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Modeling of natural gas fueled quadruple cycle for power applications

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ABSTRACT

Performance improvement being a major need of the power sector aims at increasing efficiency, lowering air pollutants and ultimately cost. This paper explores a quadruple cycle, a hybrid of solid oxide fuel cell integrated with gas turbine, steam turbine and organic Rankine cycle totaling four cycles (SOFC-GT-ST-ORC), fueled primarily by natural gas for stationary power generation. A mathematical model of the configuration of the quadruple cycle is developed and the performance investigated through a parametric study of the thermodynamic components. The power output, efficiency and other results were validated with those found in literature. The quadruple cycle produced an efficiency of 66.1% with 1,1,1,2-tetrafluoroethane, R134a as the organic working fluid. This efficiency exceeded the performance of traditional thermodynamic cycles like single steam cycle, combined and triple cycle at similar operating conditions. Lastly, the quadruple cycle presents a potential for optimization with waste heat recovery.

Introduction

There have been many propositions over the past decades of single power cycles ranging from the steam turbine (ST) through gas turbine (GT) to organic Rankine cycle (ORC) aimed at improving performance of stationary power plants [1]. These cycles have been integrated to form combined cycle or hybridized with solid oxide fuel cell (SOFC) in order to achieve a higher efficiency over single conventional thermodynamic cycles. For example, Haseli et al. [2] combined a solid oxide fuel cell combined with a recuperative gas turbine (GT–SOFC) plant and showed that about 60% thermal efficiency could be obtained at an optimum compression ratio of 4. Muñoz de Escalona et al. [3] considered the part load analysis of gas turbines and ORC combined cycles (GT–ORC) with the goal of maximizing the overall efficiency of the plant. Furthermore, cases of GT–ST are commonly reported in textbooks [4]. Al-Sulaiman conducted exergy analysis on a system that combined a solid oxide fuel cell and an organic Rankine cycle (SOFC–ORC). The study revealed that there is 3–25% gain on exergy efficiency when trigeneration is used compared with the power cycle only [5]. Ugartemendia developed a dynamic model of an alternative hybrid SOFC–ST configuration and showed that maximum efficiency is obtained when the utilization factor is 0.65 at a temperature of 900 °C for a 120 KW rated SOFC [6].

Other researches have integrated three traditional thermodynamic cycles or hybridized two traditional thermodynamic cycles with high temperature solid oxide fuel cell to form a triple cycle [9]. For example, Yan integrated SOFC–GT system with an organic Rankine cycle (SOFC–GT–ORC) using liquefied natural gas (LNG) as a heat sink to recover the cryogenic energy of LNG to achieve higher efficiency [10].

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Nomenclature

A	cell area, m^2
C_p	specific heat, $\frac{J}{kg\ K}$
E_r	Nernst potential, V
F	Faraday constant (96,485 C/mole)
ΔG^0	Gibbs free energy at standard pressure and temperature, $\frac{J}{mol}$
h	enthalpy, kJ/kg
I	current, mA
J	current density, mA/cm^2
J_o	exchange current density, mA/cm^2
LHV	lower heating value, kJ/kg
$\dot{m}$	mass flow rate, kg/s
$\dot{n}$	molar flow rate, mol/s
n_e	number of electrons
P	pressure, kPa
$\dot{Q}$	heat transfer rate, kW
R	universal gas constant, 8.314 J/mole K
r_p	compression ratio
s	specific entropy, kJ/kg K
SCR	steam to carbon ratio
T	temperature, K
U_f	fuel utilization factor
V	voltage, V
$\dot{\omega}$	power, kW

Greek letters

α	resistivity
β	temperature constant
δ	thickness
ε	effectiveness
η	efficiency
γ	resistance constant

Superscript

K	heat capacity ratio
i	isentropic

Subscripts

a	air
act	activation
c	compressor
comb	combustor
conc	concentration
g	gas turbine
i	index
inv	inversion
ohm	ohmic
p	pump
s	steam turbine

Hung discussed a series and parallel type triple cycles, which was a combination of GT–ST–ORC. The study showed that by properly combining ORC with a ST, the organic Rankine cycle efficiently utilizes residual yet available energy to an optimal extent [11]. Choi simulated a triple combined cycle with a gas turbine combined cycle and a solid oxide fuel cell system (SOFC–GT–ST) considering a commercially available F-class and J-class gas turbines. The analysis showed that the efficiency of the triple combined cycle is a weak function of the gas turbine class and the power share of the gas and steam turbine increases with increasing turbine inlet temperature (TIT) [12].

It is understood that with every successful addition of a cycle, efficiency tends to increase. Traditional steam cycles show efficiencies between 30% and 45%, combined cycle-between 45% to 60% and triple cycle between 60% and 65% [13–15]. It could be inferred that with another successful addition of a fourth cycle to form a quadruple cycle, the potential of achieving an average efficiency above 65% exist. In addition, considering the advantages and disadvantages [7,16,17] of SOFC hybridized with GT, ST and ORC, a better performance could be achieved with lower greenhouse gas emissions [18–20]. The cycle arrangement is not a mere combination of conventional thermodynamic cycle with SOFC but rather it is dependent on the exhaust gas temperature of the outgoing cycle and standard inlet gas temperature requirement of the incoming cycle.

Previous studies have investigated single, combined and even triple cycles. A comprehensive literature survey showed that in combined and triple cycle designs, waste heat of around 1000 °C [20,21] from SOFC, the topping cycle, is burned in the combustion chamber and utilized in gas turbine. The exhaust gas from the gas turbine is then cascaded down to the steam turbine or organic Rankine cycle. It was observed in the survey that the energy of the bottoming cycle does not get completely expanded to room temperature. Typically, energy of temperature between 320 K and 400 K [22] gets vented off. This waste energy of such low temperatures could be harvested by a fourth and bottoming organic Rankine cycle.

Furthermore, the literature survey showed that the power generated in the solid oxide fuel cell is 3–5 times [7] larger than the power generated in the other sections of the combined or triple cycle system. In such design, the focus is solely on the SOFC, the remaining components of the system such as gas turbine, steam turbine and or ORC, although being power-generating systems, are merely introduced to salvage the waste heat from SOFC. These remaining components being themselves power-generating components could contribute more towards the entire system. Hence, in the proposed quadruple cycle system layout, SOFC serves to boost the capacity of the triple cycle. It is not an oversized portion that makes the work contribution of other components of the system such as gas turbine and steam turbine insignificant. On the contrary, it generates a comparable portion of energy, making it a desirable design for power generation.

This study aims to investigate a new concept of quadruple cycle – a hybridization of internal reforming solid oxide fuel cell with gas turbine integrated with steam turbine and organic Rankine cycle (SOFC–GT–ST–ORC) and fueled by natural gas. A workable configuration is developed at steady state and simulated with organic agent in the ORC. The organic agent, R134a, was selected because it has optimum thermodynamic properties at low temperatures and pressures, and also satisfies criteria of being economical, nontoxic, nonflammable, environmentally-friendly, while allowing a high utilization of the available energy from the heat source [23]. The mathematical model of the quadruple cycle is developed in Matlab and Simulink, and it contains the energy

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