Applied Energy 156 (2015) 32–85

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Review

Hybrid solid oxide fuel cells–gas turbine systems for combined heat and power: A review

Annamaria Buonomano, Francesco Calise *, Massimo Dentice d'Accadia, Adolfo Palombo, Maria Vicidomini

Department of Industrial Engineering, University of Naples Federico II, P.le Tecchio 80, 80125 Napoli, Italy

HIGHLIGHTS

- A comprehensive review of SOFC–GT power plant is provided.
- Different layout configurations are analyzed.
- SOFC–GT energetic efficiency is extremely high.
- SOFC–GT are extremely flexible regarding the type of fuel.
- System commercialization is limited by the cost of materials.

ARTICLE INFO

Article history:
Received 23 April 2015
Received in revised form 6 June 2015
Accepted 14 June 2015

Keywords:
SOFC
Gas turbine
CHP
Hybrid systems
Fuel cells

ABSTRACT

This paper presents a comprehensive review of the possible layout configurations of hybrid power plants based on the integration of solid oxide fuel cells (SOFC) and gas turbine (GT) technologies. SOFC/GT power plants have been investigated by using a plurality of approaches, such as: numerical simulations, experimental analyses, and thermo-economic optimizations. The majority of SOFC/GT hybrid systems are fed by methane, which is much cheaper and easier to manage than hydrogen. In fact, SOFC/GT systems use the capability of the fuel cell to internally perform the reforming process required to convert methane into hydrogen. The steam required to drive the reforming reaction can be supplied by the anode recirculated stream. Alternatively, such steam can be produced externally, by using the heat of the exhaust gases. In this case, steam can be used also for thermal purposes and/or for further system hybridization (e.g. Cheng cycle). The majority of the SOFC/GT power plants analyzed in literature are based on the pressurized arrangement, potentially able to ensure lower capital costs and higher efficiencies. Conversely, atmospheric plants are easier to manage, due to the possibility of operate the SOFC and the GT independently one of each other. The paper also investigates more complex SOFC/GT configurations, including: HAT turbines, IGCC SOFC/GT power plants, ORC cycles, etc. A detailed analysis of the SOFC/GT control strategies and part-load performance analyses is also presented, showing that such systems reach their best performance at nominal capacity, and are affected by significant reduction of the electrical efficiency in case of large variations of the load. Finally, the paper also presents a review of hybrid SOFC/GT power plants fed by alternative fuels, such as coal and biomass.

Contents

1. Introduction . . . 33
2. Overview of SOFC technologies . . . 34
   2.1. Tubular . . . 34
   2.2. Microtubular . . . 34
      2.2.1. Progress in fabrication techniques . . . 35

* Corresponding author. Tel.: +39 0817682301; fax: +39 0812390364.
E-mail address: frcalise@unina.it (F. Calise).

http://dx.doi.org/10.1016/j.apenergy.2015.06.027
0306-2619/

2.2.2. Durability and reliability analyses . . . 35
2.3. Planar . . . 35
2.3.1. Innovative materials and cells design . . . 35
2.3.2. Progress in fabrication techniques . . . 36
2.3.3. Modeling and numerical simulation of performances . . . 37
2.4. Intermediate temperature SOFCs . . . 37
3. SOFC/GT layouts classification . . . 38
4. SOFC/GT pressurized cycles . . . 38
4.1. Internally reformed SOFC/GT cycles . . . 39
4.1.1. Anode recirculation . . . 39
4.1.2. Heat Recovery Steam Generator (HRSG) . . . 41
4.2. Externally reformed SOFC/GT cycles . . . 43
4.3. Hybrid SOFC/GT-Rankine cycles . . . 46
4.3.1. Hybrid SOFC/GT-Organic Rankine Cycles . . . 47
4.4. Hybrid SOFC/GT with air recirculation or Exhaust Gas Recirculation (EGR) . . . 50
5. SOFC/GT atmospheric cycles . . . 51
6. SOFC/GT power plant: control strategies . . . 54
7. Hybrid SOFC/GT systems fed by fuels different from natural gas . . . 57
7.1. Alternative fuels: biomass . . . 58
7.2. Conventional fuels: coal . . . 61
7.3. Others . . . 62
8. IGCC SOFC/GT power plants . . . 65
9. Experimental studies . . . 65
9.1. Hybrid SOFC/GT systems: prototypes and experimental analyses . . . 65
9.2. Experimental performance analyses of non-hybridized SOFCs . . . 69
10. R&D projects and topics . . . 71
10.1. SOFCs stacks operation, materials and fabrication techniques . . . 72
10.2. Innovative hybrid systems . . . 73
10.2.1. SOFC–desalination plants . . . 73
10.2.2. SOFC–CCP systems . . . 75
10.3. Hybrid SOFC/GT-Cheng cycles . . . 76
10.4. Hybrid SOFC/Humidified Air Turbine (HAT) . . . 77
10.5. Hybrid SOFC/GT-ITSOFC cycles . . . 78
11. Market perspectives . . . 79
12. Conclusions . . . 80
References . . . 80

1. Introduction

One of the main goals of the research in the energy field is the development of novel conversion technologies, allowing one to achieve higher efficiencies and a lower environmental impact. In fact, the energy sector must face with a constant increase of the world energy consumption, especially due to dramatic development of the emerging countries. As a consequence, it is crucial to make such development "sustainable", considering the limited availability of natural resources [1]. In addition, energy conversion processes must not be harmful to the environment, and undesirable effects must be prevented, such as: global warming and emissions of pollutants [2].

This goal can be achieved by a simultaneous development of renewable energy sources and highly efficient energy conversion devices. In fact, several governments are promoting and forcing the use of renewable energy sources (solar, wind, hydro, etc.) [3–7]. Similarly, innovative technologies must be also used for the conventional conversion of fossil fuels, providing simultaneously ultra-high conversion efficiencies and ultra-low environmental impact [8–13].

Several novel and efficient renewable technologies were developed during the past few years, dramatically reducing their capital cost and improving their power density [14,15]. Such renewable energy sources, as wind [16,17], solar [18–23], hydro based energies [24,25], etc., are widely combined with back-up units to obtain efficient and environmental friendly hybrid systems. Simultaneously, novel highly efficient energy conversion systems using fossil fuels are now commercially available, such as: combined cycles [26–28], carbon capture technology [29–35], integrated gasification combined cycles [36–39] and fuel cell-based power plants [40–42].

Among these innovative technologies, fuel cells are considered as one of the most promising energy conversion systems [40]. In fact, they can electrochemically oxidize the fuel without combustion, leading to ultra-high electrical efficiencies [40,43–45]. Fuel cells can also benefit of low emissions, due to the intrinsic characteristics of their electrochemical reaction, whose by-products, in case hydrogen is used as a fuel, are just CO_2 and H_2O [46,47]. Fuel cells are also very attractive for their intrinsic modularity which also allows one to assembly power plants from micro-scale (<1 kW) to large-scale (>10 MW) systems [40,46,47]. Finally, it is worth noting that the electrochemical reaction is highly exothermic, releasing a significant amount of heat which can be profitably used for cogeneration purposes (space heating, domestic hot water, district heating, steam production, etc.), depending on the operating temperature of the fuel cell [2,45,48–55]. In case of high temperature fuel cells, their exhaust gases can be also used to drive a bottomed thermodynamic cycle (e.g., Rankine cycle, Brayton cycle) [2,45,48,49,56–63]. In this case, the overall efficiency of the overall hybrid cycle can theoretically be higher than 70% [2,40,45]. In particular, solid oxide fuel cell (SOFC) is the most attractive fuel cell technology for possible system hybridization, since their operating temperature is very high (up to 1000 °C) [64], leading to a plurality of hybrid power plants [2,40,45–48,61,65], including steam or Organic Rankine Cycles [45,66–69] and/or Brayton cycles [2,45–47] and many other configurations, as shown later on in the paper.