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Comparative study of combined solid oxide fuel cell-gas turbine-Organic Rankine cycle for different working fluid in bottoming cycle

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ABSTRACT

Worldwide efforts are being made for evolving viable electricity generation alternative to the traditional fossil fuel based power generation systems and also to enhance the efficiency of existing power generation systems. Studies have been made for integrating fuel cell with gas turbine cycle and Organic Rankine cycle, but there exist possibility of further investigation by incorporating the measures to increase effective energy utilization in the cycle along with consideration of different working fluids in Organic Rankine cycle. In the present paper, a combined cycle system consisting of technologies namely solid oxide fuel cell, gas turbine and Organic Rankine cycle is studied. The considered combined cycle system employs Heat Recovery Steam Generator followed by Organic Rankine cycle as bottoming cycle for recovering the waste heat coming out from hybrid SOFC-GT system through a Heat Recovery Vapour Generator. The considered SOFC-GT system has methane gas being used as fuel which is reformed by both external and internal reformers with anode gas recycling. Here three different working fluids namely R141b, R245fa and R236fa are used in bottoming Organic Rankine cycle for comparing their effects on the cycle performance of proposed SOFC-GT-ORC combined cycle system based on first law of the thermodynamics. Results have been obtained from the computer simulation based on thermodynamic modeling of SOFC-GT-ORC combined cycle and the effects of gas turbine inlet temperature, cycle pressure ratio, fuel utilization factor and ORC turbine inlet temperature are investigated on the cycle performance. The study indicates that the efficiency is increased about 8%-12% by recovering SOFC-GT waste heat through ORC and R236fa is found to be the best in terms of power generation capacity and efficiency of SOFC-GT-ORC system. Outcome from this paper gives insight to the power sector professionals and research community working for evolving efficient and robust power generation alternatives based on the combination of direct energy conversion system and indirect energy conversion system.

1. Introduction

With increasing energy demands and various environmental concerns like pollutants and greenhouse gases, focus is made upon the unconventional energy sources which have low emissions along with potential to offer good efficiency. In view of the prevailing circumstances, the efforts are made for developing efficient energy conversion technologies with less adverse impact on environment. This goal can be achieved by using innovative technologies for the conventional energy conversion using fossil fuels and also by producing power directly from renewable energy resources, so as to get high conversion efficiency and low environmental impact simultaneously.

Amongst the various innovative technologies, fuel cells are the potential clean energy alternatives. Fuel cells are efficient and reliable means of producing electricity with low emission to no emission along with many other advantages over conventional power sources. Fuel cells are capable of producing electricity directly through electrochemical processes without any combustion. There are different fuel cells available, but the solid oxide fuel cell (SOFC) has many advantages over others fuel cells. SOFC can be used in power generation in hybrid systems and combined cooling, heating and power applications as well. SOFC can operate at very high temperature up to 1000 °C, which makes it more flexible in the choice of fuels and can produce very good performance in combined cycle and hybrid applications. The hybrid SOFC cycle, which integrates a SOFC with a gas turbine cycle, offers the potential of fuel-to-electricity efficiencies in the 75–80% range [1]. There exists possibility for increasing effective energy utilization in the SOFC-GT integrated system by use of heat recovery systems to capture waste heat and inclusion of low temperature power generation cycle like Organic Rankine cycle suitably in the cycle configuration.

Literature review of the SOFC based combined cycle indicates it to be one of the better power generation systems as compared to other

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Nomenclature

A	area (m^2)
M	mass flow rate (kg/s)
N	no. of cell
V	voltage (V)
I	current density (A/m^2)
W	work (kW)
Q	heat generated
U	utilization factor
T	temperature (K)
C	specific heat capacity (kJ kg/K)
$c_{p\ fuel}$	specific heat of fuel (kJ kg/K)
$c_{p\ air}$	specific heat of air (kJ kg/K)
FC	fuel compressor
CC	capital cost
OC	operating cost
MC	maintenance cost
G	generator
GT	gas turbine
TC	total cost
LHV	lower heating value of fuel
OP	ORC pump
ORC	Organic Rankine cycle
CD	ORC condenser
HRVG	heat recovery vapour generator
P	pressure
M	mixer
OT	Organic Rankine cycle turbine
R	recuperate
S	separator
SG	heat recovery steam generator
SOFC	solid oxide fuel cell
ε	heat exchanger effectiveness
η	efficiency
Γ	gamma

Subscripts

comb	combustion
comp	compressor
ORCP	organic pump
cond	condenser
ORC	Organic Rankine cycle
HRVG	heat recovery vapour generator
OT	organic turbine
invert	DC-AC inverter efficiency
Gen	generation
AC	alternating current
A,COMP	air compressor
DC	direct current
f	fuel
aux	auxiliary
inv	inverter
tur	turbine
SOFC	solid oxide fuel cell
GT	gas turbine
tot	total

available options. Brief detail of the literature review in respect to hybrid solid oxide fuel cell – gas turbine - Organic Rankine cycle system is detailed herein.

In recent years, many researchers are doing lots of efforts to develop high efficiency power generation systems with low emissions. Due to high operating temperature and high quality waste heat, the SOFC is cornering increasing attention of several researchers as well as many energy sector industries to produce clean energy by employing SOFC with hybrid systems for combined heat and power generation. Different studies are being carried out to reduce the operating temperature of SOFC so that the range of available materials is widened and hence, the operating cost can be reduced. Chan et al. studied natural gas-fed integrated internal-reforming solid oxide fuel cell–gas turbine (IRSOFC–GT) power generation system using different natural gas reforming processes and also used combustion chamber to fully oxidize the unutilized raw gases of fuel cell stack. It reports the efficiency of SOFC-GT system to be 34% more than gas turbine cycle and SOFC-GT with ORC in bottoming cycle system offers 6% more efficiency as compared to the efficiency of hybrid SOFC-GT system. Chan et al. [2] presented the multi level modelling of SOF-GT hybrid system. Ebrahimi and Moradpoor [3] studied the combined solid oxide fuel cell, micro-gas turbine and Organic Rankine cycle for power generation (SOFC–MGT–ORC). Mehrpooya, Mehdi et al. [4] introduced and analyzed a combined system consisting of solid oxide fuel cell - gas turbine power plant, Rankine steam cycle and ammonia-water-absorption refrigeration system in which power, heat and cooling are obtained. Due to high quality waste heat of SOFC, the Kalina cycle and Organic Rankine cycle were separately employed for the comparative study of waste heat recovery from hybrid SOFC-GT system by Gholamian et al. [5]. Akkaya et al. [6] developed a model of combined power generation system consisting of a solid oxide fuel cell (SOFC) and an Organic Rankine cycle (ORC) for analyzing the combined performance and exhibited that 14% efficiency is increased due to recovery of SOFC waste heat through ORC, whereas 9–13% efficiency increased for present paper for the considered parameters. Annamaria et al. [7,1] studied a different configuration of solid oxide fuel cell based gas turbine cycle with internally and externally methane reforming system and also classified SOFC in two major types, planar design and tubular design according to their geometry. To improve the power generation capacity and efficiency of plants, the indirect integration of gas turbine cycle, SOFC system and Organic Rankine cycle with different working fluids, namely toluene, benzene, cyclohexane, cyclo pentane, R123 and R245fa in bottoming cycle been done by Valerie Eveloy et al. [8]. Volkan, and Sahin [9] studied the performance of solid oxide fuel cell-Organic Rankine cycle combined system. The Department of Energy Science at Lund University in Sweden conducted a project which studied the heat transfer phenomena in SOFC and different reforming processes of hydrocarbon fuel before entering the SOFC [10]. The present system's electrical efficiency is approximately 1% higher than that reported by Xiongwen Zhang et al. i.e. 62.2% [11] for SOFC-GT hybrid system. Al-Weshahi et al. [14] revealed that on the basis of selection criteria and considered ORC unit operating conditions, R236ea, R236fa and R227ea were the preferred refrigerants. Chen et al. [15] studied the ORC working fluid properties and summarized 35 potential working fluids for organic Rankine cycle and super critical Rankine cycle. Mikielewicz et al. [17] presented the study on, utilisation of waste heat from the power plant by use of the ORC aided with bleed steam and extra source of heat. Theoretical performance of 20 organic fluids were investigated by Mikielewicz et al. [18] and it was found that R123 and R141b appear as most suitable for the small scale domestic CHP applications. However from environmental consideration, the properties of R123 are not acceptable and use of R123 will be restricted by the year 2020 [16]. A comparative study of organic Rankine cycle and steam Rankine cycle is carried out by Zhang et al. [20]. In this paper, mathematical models are developed to explore the feasibility that combines the low temperature waste heat steam (150–350 °C) and low-boiling point organic working fluids for power generation. The results show that for the temperature range of 150–210 °C of heat