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Hybrid gas turbine–organic Rankine cycle for seawater desalination by reverse osmosis in a hydrocarbon production facility

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ABSTRACT

Despite water scarcity, the use of industrial waste heat for seawater desalination has been limited in the Middle East to date. This study evaluates the technical and economic feasibility of integrating on-site gas turbine power generation and reverse osmosis equipment for the production of both electricity and fresh water in a coastal hydrocarbon production facility. Gas turbine exhaust gas waste heat is recovered using an intermediate heat transfer fluid and fed to an organic Rankine cycle evaporator, to generate mechanical power to drive the reverse osmosis high pressure pump. Six candidate organic working fluids are evaluated, namely toluene, benzene, cyclohexane, cyclopentane, n-pentane and R245fa. Thermodynamic and desalination performance are assessed in the harsh climatic and salinity conditions of the Arabian Gulf. The performance metrics considered incorporate electric power and permeate production, thermal and exergy efficiency, specific energy consumption, system size, and permeate quality. Using toluene in the bottoming power cycle, a gain in power generation efficiency of approximately 12% is achieved relative to the existing gas turbine cycle, with an annual average of 2260 m^3/h of fresh water produced. Depending upon the projected evolution of local water prices, the investment becomes profitable after two to four years, with an end-of-life net present value of 220–380 million USD, and internal rate of return of 26–48%.

1. Introduction

Owing to the abundance and affordability of hydrocarbon energy sources, rising economic activity and demographics, energy consumption in the Arabian Gulf [1] has soared over the past decade. Certain Arabian Gulf countries have reached among the highest carbon footprints per capita in the world [2]. The hydrocarbon industry itself is an energy-intensive sector, which consumes up to 10% of its gross production [3]. In parallel, the exploitation of aging and sour hydrocarbon reservoirs is associated with increased production costs [1]. This context is prompting energy efficiency enhancement and conservation measures [4].

Oil and gas facilities consume substantial fresh water volumes for enhanced hydrocarbon recovery and refining, as well as on-site domestic uses. The scarcity of local fresh water sources, combined with a projected 45% increase in water demand by 2030 in for example the United Arab Emirates (UAE) [5], place an increasing reliance on seawater desalination, which is energy-intensive, with an associated carbon footprint. Saudi Arabia, the UAE,[1] Kuwait, and Qatar hold among the top five largest seawater desalination capacities in the world [6]. The high salinity, turbidity, temperature and abundant marine life of the Gulf seawater pose challenges for desalination, in terms of performance, maintenance (i.e., fouling), energy requirement and cost [7]. Nearly a third of the UAE's greenhouse gas emissions are produced by desalination plants [8]. Whereas reverse osmosis (RO) has the dominant share of seawater desalination globally, multi-stage flash (MSF) still accounts for over 60% of the UAE's desalination capacity, followed by RO (~12%) and multiple-effect distillation (MED) (~6%) [7]. This is attributable to low energy prices, and MSF reliability and suitability to both high-volume production and co-generation [7]. However, as a result of technological improvements, RO now offers lower specific energy consumption (SEC) and specific water cost,[2] lower environmental impact and footprint, and more flexible capacity relative to either MSF or MED. This has resulted in the use of RO growing substantially in the Middle East over the past decade [7]. In addition, RO is suitable for small to medium capacity [10] in remote locations with

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[1] The UAE holds the second largest seawater desalination capacity in the world, 7.3 million m^3/day [6].

[2] RO's SEC ranges from 4 to 6 kW he/m^3 internationally for seawater, compared with 19.6–27.3 kWhe/m^3 for MSF, and 14.4 to 21.4 kWhe/m^3 for MED. The desalination cost of RO is of 0.45–1.72 USD/m^3 internationally for seawater, compared with 0.52–1.75 US$/$m^3$ for MSF, and 0.52–1.01 USD/m^3 for MED [9].

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Nomenclature

Notations

C_p	specific heat capacity at constant pressure (kJ/(kg C))
Ex	exergy transfer rate (kW)
F	power correction factor (–)
g	gravitational acceleration (m/s^2)
h	specific enthalpy (kJ/kg)
HR	heat rate (kJ/MW h)
L	latent heat (kJ/kg)
LHV	lower heating value (kJ/kg)
M	molecular mass (kg/kmol)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa)
$\dot{Q}$	heat transfer rate (kW) or volumetric flow rate (m^3/s)
s	specific entropy (kJ/kg K)
T	temperature (°C)
V	volume (m^3) or velocity (m/s)
w	specific humidity (kg water vapor/kg dry air) or salt mass fraction (–)
$\dot{W}$	power (kW)
x	molar faction (–)
z	elevation (m)

Greek symbols

c	critical
Δ	difference
μ	chemical potential (J/kg)
ρ	density (kg/m^3)
η	thermal or isentropic efficiency (–)
φ	exergy efficiency (–)
υ	specific volume (m^3/kg)

Superscripts

ch	chemical
ph	physical
$*$	restricted dead state

Subscripts

a	ambient air
cd	condenser or condensation
d	destruction
e	electric
eva	evaporation
f	feed water or fuel
HX	heat exchanger
in	inlet
$isen$	isentropic
net	net
out	outlet
oil	oil
P	pressure
T	turbine
v	vapor
w	water
0	environmental dead state

difficult or no access to the centralized distribution network, which is of interest to oil/gas fields.

Despite a high degree of heat integration in oil/gas facilities, a significant potential remains for indirect waste heat utilization [11]. Many oil/gas facilities in the Arabian Gulf have on-site seawater desalination units for e.g. boiler and domestic consumption, that are powered using conventional energy sources. In this study the feasibility of integrating existing on-site gas turbine (GT) power generation and RO desalination equipment in a coastal hydrocarbon processing plant is evaluated thermodynamically and economically to reduce facility energy consumption. The technical performance metrics include electric power and permeate production, system thermal and exergy efficiency, size, and RO specific energy consumption and permeate quality. Before describing the proposed approach, previous efforts on enhancing the sustainability of seawater desalination using recycled waste heat, and on recovering medium grade waste heat (i.e., 250–650 °C) [12] using organic Rankine cycles (ORCs), are summarized.

2. Energy conversion approaches for sustainable desalination

2.1. Waste heat sources

Several studies have investigated the use of waste heat from power plants, LNG regasification terminals and industrial processes for thermal desalination (i.e., MSF, MED). Considering gas power plants, which are the focus of the present work, examples include El Nashar [13], who presented a thermoeconomic and reliability optimization of a MSF desalination plant powered by steam generated from GT flue gases. In addition, Sommarva [14] discussed different waste heat recovery options to optimize the performance ratio and production of hybrid MSF/MED plants. The waste heat streams considered included GT flue gases from a combined cycle plant with supplemental firing, steam extracted from the bottoming steam turbine, and MSF steam condensate for brine pre-heating.

Fewer studies have dealt with the conversion of either power plant or industrial waste heat [15,16] to drive membrane-based (e.g., RO) desalination. Instead, efforts to enhance the sustainability of seawater RO (SWRO) have focused on renewable energy sources including solar photovoltaic electricity [e.g., 17] and solar thermal collector heat [e.g., 18]. In most cases, solar energy-powered ORCs were used to drive RO high pressure pumps (HPPs) [e.g., 18]. Unlike water/steam Rankine cycles (SRCs), ORCs do not consume large volumes of water, operate at lower pressures, offer flexibility in terms of heat source temperature in the low/medium grade range, have low operating costs, and require little maintenance [19]. A variety of working fluids, including refrigerants, alkanes and aromatic hydrocarbons, have been proposed depending upon the heat source enthalpy and operating conditions [19], with many studies [e.g., 20] detailing cycle design and fluid selection.

Although renewable-energy powered desalination can contribute to meet fresh water demands, the intermittency of the energy source may not provide a stable output, which can be critical for industrial applications. Also, additional capital investment and facility footprint are required for renewable energy conversion. RO systems can be powered by energy sources abundantly available in hydrocarbon plants, such as power generation or process waste heat. Bouyazani et al. [15] presented a mechanically and thermally coupled SRC–RO system. Pre-heating the RO feed water using SRC condenser waste heat was found to increase permeate production, but decreased its quality, although still below the selected limit of 1000 ppm totally dissolved salts (TDS). Esfahani and Yoo [21] proposed the use of micro-gas turbine shaft mechanical power, rather than flue gas waste heat, to drive the high pressure pump of a RO unit. In addition, GT exhaust gas waste heat was employed to drive an absorption refrigeration system for