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Thermodynamic analysis of hybrid cycles based on a regenerative steam Rankine cycle for cogeneration and trigeneration

Kasra Mohammadi*, Jon G. McGowan

Department of Mechanical and Industrial Engineering, University of Massachusetts, Amherst, MA 01003, USA

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ABSTRACT

In this study, different feasible integrated configurations were proposed and thermodynamically evaluated for cogeneration of power and fresh water/cooling, and trigeneration of power, cooling and fresh water. A steam regenerative Rankine cycle with condensation and steam extractions, driven by a concentrated solar tower, was designed to supply the thermal heat requirements of absorption cooling and multi effect distillation, or thermal vapor compression-multi effect distillation. The results showed the configurations that utilize steam extraction with a lower temperature and pressure were more efficient. For power and fresh water cogeneration, utilizing the condensation steam to integrate multi effect distillation with a power cycle was thermodynamically more efficient than the integration of thermal vapor compression-multi effect distillation using extraction steams. Integrated Rankine cycle-multi effect distillation configuration was found to be very competitive with the direct supply of electricity to reverse osmosis systems, particularly at higher fresh water productions. However, further examinations are required considering geographical, environmental and economic factors. For power and cooling cogeneration, all proposed absorption cooling configurations were more efficient than supplying electricity directly to vapor compression cooling. Moreover, despite significantly lower steam requirements of double and triple effects absorption cooling, integration of a single effect absorption cooling to the power cycle was more efficient. The most efficient trigeneration configuration was identified when multi effect distillation and single effect absorption cooling were integrated to a Rankine cycle. The results and conclusions of this study can be generalized to other coal and natural gas power plants that employ similar Rankine cycle configurations.

1. Introduction

Recently, growth in the world population, economic and living standards have been responsible for a substantial increase in global energy consumption. Moreover, exploitation of fossil fuels to supply energy demands has led to climate change which is expected to have far-reaching and long-lasting consequences on the planet [1]. These factors have motivated the importance and necessity of developing more efficient ways for energy generation and conservation that avoid the production of greenhouse gases that contribute to climate change [2]. One method to address these issues is to develop combined production such as cogeneration and trigeneration for simultaneous production of power with heating and cooling [3] or multigeneration of different products using renewable energy sources such as solar [4]. By using hybrid systems with multiple output products, the overall efficiency of the system can be increased over a single output system, and by using renewable sources, carbon and other harmful emissions are avoided.

Water desalination systems have been developed and utilized as a potential solution to address the fresh water supply in many parts of the world. Reduction of costs and energy requirements as well as improve of reliability to produce a higher quality fresh water have been the main contributors in order to advance the desalination processes. Available desalination technologies can generally be classified as: Thermal desalination such as multi effect distillation (MED), and Membrane desalination such as reverse osmosis (RO). Thermal desalination technologies offer an appealing technological option for integration to power plants for dual-purpose schemes or cogeneration. Via cogeneration, power and fresh water can be produced simultaneously, which may increase the economic and overall performance of hybrid plants [5].

Along with electricity and fresh water outputs, cooling is a critical requirement in both the residential [6] and industrial sectors [7]. Two main types of cooling or refrigeration systems are: (1) Vapor compression cooling (VCC) that requires electrical energy, and (2) absorption cooling (ABC) that uses thermal energy. Water-lithium bromide

* Corresponding author.
E-mail address: kmohammadi@umass.edu (K. Mohammadi).

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Nomenclature

A	absorber
ABC	absorption cooling
BPE	boiling point elevation
BFP	boiler feed water pump
C	condenser
CEP	condensate extraction pump
CFWH	closed feed water heater
COP	coefficient of performance (−)
C_r	compression ratio
DCA	drain cooling approach
E	evaporator
E_r	expansion ratio
FB	flash box
G	generator
GOR	gain of ratio
h	enthalpy (kJ/kg)
HP	high pressure
HTC	high temperature condenser
HTG	high temperature generator
HTHX	high temperature heat exchanger
HX	heat exchanger
LiBr	lithium bromide
LP	low pressure
LTG	low temperature generator
LTHX	low temperature heat exchanger
$\dot{m}$	mass flow rate (kg/s)
MED	multi effect distillation
MTC	medium temperature condenser
MTG	medium temperature generator
MTHX	medium temperature heat exchanger
M_r	mixing ratio (entrainment ratio)
N	number of effects
NEA	non-equilibrium allowance
OFWH	open feed water heater
$\dot{Q}$	heat transfer rate (kW)
P	pressure (kPa)
RO	reverse osmosis
SSSF	steady state and steady flow
T	temperature (°C)
TTD	terminal temperature difference
TVC-MED	thermal vapor compression
VCC	vapor compression cooling
$\dot{W}$	work (kW)
x	LiBr concentration ratio (%)
X	salinity of water (ppm)

Symbols

desal	desalination
ph	preheater
sh	super heater
$\in$	effectiveness
λ	latent heat
η	energy efficiency

Subscripts

c	condensate
B	brine
D	distillate
ev	entrained vapor
F	feed seawater
in	input
ise	isentropic
ms	motive steam
out	outlet
S	steam
sw	sea water
tur	turbine

(H_2O-LiBr) ABC systems have received attention for district cooling and air conditioning purposes due to minimal environmental impacts and the possibility of using low to middle temperature heat sources [8].

In general, constructing separate plants for producing electricity, fresh water and cooling requires significant capital costs, infrastructure and materials, and does not take advantage of the potential benefits of hybridization. The coupling of these systems is attractive not only to reduce costs and to improve the flexibility in operation, but also to reduce the environmental impacts and enhance sustainability [9]. Thus, there is a critical need for new approaches and configurations that can simultaneously address the energy supply, water treatment processes, and cooling demands. Hybrid plants, such as cogeneration or trigeneration, combine these processes to provide lower cost products than any of the individuals processes [10]. The configurations, performances and analysis of cogeneration of power and fresh water have been reviewed in previous studies. In [11], the authors reviewed the cogeneration of power and fresh water with a further focus on drawbacks and possible enhancements of using hybrid desalination plants. They also reviewed and discussed the system configurations as well as design and economic aspects of hybrid desalination plants. El-Nashar [12], provided a review of the state of the art of cogeneration for power and desalination systems. The also discussed a method of determining the optimal cogeneration option to supply specified power and fresh water demands. Wu and Wang [13] presented a review on different aspects of combined cooling, heating, and power (CCHP) systems such as definition, characteristic and advantages of CCHP systems as well as different configurations of CCHP technologies. Cho et al. [14] reviewed CCHP systems with an emphasis on the thermodynamic analysis, optimization and performance enhancement methods of the systems presented in the literature.

Concentrated solar power (CSP) represents a promising renewable energy system that can provide high temperature thermal energy for electricity generation [15]. A CSP system is a suitable option for hybridization with other systems. That is, a CSP system can provide electricity and also supply the thermal energy demands of MED and ABC units.

Many investigations have been conducted regarding the hybridization of CSP-desalination plants. For example, the viability of combining CSPs with desalination was studied for Mediterranean region in [16] and for MENA (Middle East and North of Africa) region in [17]. These authors concluded that seawater desalination using CSPs provide affordable, sustainable and secure large-scale freshwater to supply the growing fresh water demands in these regions. Other investigations assessed the potential of combined CSP-desalination in different regions such as the Gaza strip in Mediterranean region [18], in New Mexico, USA [19], and in Oman [20]. Alexopoulos and Hoffschmidt [21] discussed the possible development of combined solar power tower and desalination plants in Greece and Cyprus. Palenzuela et al. [22] assessed different combinations of parabolic trough CSP with desalination units for operating in Abu Dhabi, UAE. They showed that integrated CSP-MED plant provides a higher thermodynamic efficiency than combined CSP-RO plant. Olwig et al. [23] studied the thermodynamic and economic aspects of combining a parabolic trough CSP with MED and RO units for cogeneration of power and fresh water in two locations