Applied Thermal Engineering 121 (2017) 1059–1069

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Solar energy based integrated system for power generation, refrigeration and desalination

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HIGHLIGHTS

- Concentrated solar collectors are used in multigeneration of power and commodities.
- Energy and exergy analyses of system and subsystems are described and conducted.
- Performance comparisons of multigeneration system to referenced baseline system (power only) are done.
- The present system helps improve the use of renewable sources for better sustainability.

ARTICLE INFO

Article history:
Received 18 November 2015
Revised 14 January 2017
Accepted 25 March 2017
Available online 28 March 2017

Keywords:
Solar power
Gas turbine
Efficiency
Energy
Exergy
Multigeneration

ABSTRACT

In this study, a multigeneration system is proposed to integrate a solar-driven gas turbine with an organic Rankine cycle, a small capacity absorption refrigeration system, single stage flash desalination, and direct space heating. Three concentrated solar collectors with rated concentration ratios of 300, 500, and 800, at a solar insolation of $I = 800\ \text{W/m}^2$, produce 1000 °C air at the gas turbine inlet. Heat recovery from compressor intercooling and exhaust streams supply heat to the absorption refrigeration system generator, desalination process, and organic Rankine cycle boiler. These subsystems include secondary power generation, chilled water storage for space cooling, and domestic hot water production from heated desalinated water. Space heating is obtained through heat exchange with warm waste brine from the desalination process. The proposed system is compared to a reference system integrating the same solar power system with a Kalina cycle at energy and exergy efficiencies of 0.275 and 0.29. The multigeneration system indicates energetic and exergetic efficiencies of 0.284 and 0.27, respectively. Although the solar gas turbine-Kalina system suggests similar efficiency results, the multigeneration system provides a more sustainable and promising for additional commodity production from a single heat source at suitable levels for community or small commercial applications, which would otherwise require additional primary energy sources.

1. Introduction

Efficient resource utilisation in power generation applications is a critical engineering challenge in meeting the world's energy sustainability goals. Many past studies focused on improving energy and exergy efficiencies, and reducing environmental impact of major traditional power generation systems such as gas turbine-generators and steam power plants. Current technologies are continuously being developed to address key issues—investigation of turbine materials that are able to operate at and withstand higher temperatures, reduction and/or recovery of heat losses, as well as the use of sustainable energy resources in place of or in combination with traditional non-renewable resources.

Gas turbine Brayton cycles are among the most prevalent methods of power generation world-wide, with electricity generation via natural gas turbines accounting for 22% of global electricity production in 2013 [1]. Methods to improve the efficiency of these systems and other primary power generation systems have been extensively studied, such as compressor intake-air cooling and/or inter-cooling, combustion air pre-heating in gas turbine cycles [2,3], and exhaust heat recovery options in steam [4] and gas turbine power plants. Combined cycle arrangements for secondary power generation via heat recovery from high temperature exhaust streams typically consider steam Rankine cycles [5]. In the medium-to-low temperature heat source range (300–400 °C,

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http://dx.doi.org/10.1016/j.applthermaleng.2017.03.116
1359-4311/

Nomenclature

A	area, m^2
c_p	specific heat capacity, kJ/kg K
C	concentration ratio
ex	specific exergy, kJ/kg
$\dot{Ex}$	exergy rate, kW
h	specific enthalpy, kJ/kg
$\dot{H}$	flow enthalpy, kW
I	solar insolation, W/m^2
$\dot{m}$	mass flow rate, kg/s
P	pressure, kPa
pr	pressure ratio
$\dot{Q}$	heat rate, kW
s	specific entropy, kJ/kg K
$\dot{S}_{gen}$	entropy generation for component, kW/K
T	temperature, K
$\dot{V}$	volume flow rate, m^3/s
$\dot{W}$	shaft power, kW
x	vapour quality

Greek letters

Δ	difference
ε	effectiveness
η	efficiency
ρ	density, kg/m^3
σ	Stefan-Boltzmann constant
ψ	exergy efficiency

Acronyms

ACH	air change per hour
ARS	absorption refrigeration system
COP	coefficient of performance
CTES	cold thermal energy storage
DHW	domestic hot water
GT	gas turbine
HX	heat exchanger
LMTD	logarithmic mean temperature difference
ORC	organic Rankine cycle
SGT	solar-driven gas turbine

Subscripts

a	air
ap	aperture
B	boiler
BR	brine
C	compressor
CB	combustion boiler
CH	chiller
COOL	cooling
Cond	condenser
CW	cooling water
d	destruction
ev	evaporation
ex	exhaust, exit
f	fluid (liquid) state
fg	liquid-gas phase change
g	gas (vapour) state
GEN	generator
Heat	heating (or ‘H’)
HPC	high pressure condenser
HW	hot water
i $\{i = 1,2,3,\ldots,n\}$	state points (or inlet)
IC	intercooler
K	Kalina
LPC	low pressure condenser
MX	mixer
NET	net value
o	reference state
P	pump
ph	preheat
PP	pinch point
R	receiver
s	steam, isentropic
sat	saturation state
Sep	separator
sh	superheat
SC_j	solar collector (j = 1–3)
ST	steam (vapour) turbine
SW	seawater
sw	fraction salt water
w	water

Superscripts

$'$	liquid (or alternative value)
$''$	vapour
Q	heat (exergy)

[5]) two cycles often considered are the organic Rankine cycle (ORC) and the Kalina cycle. The varying evaporation temperature of the Kalina cycle, due to the properties of the working fluid mixture (typically H_2O-NH_3 or H_2O-LiBr), make it possible to reduce the irreversibility of the heat recovery process by minimizing the logarithmic mean temperature difference (LMTD) across the heat exchanger components [5]. The ORC, although unable to achieve the same temperature matching characteristics of the Kalina cycle, is competitive due to its simpler design as it generally does not require operating pressures as high as those required for the Kalina cycle [5,6]. Furthermore, it is possible to minimize the LMTD between the heat source and working fluid in the boiler component of the ORC by selecting suitable organic working fluids based on the source temperature and thermophysical properties [5]. Many of the organic fluids commonly considered exhibit a positive (or nearly vertical) slope of the saturated-vapour line of the vapour-liquid dome, which allows expansion from a saturated vapour without the risk of liquid formation in the turbine [7] as well as the potential for pairing with lower temperature heat sources.

In addition to secondary power generation arrangements, combined heat and power systems also provide an opportunity for multigeneration of other valuable commodities by means of process heating and/or power supply, such as syngas and hydrogen fuel [8], CO_2 capture from exhaust streams [9], and consumer commodities such as fresh water [10], domestic hot water [11], and space conditioning [12,13]. By producing outputs that would otherwise require additional energy inputs (very often from fossil fuels), multigeneration systems improve the efficiency of primary power generation systems by more completely utilizing the energy input and reducing the consumption of non-renewable resources.

To aid the sustainability efforts of reducing environmental emissions, it is critical to integrate renewable energy sources in primary power applications to supplement or replace fossil fuel energy. Implementation of sustainable energy technologies reduces the dependence on non-renewable resources and the envi-