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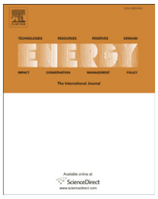

Development and analysis of a new renewable energy-based multi-generation system

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ABSTRACT

A renewable energy-based multi-generation system is developed and studied energetically and exergetically. Two renewable sources of energy, biomass and geothermal, are combined to deliver five useful outputs for residential applications. The energy products from biomass sources are used to drive an organic Rankine cycle and a vapour absorption chiller, and further used to dry the wet material in an industrial dryer. A double flash system is used in the geothermal power cycle, which includes a multi-stage steam turbine. Outlet water flows from the separators and the steam turbine are used to heat water used in households. Liquefied gas is produced through the Linde Hampson liquefaction cycle, in which the compressor is directly coupled to organic Rankine cycle turbine. The energy efficiency of the system is found to be 56.5% and the exergy efficiency 20.3%. The largest exergy destructions are found to occur in both combustion chamber and boiler. The variations in exergy efficiencies and exergy destructions for the system components are determined with respect to changes in the reference-environment temperature and other major system parameters.

1. Introduction

Energy plays an important role in the development of a country. With increases in world population and living standards, world energy demand is increasing steadily. But fossil fuel reserves are limited. The oil price shocks in the mid-1970s hastened the search for alternative energy sources like renewable energy, which can help overcome energy challenges. These efforts have continued since then, as have efforts to improve the efficiencies of energy systems.

Numerous renewable energy sources are available in nature like solar, biomass, hydro, wind, wave, tidal, ocean current, ocean thermal, and geothermal. Geothermal energy is an environmentally benign and sustainable energy source, as pointed out by Murphy et al. [1], Gunerhan et al. [2] and others. Ozgener et al. [3] have investigated geothermal energy applications such as electricity generation, heating, cooling and drying; these vary depending on the geothermal source temperature. Coskun et al. [4] performed an exergoeconomic analysis of geothermal power plants. Recently much research has been reported on biomass as a renewable source of energy (e.g., Dincer et al. [5]). Biomass is biological material from living matter on Earth, and can either be used directly as energy or converted into other energy products such as biofuels. Filho et al. [6] point out that biomass energy is used for such applications as heating, cooling and electricity production. Al-Sulaiman et al. [7] carried out energy and exergy analyses of an organic Rankine cycle driven by biomass.

To shift towards sustainability, it is important to utilize energy resources efficiently, in terms of avoiding external waste emissions and irreversibilities. In single generation (or product) cycles, there are always some losses due to thermal energy dissipation, e.g. exhaust gases from a gas turbine. In order to increase the efficiency of a system, such waste energy can be utilized for useful purposes (space or water heating, cooling using absorption chillers, industrial drying, etc.). Multi-generation is one approach to increasing the efficiency of energy systems and, as described by Dincer et al. [8,9], the combination of multi-generation and renewable energy systems can provide significant benefits. A multi-generation energy system produces, from one or more primary energy inputs, several useful outputs (e.g., electricity, heating, cooling, drying and gas liquefaction) according to Pouria et al. [10]. Zamfirescu et al. [11] demonstrated that the energy efficiency of a concentrated solar power system can be increased from 15 to 80% through cogeneration by recovering the heat which is normally rejected by the

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Nomenclature

ex	specific exergy (kJ/kg)
$\dot{E}x$	exergy rate (kW)
$\dot{E}x^{Q}$	thermal exergy rate (kW)
h	specific enthalpy (kJ/kg)
LHV	lower heating value (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
M_u	moisture content in biomass (%)
P	pressure (kPa)
$\dot{Q}$	heat transfer rate (kW)
R	gas constant (kJ/kg K)
s	specific entropy (kJ/kg K)
T	temperature (K)
v	specific volume (m^3/kg)
w,a,b,c	stoichiometric constant in biomass combustion reaction in Eq. (1) (moles)
$\dot{W}$	work rate (kW)
x_k	number of molecules of gas k (molecules)
y,z	constant in Eq. (2) related to number of atoms of hydrogen and oxygen in biomass

Greek letters

η	energy efficiency
Ψ	exergy efficiency
Φ	exergy-to-energy ratio of fuel
μ_m	mineral matter content in biomass
λ	stoichiometric constant in biomass combustion reaction in Eq. (1) (moles)
$\alpha,\beta,\delta,\gamma$	number of atoms of carbon, hydrogen, nitrogen and oxygen in biomass (atoms/mole)

Subscripts

ACS	absorption chiller system
c	compressor
cc	combustion chamber
ch	chemical
d	destruction
dry	dry with no moisture content
e	evaporator
en	energetic
ex	exergetic
f	fuel
gen	absorption generator
geo	geothermal
HE	heat exchanger
l	loss
liq	liquefaction
mois	moisture
mg	multi-generation
o	overall
ORC	organic Rankine cycle
p	pump
ph	physical
s	source
sg	single generation
T	turbine
TIT	turbine inlet temperature
x,y,z	number of atoms of carbon, hydrogen and oxygen in biomass (atoms/molecule)
0	ambient (or reference-environment) condition
1 … 47	state numbers

thermal cycle. Bhattacharyya and Thuy [12] similarly assessed a cogeneration system for power and heat for the pulp and paper industry. Al-Sulaiman et al. [13] investigated a multi-generation system that integrates a SOFC (solid oxide fuel cell) with an organic Rankine cycle to generate electricity and an absorption chiller for cooling. Using exergy analysis, Dincer et al. [14] showed for a cogeneration system that integrates a gas turbine with a SOFC that cogeneration raises the overall energy efficiency to 66%. These studies show that multi-generation often has the potential to increase system efficiency.

The LH (Linde Hampson) cycle is a well-known cryogenic cycle for gas liquefaction and has been used for various purposes. Wiegerinck et al. [15] used the Linde Hampson cold stage in a sorption compressor cell with a single sorber bed, whereas Maytal [16] optimized the mass flow rate in order to maximize the rate of production of a liquid cryogen. In a study, Kanoglu et al. [17] used the LH cycle for the liquefaction of hydrogen gas using geothermal energy. Presently, however, hybrid membrane/cryogenic separation through cryogenic distillation is commonly employed [18].

The organic Rankine cycle is most common cycle used for low and medium temperature applications. Carcasci et al. [19] used the organic Rankine cycle for waste heat recovery from gas turbines and perform a thermodynamic analysis. In another study, Calise et al. [20] carried out a thermo-economic analysis and performance assessment of an organic Rankine cycle driven by medium temperature heat sources. Numerous types of fluids can be used as the working fluid in an organic Rankine cycle, one of the most common being n-octane due to its various advantages. Markus et al. [21] utilized n-octane in a double-stage biomass fired organic Rankine cycle for micro-cogeneration and provide a list of potential high-temperature circuit working fluids.

In the present paper, a new renewable energy-based multi-generation system is developed and assessed based on energy and exergy analyses. The present system employs two renewable energy inputs (e.g., biomass and geothermal) and yields five outputs (e.g., electricity, hot water, cooling, liquefied gas and heated drying air). The parametric studies are conducted to investigate the effects varying operating conditions and state properties on the system performance. Another objective of this study is to improve understanding of such integrated systems for multi-generation purposes.

2. System description

The multi-generation system considered here (see Fig. 1) consists of a biomass combustion cycle, an ORC (organic Rankine cycle), an absorption chiller cycle, a Linde Hampson liquefaction cycle, a geothermal power plant, a water heating system and a dryer. Biomass and geothermal water are the primary energy inputs, but the energy sources are combined so that the ORC output heat warms the incoming saturated water from the geothermal well.

At points 16 and 17 in Fig. 1, biomass and air respectively, at a specified air fuel ratio, enter a high-temperature combustion chamber. The high-temperature combustion gas exits the chamber at point 18, and passes through a cyclone where ash is removed. At the exit of cyclone at point 19 the combustion gas enters the boiler where heat is transferred from it to an organic fluid (n-octane). The combustion gas exits the boiler at a comparatively low temperature

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