</td>
</tr>
<tr>
<td>Outlet gasses temperature °C</td>
<td>140</td>
</tr>
</tbody>
</table>

**Dual-Purpose Plants FC/RO**

The production of desalted water applying distillation technologies is less than 5% compared to membrane technology production capacity. Therefore, a new proposal disregarding MSF unit has been done.

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**Results and discussion**

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For the selected case study the total power of fuel cells is 21383 kW. The power lost in heat in fuel cell is 12267 kW. The following two Fig. 3 & 4 show relation between fuel cells output power and amount of fresh water generated using the waste heat and the relation between fuel cell voltage and amount of heat generated.

![Fig. 3. Relation between fuel cells output power and amount of fresh water generated using heat recovery steam generator at different fuel cell individual voltage.](image-url)
The individual cell voltage has played an important role in determining the characteristics of fuel cell. For most practical fuel cell applications, unit cells must be combined in a modular fashion into a cell stack to achieve the voltage and power output level required for the application. Generally, the stacking involves connecting multiple unit cells in series via electrically conductive interconnects. The effect of cell voltage on the waste heat and amount of fresh water generated and required sea water flow rate which can be used in a Heat Recovery Steam Generator (HRSG) are shown in Fig. 5 & 6.
Although a fuel cell produces electricity, a fuel cell power system requires the integration of many components beyond the fuel cell stack itself, for the fuel cell will produce only dc power and utilize only certain processed fuel. Various system components are incorporated into a power system to allow operation with conventional fuels, to tie into the ac power grid, and often, to utilize rejected heat to achieve high efficiency. In a rudimentary form, fuel cell power systems consist of a fuel processor, fuel cell power section, power conditioner, and potentially a cogeneration or bottoming cycle to utilize the rejected heat. For the selected case study the fuel is assumed to be pure Hydrogen or green Hydrogen. Figures 7 & 8 show the effect of Hydrogen consumption rate and its storage tanks at different fuel cell output electric power.
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Fig. 8. Relation between Hydrogen density and volume of Hydrogen storage tanks at different fuel cell output electric power.

Heat recovery steam generator system make use of 12267 kW of heat power and that increases the total efficiency of the plant. There are a lot of factors which affect on performance of the system of heat recovery generator like sea water temperature difference as shown in the following two Fig. 9 & 10.

Fig. 9. Relation between sea water temperature of heat recovery steam generator and amount of sea water flow rate using heat recovery steam generator at different fuel cell output electric power.
Conclusion

A conceptual study of an innovative combined fuel cell/MSF desalination system and the recovery of the waste heat from the fuel cell is used in a MSF desalination plant has been investigated. From this study, it is observed that regardless of the type of desalination unit (RO and MSF), fuel cells can be efficiently integrated into the system with the waste heat and power generated by the fuel cell being efficiently utilized by the desalination process.

A novel concept for integrating fuel cells with desalination systems is proposed and investigated in this work. Two unique case studies are discussed. The First involving repowering system with a fuel cell and a reverse osmosis (RO) unit and the second; integrating the waste heat from fuel cell with a thermal desalination process such as multi-stage flash (MSF). The underlying motivation for this system integration is that the exhaust gas from the fuel cell power plant contains considerable amount of thermal energy, which may be utilized in desalination units. This exhaust heat can be suitably used for potable water production, but also decreases the relative energy consumption by approximately 20% when using waste heat from exhaust gases in the desalination process.

The first case study includes repowering of Preussag mobile floating seawater desalination plant with fuel cells having capacity of 18.4 MW.
This power used for desalination plant and other electric loads. The RO desalination plant consumes 16 MW in addition to 2.4 MW used for electric loads.

The second case study, integrate the waste heat from fuel cell with a multi-stage flash (MSF) desalination process. The MSF desalination unit produces 10560 m$^3$/day which equals to 3.89 MW electric power if this amount produced by RO desalination plant.

The results have indicated that the total thermal efficiency of the combined system can be further increased by approximately 20%. The analysis has also indicated that the combined fuel cell/desalination systems can save 3.89 MW electric power which can be used for fresh water generation of electric load supply.

References


<table>
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<th>Notations</th>
<th>Description</th>
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<tr>
<td>CO₂</td>
<td>Carbon dioxide oxides</td>
</tr>
<tr>
<td>FC</td>
<td>Fuel Cell</td>
</tr>
<tr>
<td>HRSG</td>
<td>Heat Recovery Steam Generator</td>
</tr>
<tr>
<td>HD</td>
<td>Humidification–dehumidification</td>
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<tr>
<td>MCFC</td>
<td>Molten carbonate fuel cell</td>
</tr>
<tr>
<td>ME</td>
<td>Multi-effect</td>
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<tr>
<td>MSF</td>
<td>multi-stage flash</td>
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<tr>
<td>RO</td>
<td>Reverse osmosis</td>
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<tr>
<td>SOFC</td>
<td>Solid oxide fuel cell</td>
</tr>
<tr>
<td>SOX</td>
<td>Sulphure oxides</td>
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<td>VC</td>
<td>Vapor compression</td>
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محطة مشتركة عامة متنقلة لتوليد الطاقة وتحلية المياه وتطبيقها على سفينة إمداد بحري

هبة لهيطة، و على المقر

جامعة الإسكندرية، كلية الهندسة، قسم الهندسة البحرية وعمارة السفن،

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المستخلص: الهدف الرئيسي من هذا البحث هو تزويد كل من الطاقة الكهربائية ومياه الشرب المحلاة من مياه البحر عن طريق سفينة تموين بحرية مخصصة لهذا الغرض، سوف تنتج مياه عذبة لأغراض الشرب والعسل وذلك مساهمة في ارتفاع الطلب على المياه بالذات في المناطق الساحلية المجهزة بمحطات تحلية مياه وتحتاج إلى زيادة إنتاجها في بعض الأوقات الحرجة لها أو أوقات الندرة مثل فترات الصيانة، أو الأعطال المفاجئة. الفكرة الرئيسية لهذه السفينة المقترحة هو استخدام الطاقة المتعددة لإنتاج الكهرباء والماء على حد سواء، والتي تحل المشكلات الرئيسية السريعة للإنتاج المزدوج في بلادنا، وسوف تولد الماء النقي الصافي الذي يستخدم في دائرة الدفع للسفينة، وستغلف أفضل تغيير حراري تبديد الماء والهواء، وبالتالي يستفاد من الطاقة الحرارية المصنعة بكاملها مما يزيد في الكفاءة العامة للمنظومة بنسبة 20٪.