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Thermo-economic analysis and multi-objective optimization of a transcritical CO_2 power cycle driven by solar energy and LNG cold recovery

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ABSTRACT

This study implements a thermodynamic study of a small-scale transcritical CO_2 power cycle using flat plate collectors and a storage tank as a heat source and liquefied natural gas (LNG) as the heat sink. A parametric study was carried out to see the influence of key variables on the system performance under various circumstances. Using cost estimation equations and cost indices, the total cost of the system is calculated, and its relation to key parameters is studied. An optimal turbine inlet pressure occurs under assumed circumstances where the system efficiency and the net power output along with the investment cost achieve maximum values. The condensation temperature has the effect on the performance of the system; however, the system efficiency and the net power output are less sensitive to the change in inlet temperature of the turbine. Changes in the turbine inlet pressure have no considerable effect on the heat exchanging area under the assumed circumstances and thus the heat exchangers costs; however, the rise in the turbine inlet temperature causes the increasing surface area of heat exchangers. For optimization purpose, four decision variables comprising turbine inlet temperature, turbine inlet pressure, minimum pinch temperature of the vapor generator and condensation temperature are selected as the effective decision variables. A multi-objective optimization is done to achieve a set of solutions to gain the maximum thermal efficiency and solar fraction while minimum total investment of the plant. Decision making including FUZZY, TOPSIS and LINMAP methods have been used and compared with each other.

1. Introduction

In recent few decades, special attention has been given to renewable sources such as solar energy mainly due to its sustainable nature and abundant supply. Therefore, if applied properly, solar energy can deliver a high-quality thermal energy and is a good substitution for fossil fuels.

In general, one of the promising methods to accumulate solar radiation is solar energy in which a low-grade heat source is employing non-concentrated solar collectors. With the purpose of making complete utilization of the solar energy, substitute working fluids, such as R134a, R123, R245fa, zeotropic mixtures [1–3] and carbon dioxide are employed in power systems rather than water to produce power. CO_2, owing to its non-explosive and non-toxic properties, low ecological effect, and promising thermodynamic features, has been used as favorable working fluid in the power cycles. Moreover, CO_2 can straightforwardly achieve its supercritical condition, and its temperature slides greater than critical point letting enhanced temperature profile corresponding to the heat source's temperature which is better than fluids with an isothermal subcritical evaporation. Nowadays, many types of research dedicated efforts to the transcritical CO_2 power cycle with low-grade energy sources. Chen et al. [4] compared a CO_2 transcritical power cycle and an Organic Rankine Cycle using a low-grade heat source. Results show that, under similar conditions, carbon dioxide cycle has a higher power output than ORC. The same authors [5] modeled a CO_2 power cycle powered with solar energy and evaluated its performance throughout the day and a year using some variables to control the system. Wang et al. [6] studied the performance of a CO_2 power cycle and improved it with machine

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Nomenclature

A	area [m^2]
Cd	condenser
C_p	specific heat capacity [J/kg K]
C_S	the total investment per solar fraction [$]
D_i	inner diameter [m]
D_o	outer diameter [m]
F_R	heat Removal Factor
g	gravity acceleration [m/s^2]
h	specific enthalpy [kJ/kg]; Convective heat transfer coefficient [W/m^2K]
h_w	wind heat transfer coefficient
I_b	beam radiation [W/m^2]
k	thermal conductivity [W/mK]
$\dot{m}$	mass flow [kg/s]
m	mass [kg]
N	number of glass
Pr	Prandtl number
Q_{TS}	thermal storage load
$\dot{Q}_u$	useful heat gain [kW]
Ra	Rayleigh number
S_{abs}	absorbed radiation [W/m^2]
SF	solar fraction
T	Temperature [°C; K]
TIT	turbine inlet temperature
TIP	turbine inlet pressure
t	time [h]
U	heat transfer coefficient [W/m^2K]
$\dot{W}$	power [kW]
R_b	the beam radiation tilt factor
$\dot{Q}$	heat [kW]
α	absorbance
ε	emissivity
$\delta_{b,i}$	the insulation thickness
η	isentropic efficiency
θ	incident angle [degree]
π	Pi number
ν	dynamic viscosity [m2/s]
ρ	Reflectivity; Density [kg/m3]
ω	the hour angle
τ	transmittance
β	the tilted angle
δ	the solar declination
φ	local latitude

Subscript

u	useful
C	capital cost
amb	ambient
loss	lost heat
l	load
c	collector
b	bottom loss
P	pressure
LNG	liquid natural gas
gen	generator
tur	turbine

learning method. Zhang et al. [7–13] studied a solar energy powered Rankine cycle employing supercritical CO_2 as the working fluid for combining heat and power generation. A sequence of tests was conducted to confirm the numerical simulation besides examining the heat transfer features of supercritical CO_2 in solar collectors of the system. Cayer and colleagues [14] carried out a thermodynamic study of a CO_2 transcritical power cycle employing low-grade heat source and examined the influence of high pressure on the cycle performance with a fixed sink temperature and fixed minimum and maximum temperatures in the cycle. Furthermore, they [15] altered the highest working fluid's temperature and gained a parametric optimization employing six performance pointers: specific net output, thermal efficiency, total UA, exergetic efficiency, and the relative cost of the system in addition to the surface of the heat exchangers. Moreover, Lakew and colleagues [16] proposed to enhance the performance of CO_2 Rankine cycle with low-temperature heat source by substituting the mechanical pump with a thermally driven pump. This replacement helps the system to improve the new power output using additional heat at low temperature (60 °C) to pressure the working fluid.

One of the promising methods for extracting energy in power cycles during last two decades is using the LNG cold as a heat sink. Dispenza et al. [17] studied the problem of cold recovery for direct utilization both away from the site of the regasification facility addition to in the site by employing a modular unit. Air coolers is commonly employed as a heat sink, making it inflexible to enhance the cycle performance. Therefore, several scholars presented LNG as a heat sink in the CO_2 power cycle in which LNG comprises huge cold energy which was transformed from mechanical work throughout its liquefaction. Zhang and Lior [18], Liu and colleagues [19] suggested a new LNG driven power plant that works in a quasi-combined cycle mode with a CO_2 Brayton cycle and a supercritical CO_2 Rankine-like cycle which is joined with the LNG evaporation system. Both thermal-economic and thermodynamic studies were carried out to specify the circumstances and costs for optimum system working and arrangement. Lin and colleagues [20] introduced a transcritical CO_2 power cycle with dissipation to LNG as its heat sink and a gas turbine as its heat source to enhance the cycle performance. The above system not only gained larger temperature difference between the heat sink and heat source but also employed the cold energy of LNG. Angelino and Invernizzi [21] also suggested several new schemes for the CO_2 power cycle with LNG as a heat sink with the purpose of fully utilizing the cryogenic exergy of LNG and to enhance the overall performance of the system.

One of the common methods in solving engineering problems with different objectives is using Multi-objective optimization [22–24]. Özyer et al., [22] proposed a machine learning based method for calculating prospect via evolutionary algorithms. The multi-objective optimization method can be applied in different disciples, for instance, vehicle routing problems with Time Windows [23]. Blecic et al., [24] employed Bayesian analysis and multi-objective optimization to develop a decision support system which is known as Bay MODE.

Different methods can be applied to solve the problems with various objectives, and one of them is evolutionary algorithms (EA) which were developed during last decade [25,26]. Answers gained from the multi-objective optimization are known as Pareto frontier which revealed practical solutions in the objective area. Nowadays, numerous researches based on the multi-objective optimization method have been carried out in energy systems engineering [27–50]. The output power and the thermal efficiency