Energy Conversion and Management 138 (2017) 299–311

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Modeling, simulation, parametric study and economic assessment of reciprocating internal combustion engine integrated with multi-effect desalination unit

Mohsen Salimi, Majid Amidpour *

Department of Mechanical Engineering, K.N. Toosi University of Technology, Energy Systems Division, No. 19, Pardis Street, Molla Sadra Ave., Vanak Sq., P.O. Box 19395-1999, Tehran, Iran

ARTICLE INFO

Article history:
Received 5 December 2016
Received in revised form 17 January 2017
Accepted 29 January 2017

Keywords:
Reciprocating internal combustion engine
Multi-effect desalination
Heat recovery
Thermal integration
Annualized cost of system

ABSTRACT

Due to thermal nature of multi-effect desalination (MED), its integration with a suitable power cycle is highly desirable for waste heat recovery. One of the proper power cycle for proposed integration is internal combustion engine (ICE). The exhaust gas heat of ICE is used to produce motive steam for the required heat for the first effect of MED system. Also, the water jacket heat is utilized in a heat exchanger to preheat the seawater. This paper studies a thermodynamic model for a tri-generation system composed of ICE integrated with MED. The ICE thermodynamic model has been used in place of different empirical efficiency relations to estimate performance – load curves reasonably. The entire system performance has been coded in MATLAB, and the results of proposed thermodynamic model for the engine have been verified by manufacturer catalogue. By increasing the engine load from 40% to 100%, the water production of MED unit will increase from 4.38 cubic meters per day to 26.78 cubic meters per day and the tri-generation efficiency from 31% to 56%. Economic analyses of the MED unit integrated with ICE was performed based on Annualized Cost of System method. This integration makes the system more economical. It has been determined that in higher market prices for fresh water (more than 7 US$ per cubic meter), the increase in effects number is more significant to the period of return decrement.

1. Introduction

The sustainable energy and drinkable water supply are the most vital requirements for decent human life. Thermal process for seawater desalination are highly energy intensive and become more economical, by incorporating available waste heat from power cycles to produce motive steam.

In Iran, there is more than 1500 MW capacity of small-scale DG internal combustion engine power production totally. Most of these DG power plants are located in remotes areas, and electricity and water supply are vital issues for local communities. The production of potable water by waste heat has a high economic advantage in the coastline of the Persian Gulf and Oman Sea, because unlike energy, there are no subsidies for drinkable water in Iran.

The power and heating were generated separately since the first power plant was built in the late nineteenth century. On the other hand, in Cogeneration of Heating and Power (CHP) systems, power is generated near the consumer and the waste heat is recovered to produce useful heating. This procedure has several advantages; firstly, the transmission and distribution losses are omitted. The CHP system increases the energy efficiency by recovering heat loss. These systems are less fragile than centralized power plants when natural disasters such as earthquakes occur. Because they are locally distributed, they can run independently from the grid and also can be designed to operate with different fuels [1].

Due to irreversibility in fuel energy conversion in Internal Combustion Engine, a high percentage of fuel energy is discharged to the environment in forms of exhaust gas, water jacket cooler, air cooler, lube oil and radiation. To improve the thermal efficiency, a CHP system can be utilized to improve the thermal efficiency to achieve a better fuel consumption and more environmentally friendly system by reclaiming a significant share of "waste heat". Unlike the automobile engine, the power generation units (PGU) have an engine that runs at constant speed for the most of the equipment lifetime. Although after treatment technology has become matured, to meet emission regulation, waste heat recovery is an effective way to achieve higher thermal efficiency with the same emission. In this study, the exhaust gas and water jacket waste heat has been utilized to produce fresh water.

* Corresponding author.
E-mail address: amidpour@kntu.ac.ir (M. Amidpour).

http://dx.doi.org/10.1016/j.enconman.2017.01.080
0196-8904/

Nomenclature

A	area, m^2
A_c	heat transfer area of condenser, m^2
A_i	heat transfer area of effect i, m^2
A_V	valve area, m^2
A_W	cylinder surface area exposed for heat transfer, m^2
a	Wiebe efficiency factor, crank radius
B	brine
b_c	cylinder bore, m
$bmep$	break mean effective pressure, kPa
C	cost, US$
C_D	valve discharge coefficient
c_p	specific heat at constant pressure, kJ kg^{-1} K^{-1}
c_v	specific heat at constant volume, kJ kg^{-1} K^{-1}
D_i and D_i'	desalinated water in effect i (boiling and flash), kg s^{-1}
E_{fuel}	fuel energy, kJ
F_t	correction factor of heat exchanger
F_W	feed water
$fmep$	friction mean effective pressure, kPa
H	enthalpy, kJ
h	specific enthalpy, kJ kg^{-1}
h_g	heat transfer coefficient
h_{ex}	enthalpy of exhaust gas, kJ kg^{-1}
i	annual real interest rate and effect number
$imep$	indicated mean effective pressure, kPa
IVC	intake valve closure
l_c	length of the connecting rod, m
LHV	fuel lower heating value of fuel, kJ kg^{-1}
L_i	latent heat of effect i, kJ kg^{-1}
L_v	valve lift, m
M_i	molecular weight, kg $kmol^{-1}$
m and M	mass flow rate, kg s^{-1}
m_{fuel}	mass of fuel, kg
m_{ex}	mass of exhaust gas, kg
N	number of effects
n	number of cylinders, Molar flow rate, mol s^{-1}
N_e	engine speed, rev s^{-1}
n_w	Wiebe form factor
P	pressure in cylinder, kPa
P_m	motored cylinder pressure, kPa
P_{max}	maximum cylinder pressure, kPa
$Power_{out}$	power output, kW
Q_c	heat release during combustion process, kJ
Q_{wj}	heat rejection to water jacket, kJ
Q_{ex}	heat rejection through exhaust gas, kJ
Q_W	net heat transfer of cylinder wall, kJ
Q_{loss}	heat loss to surrounding environment, kJ
Q_t	total heat generation during combustion process, kJ
R	universal gas constant, kJ kg^{-1} K^{-1}
Ra	entrainment ratio
r_c	compression ratio
s_c	stroke, m
T	gas temperature, K
$T_{1,...,N}$	temperature of the effect one to N, K
T_i'	temperature of flash box in effect i, K
T_W	cylinder wall temperature, K
U	overall heat transfer coefficient, kW m^{-2} K^{-1}, internal energy, kJ
U_c	overall heat transfer coefficient of condenser, kW m^{-2} - K^{-1}
U_{ei}	overall heat transfer coefficient of evaporator i, kW m^{-2} K^{-1}
u	specific internal energy, kJ kg^{-1}
V	cylinder volume, m^3
V_d	displacement volume, m^3
w	average gas velocity, m s^{-1}
W_{shaft}	shaft work, kJ
x	salinity, ppm
x_i	molar concentration of i-th component

Abbreviation

AB	Annual Benefit
ACS	Annualized Cost of System
AV	Additive Value
CC	Capital Costs
CHP	Combined Heat and Power
COP	Cost of product
CRF	capital recovery factor
GOR	Gain Output Ratio
HRSG	Heat Recovery Steam Generator
LCOP	Levelized cost of product
LHV	Low heating value, J mol^{-1}
LHV	Life Year of project
MED	Multiple Effects Distillation
NAB	Net Annual Benefit
NPV	Net present value
OFC	Operating flow costs
PC	Prime cost
POP	Price of product
POR	Period of return
ROR	Rate of Return
SOPC	Summation of product cost
TCF	Temperature correction factor
TVC	Thermo Vapor Compressor
VOP	Volume of Product

Greek letter

η_{gen}	Generator efficiency
γ	Specific heat ratio ($=c_p/c_v$)
θ	Crank angle
θ_s	Crank angle at start of combustion
θ_d	Crank angle of combustion duration

Subscript

acap and *cap*	annualized capital cost and capital cost
amain and main	annualized maintenance cost and maintenance cost
aope and *ope*	annualized operating cost and operating cost
ap, *pp*	approach point and pinch point
c, *h*	cold and hot streams
cond	condenser
c, *i* and *c*, *o*	cold stream inlet and outlet
cw, *d*, *b*	cooling water, desalinated water and brine
eV	evaporating steam, exhaust valve
f	feed water
g	hot flow gas
h, *i* and *h*, *o*	hot stream inlet and outlet
hs	heating steam
i	inlet
iv	intake valve
ms	motive steam
O	outlet
o	initial condition
p, *g*	constant pressure of hot flow gas
s	stagnation condition
sat	saturated
s, *o*	isentropic outlet
v	valve condition