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Performance investigation of a power, heating and seawater desalination poly-generation scheme in an off-shore oil field

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ABSTRACT

Hydrocarbon production fields are energy-intensive, with significant demands for on-site power, process heat and fresh water, particularly in arid climates. A poly-generation scheme based on the conversion of gas turbine exhaust thermal power into mechanical work to drive a seawater reverse osmosis unit and generate process heat in an off-shore oil field in the Arabian Gulf is evaluated thermodynamically and economically. The prime mover exhaust thermal power is recovered using a bottoming organic Rankine cycle (ORC), with four working fluids used in commercial ORC systems evaluated. The performance of the poly-generation system is assessed both on a yearly and a seasonal basis. The octamethyltrisiloxane (MDM) cycle yields 6 MW of net power output at ideal and overall exhaust gas heat recovery efficiencies of 14% and 10%, respectively, 37 MW of process heat, and 1380 m^3/hour of permeate. The reverse osmosis unit operates at a specific energy consumption and exergy efficiency of 4.1 kWh/m^3 and 29%, respectively. The exergetic efficiency of the poly-generation system is estimated at 32%, thereby enhancing the efficiency of the original gas turbine power generation system by 6%. The system becomes profitable after approximately three years for subsidized local water and natural gas prices.

1. Introduction

The scarcity of fresh water sources in the Arabian Gulf, combined with a projected 45% increase in water demand by 2030 in for example the United Arab Emirates (UAE) [1], place an increasing reliance on seawater desalination, which is energy-intensive, with an associated carbon footprint. Saudi Arabia, the UAE, Kuwait, and Qatar hold among the top five largest seawater desalination capacities in the world [2]. Nearly a third of the UAE's greenhouse gas emissions are produced by desalination plants [3]. The high salinity, turbidity, temperature and abundant marine life of the Gulf seawater pose challenges for desalination, in terms of performance, maintenance, energy requirement and cost [4]. Reverse osmosis (RO) offers lower specific energy consumption (SEC) and specific water cost, lower environmental impact and footprint, and more flexible capacity relative to either multi-stage flash (MSF) or multiple-effect distillation (MED), which account for over 60% and 6% of the UAE's desalination capacity, respectively [2,4]. This has resulted in the share of RO growing substantially in the Middle East over the past decade [4,5]. In addition, RO is suitable for small to medium capacity [6] in remote locations with difficult or no access to the centralized distribution network, which is of interest to oil/gas fields.

Oil and gas facilities consume substantial fresh water volumes for hydrocarbon recovery and processing, and on-site domestic uses. Certain Arabian Gulf facilities have on-site seawater desalination units that are powered using conventional energy sources. However, despite a high degree of heat integration, the use of power generation- or process waste heat has been limited in the region's industry, particularly for seawater desalination [7,8]. Waste heat utilization for on-site water desalination could save substantial amounts of energy that are currently expended both for producing and bringing water on-site [9].

Waste heat utilization from fossil [10–14], nuclear [15–17], and biomass [18] power generation plants, sulfur burning [19], SO_2 scrubbing [20] and cement kilns and clinker coolers [21], has been actively investigated for thermal desalination (i.e., MSF, MED). The potential of waste heat utilization for adsorption desalination, membrane distillation, and forward osmosis desalination has also been recently highlighted [22,23]. Although RO energy costs can contribute up to 70% of the overall water production cost [24], the conversion of power plant or industrial waste heat [25,26] to drive

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Nomenclature

Abbreviations

RO	reverse osmosis
SWRO	seawater reverse osmosis

Notations

C_p	specific heat capacity at constant pressure (kJ/(kg-C))
$\dot{E}x$	exergy transfer rate (kW)
F	power correction factor (−)
h	specific enthalpy (kJ/kg)
HR	heat rate (kJ/MWh)
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)
SEC	specific energy consumption (kWh/m^3)
T	temperature (°C)
TDS	total dissolved solids concentration (mg/l)
V	volume (m^3) or velocity (m/s)
w	ambient air specific humidity (kg water vapor/kg dry air) or salt mass fraction (−)
$\dot{W}$	power (kW)
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 (-)
τ	exergetic temperature factor (−)
υ	specific volume (m^3/kg)

Superscripts

ch	chemical
ph	physical
*	restricted dead state

Subscripts

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

RO desalination has received little attention. Rather than waste heat, the use of renewable energy to power ORCs that drive RO high pressure pumps (HPPs) [6,24,27–36] has been emphasized. 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 (i.e., 250–650 °C [37]) have low operating costs, and require little maintenance [30,38–40]. However, renewable energy sources are intermittently available, require additional investment and footprint and potentially energy storage [41] for installation in industrial facilities. Instead, RO systems could be powered by energy sources readily available in industrial plants, such as power generation or process waste heat. Combustion processes (i.e., power generation, fired and furnace heating, boiling), which are typically the largest industrial energy consumers, offer substantial energy conservation opportunities [9]. Bouyazani et al. [25] presented a mechanically and thermally coupled SRC-RO system. The RO feed water was pre-heated using SRC condenser waste heat to increase permeate production. Kosmadakis et al. [26] recovered diesel engine waste heat at 450 °C using a cascaded ORC to drive a RO plant. Using R245fa and R134 in the topping and bottoming ORCs, respectively, an annual 60 MWh of net power was produced at a thermal efficiency of 6.9%, yielding 24,000 m^3 of RO fresh water annually at a specific cost of 1.06 €/m^3. The system capital expenditure was estimated to be 40% lower than that using solar collectors as energy source. Esfahani and Yoo [42] proposed a tri-generation system recovering the waste heat of a micro-gas turbine (GT) to drive an absorption refrigeration system, while the HPP of the RO unit was powered using GT shaft work. Depending on the system configuration, its overall exergy efficiency and power output ranged from 26 to 30%, and 100–160 kW, respectively.

Given the limited number of studies on industrial waste heat powered-ORCs for RO desalination, summarized above, the application of such systems to other end uses is worth summarizing. Such applications have focused on low-grade sources (i.e., <250 °C [37]), with recent examples including [43] in the cement sector, [44] in the steel industry, [45] in ceramic manufacturing and [46–49] in the hydrocarbon sector. In the present study, the recovery of medium grade heat (i.e., typically in the range of 300–550 °C) produced by heavy duty GTs in oil/gas applications is targeted, given its abundance, quality, accessibility, and absence of direct interference with core industrial processes. Analyses of ORCs driven by medium grade heat to power applications other than desalination, include studies [50–59]. For large frame industrial GTs (i.e., 180–126 MW) with high exhaust gas temperatures (i.e., approximately 580 °C–640 °C), using suitable ORC fluids (e.g., toluene), the combined cycle efficiency of GT–ORCs is comparable to that of GT–SRCs with single pressure HRSGs [51]. At lower exhaust temperatures representative of aeroderivative and recuperative GTs (~380 °C–440 °C), ORCs may offer 3–6% higher combined cycle efficiency than GT-SRCs and are economically viable [51]. Pierobon et al. [56] recovered exhaust gas waste heat at a temperature of 376 °C from a 17 MW GT on an off-shore platform via an intermediate oil loop and a recuperative, superheated 6.4 MW ORC. The thermal efficiency of the ORC ranged from 14 to 28% depending upon the working fluid, with best performance