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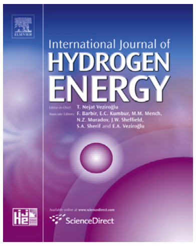

Energy, exergy and economic analysis of an integrated solid oxide fuel cell – gas turbine – organic Rankine power generation system

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ABSTRACT

To improve on-site power generation capacity and efficiency in energy-intensive process plants, the indirect integration of a standard gas turbine cycle with an internal reforming solid oxide fuel cell (SOFC) system and bottoming organic Rankine cycle (ORC) is investigated thermodynamically and economically. Among six ORC working fluids, namely toluene, benzene, cyclohexane, cyclopentane, R123 and R245fa, toluene is found to offer the best thermodynamic performance at favorable system size indicators. Using this fluid, the SOFC-GT-ORC system would enhance power generation capacity by a factor of three relative to the base gas turbine cycle, at energy and exergy efficiencies of approximately 64% and 62%, respectively. This represents efficiency improvements of approximately 34% compared with the base GT cycle, and of 6% relative to the hybrid SOFC-GT sub-system. The avoided purchase of natural gas and environmental emissions could generate net annual operating cost savings of five to nine million USD based on standard associated and sour gas prices, respectively, and would become profitable within three to six years, respectively.

Introduction

Driven by the power generation and industrial sectors, the energy intensity and environmental emissions of Arabian Gulf nations has soared over the past decade [1,2], with countries such as the United Arab Emirates (UAE) becoming net importers of natural gas [3]. The efficiency of conventional gas cycles used for distributed power generation in industrial process plants is limited, particularly at part load and under harsh climatic conditions [4]. Both to reduce primary energy consumption and focus on core businesses, certain industrial facilities have therefore opted to outsource power generation to centralized combined cycle plants. However, decentralized industrial electricity production can enable power generation in remote areas with substantial savings in infrastructure and fuel transportation, while eliminating power distribution losses and offering flexibility, such as extension to co- or tri-generation. Solid oxide fuel cells (SOFCs) are an alternative high efficiency, low emissions, fuel flexible, and modular

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power generation technology, that is anticipated to scale up to multi-hundred MW [5,6]. SOFCs can be thermally or chemically coupled with bottoming power cycles, such as Brayton [e.g., [7]], Rankine [e.g., [8]], Kalina [e.g., [9]] and Stirling [10] cycles, tri-generation systems [11], and renewable energy conversion and storage devices [e.g., [12]], to produce additional power at a higher efficiency, up to approximately 80% [13–15]. This study investigates a triple SOFC-Brayton-organic Rankine cycle to enhance power generation capacity and efficiency in a process plant. Before describing the proposed system, an overview of previously investigated hybrid SOFC power generation systems is provided.

Hybrid SOFC power generation systems

SOFC–Rankine and SOFC–Kalina cycles

Given the high rejection temperature of SOFCs (i.e., up to 1000 °C), their coupling with a bottoming steam Rankine cycle (SRC) [8,16–18] or organic Rankine cycle (ORC) [19–24], may either restrict SOFC operation to a low temperature range, and/or Rankine working fluid selection to high critical temperature fluids with high cycle pressures.

Despite reported energy efficiencies of up to 71% [17], analyses of SOFC-SRCs are therefore limited. Rokni [16,17] employed a single pressure level superheated SRC with live steam pressures of 60–70 bar to avoid excessive moisture in the last turbine stage, with hybrid SOFC-SRC thermal efficiencies of 62%–68%, depending upon the plant configuration and operating parameters. Using a three-pressure level SRC to recover heat from an atmospheric SOFC, Gandiglio et al. [8] reached approximately 65% thermal efficiency, which was found to be 6% lower than for a pressurized SOFC-GT plant. Mehrpooja et al. [18] integrated a SOFC with a three pressure level regenerative SRC at live steam pressures of 60–100 bar to obtain an optimized 62.4% electrical efficiency.

ORCs can offer several advantages over SRCs, including lower operating pressures, less complex and more compact layouts, improved reliability, and reduced maintenance [25]. Propylcyclohexane (after considering cyclohexane, cyclopentane, hexane, decane, and nonane) [22], n-octane [21], toluene [24] and ethylbenzene [19] have been selected for SOFC-afterburner exhaust gas temperatures of 780 °C [22], ~827 °C [21], >900 °C [24] and 1100 °C [19], respectively. Alternatively, SOFC-ORC thermal coupling may be facilitated when part of the SOFC exhaust heat is recovered by an upstream application, which lowers the heat addition temperature to the ORC, such as in [23], or when an intermediate heat transfer fluid is employed between the SOFC and ORC [e.g., [22]]. Verda [19] reported a net SOFC-ethylbenzene ORC electrical efficiency of 49.7%, with the ORC increasing SOFC net power by 30%. Using an ORC to recover heat from a methanol-fueled SOFC exhaust at either 279 °C or 490 °C onboard a marine vessel, Ghirardo et al. [20] found that power generation first law efficiency could be improved from 44% to 49% relative to the SOFC, with a 12% reduction in electricity cost. Pierobon et al. [22] proposed SOFC-ORC integrations rather than pressurized SOFC-GT systems, both to avoid high SOFC operating pressures and temperatures, as well as the footprint required for pressurized SOFC vessels. Thermal efficiencies of up to 56.4% were reported for an integrated biomass gasification SOFC-propylcyclohexane ORC [22]. Given the gap in typical SOFC and ORC operating temperatures and limitations in their overall combined efficiencies, analyses of such configurations are overall limited [19–24], and in several instances [21,23,24], part of tri-generation schemes to further improve efficiency, rather than standalone systems. With the exception of Ozcan and Dincer [23,24], none of the above SOFC-ORC investigations evaluated exergy efficiency, and with the exception of Ghirardo et al. [20], none evaluated SOFC-ORC economics.

The variable evaporation temperature of ammonia-water in a Kalina cycle can provide a better match with SOFC exhaust gases relative to a pure Rankine cycle working fluid, hence reduced irreversibilities [9]. Pierobon and Rokni [9] compared the performances of hybrid SOFC-SRC and SOFC-Kalina plants with overall power outputs in the region of 7–8 MW. Up to 58% hybrid thermal efficiency could be obtained with the SOFC-Kalina system. However, although the Kalina ammonia-water fluid permitted to reduce exergy losses associated with heat transfer in the bottoming cycle, more heat was recovered by the SRC than the Kalina system, resulting in a 2% gain in hybrid thermal efficiency compared with the SOFC-Kalina cycle.

SOFC-Brayton cycles

Considering the limitations of SOFC-Rankine cycles, most proposed hybrid SOFC power cycles have consisted of SOFC-Brayton integrations, which may be broadly categorized as either directly [e.g., [7,26–28]], indirectly [e.g., [29–32]] or semi-indirectly [e.g., [33,34]] coupled. Directly coupled (i.e., chemically and thermally) SOFC-Brayton systems share the same working fluid as SOFC exhaust gases are directly fed to the bottoming gas turbine, while indirectly (i.e., thermally) coupled ones are operated with two different streams thermally coupled through a heat exchanger. The heat addition of the gas cycle combustion chamber is either replaced or supplemented by exhaust heat produced by the topping SOFC and an optional afterburner. The same principle is applied in semi-indirect coupling, but the GT exhaust stream is also directly fed to the SOFC cathode, which reduces the number of coupling heat exchangers and can improve overall efficiency.

Direct coupling with pressurized SOFC operation promotes high SOFC efficiency, with projected thermal efficiencies of up to 65% on natural gas (LHV), and demonstrated efficiencies of up to 52% for prototype units in the sub-300 kW range [15]. Such systems have attracted interest mostly as micro-power plants for small-scale distributed power generation [29,30]. However, practical implementation challenges are still to be resolved, including material reliability issues associated with anodic-cathodic pressure differentials, GT pressure fluctuations, a limited pressure and mass flow operating domain, and complex controls [15,26,31]. Bakalis and Stamatis [28] note that most previously modeled hybrid SOFC-GTs are based on optimized SOFC and GT components that are not readily available, while fewer systems incorporate either existing gas turbines, or both an existing SOFC stack and gas turbine.