Renewable Energy and Smart Systems

journal homepage: https://sanad.iau.ir/journal/res

Hybridization technology of fuel cells with internal combustion engines for transportation industry energy production

Soudabeh Nikmanesh[1,*], Seyed Ali Seyedifar[2]

[1] Faculty of Basic Science Department, Abadan Faculty of Petroleum, Petroleum University of Technology
[2] BSc Student, Chemical Engineering Department, Abadan Faculty of Petroleum, Petroleum University of Technology

Article info

Keywords:
Energy Generation Optimization
Energy Consumption Control
Clean Energy
Hybrid Fuel Cell and Heat Engine
SOFC-IC

Article history:
Received: 9 June 2024
Accepted: 13 July 2024

Abstract

Despite the well-established advantages of renewable energy resources, including environmental sustainability and reduced emissions, fossil fuels continue to dominate energy supply in most industrial sectors. This persistence is largely due to the substantial capital investment required for a complete transition from conventional fossil-based systems to fully renewable infrastructures. Under such constraints, improving and optimizing existing energy generation and conversion systems represents the most realistic and cost-effective short- to medium-term solution. Among emerging energy conversion technologies, fuel cells have gained considerable attention as a viable alternative due to their high efficiency, low pollutant emissions, and operational flexibility. In particular, Solid Oxide Fuel Cells (SOFCs) are distinguished by their ability to operate at high temperatures, which enables efficient integration with heat engines (HEs) in hybrid thermodynamic cycles. These hybrid SOFC-HE systems offer enhanced overall efficiency through effective waste heat recovery, making them especially attractive for advanced energy applications. Recent developments in hybrid energy systems suggest that SOFC-based hybrid cycles can play a pivotal role in shaping future research directions in clean energy generation, intelligent energy management, and optimized energy consumption. In the transportation sector, such systems are of growing interest as intermediate technologies supporting the gradual transition from conventional internal combustion engines to fully electric powertrains. This paper focuses on a detailed performance analysis of hybrid SOFC–Internal Combustion (SOFC-IC) systems when employed as the primary power source in Hybrid Electric Vehicles (HEVs). The proposed system is systematically compared with traditional IC engines in terms of efficiency, emissions, and operational characteristics. Furthermore, the study investigates optimization strategies aimed at maximizing system performance while minimizing fuel consumption and environmental impact. The findings highlight the potential of SOFC-IC hybrid systems as an effective inter-generation solution, bridging the technological gap between fossil-fuel-based engines and next-generation electric vehicles. Such systems can significantly contribute to reducing emissions in the automotive industry while ensuring energy efficiency and technological feasibility during the ongoing energy transition.

* Corresponding author.
E-mail address: Soudabeh.Nikmanesh@Put.ac.ir

1. Introduction

Throughout the last two decades, the energy crisis and environmental pollution has increased the world temperature through emission of greenhouse gases and led to climate changes. Fossil fuels, at the moment satisfy an important portion of the energy demand, however, CO, CO_2 and SO_2 emission along other poisonous materials resulted from the fossil fuels pollute critically the environment. In addition, usage of the fossil fuels is decreasing rapidly and world moves toward renewable energies as a substitution for the fossil fuels.

Since the industrial revolution, the automotive industry has developed fast. According to published reports in 2020, transportation consumes 21 percent of the primary energy consumption and their corresponding emission of CO2 encompasses 15.9 percent of total world emission. Through the continuous development of economy and society, it is predicted that demand for automobile will increase more, thus, energy problems and environmental issues would become more serious. Therefore, development and application of more efficient as well as cleaner technology of energy provisioning within the automotive industry in inevitable [A1].

The Fuel Cell (FC) is one of the most attractive renewable energies which can directly transform the chemical energy of different types of fuels into electricity with high efficiency, low emission and without acoustic pollution. The multiple advantages of FCs have turned them into one of the most effective devices to lower the environmental pollution. The fuels cells are characterized by motor and battery properties. They can perform through mechanical energy for a long time without any variation as long as their fuel is provided. Moreover, they are of various types based on the kind of electrolyte they use and fuel they consume and their catalyzer, type of the chemical reaction and performance temperature are determined based on the type of electrolyte and fuel [A2-A3].

The fuel cells are of the following kinds.

1- Proton-Exchange Membrane (PEM) fuel cells which adopt their names from a conducting membrane located between two catalyzer layers, gas emission layer and bipolar planes. The PEM membranes of fuel cells are categorized as low and high temperature membranes.
2- Direct Methanol Fuel cells (DMFC) which has a similar architecture to hydrogen fuel cell, because they use sulfone membranes. This kind of cell operates in low temperature which is between 50 and 80 degrees centigrade.
3- Alkaline Fuel Cell (AFC) uses the liquid and low-cost KOH. However, this electrolyte makes reaction with the CO_2 gas in the air. This fuel cell can be used as a movable as well as fixed energy source.
4- The Phosphoric Acid Fuel Cell (PAFC) adopts its name from the type of electrolyte it uses. It is a medium temperature fuel cell to generate constant electricity. The operational temperature is within the 200-220 degrees centigrade. This fuel cell is among the oldest as well as most developed fuel cells which is in mass production around the 200 KW.
5- The Molten Carbonate Fuel Cell (MCFC) is a DC electricity generation system which operates at 650 degrees centigrade. The main advantage of this type of fuel cell is that it does not use noble metals in the catalyzer due to high operational temperature. Instead, it can use various fuels such as methane (CH_4), CO, and hydrogen. One of the advantages of MCFC as well as SOFC is their usage of output gases for simultaneous energy production.
6- Solid Oxide Fuel Cell (SOFC): the PEM and SOFC are two kinds of fuel cells which attracted lots of attentions. The well-known automotive companies such as Toyota, Hyundai, Honda and Nissan have PEM-FC at their disposal commercially at the moment and all of them are to prepare the SOFC in the next steps.

Recently, great capital has be dedicated for green hydrogen generation through electrolysis from renewable sources. Although storing hydrogen is still relatively hard, however it has great number of application in various sections such as an energy carrier, within transportation, industry and Power, for Ammonia generation and artificial fuels and also in oil refinement. As a fuel, hydrogen is used more in the fuel cells. Even though hydrogen has been researched to be used within Internal Combustion Engines (ICE), but it provides lower profit compared to fuel cells. The best option for ICE is usage of pure hydrogen which is needed for such applications as higher volumetric density with direct injection and thus for injectors, the motor head and blocks of high-temperature durable materials. Furthermore, the low ignition energy of hydrogen increases the possibility of inverse reaction (backfire). Moreover, mixture of hydrogen-air produces more NOx compared to ordinary fuels-air mixtures. The fuel cells are smaller, quieter and more importantly, more efficient compared to ICEs; they affect the environment negligibly and can be used for multiple application in which electricity demand spans over a few watts up to hundreds of megawatts; lots of researches have been done over the control strategies that depends upon the requested load and optimization of different parameters which impact performance, efficiency and cost [A4-A6].

The efficiency of SOFCs goes beyond systems that operate using ordinary heat cycles. Also, by restoring the exhaust heat and transform it into usable energy simultaneously, the overall efficiency of the generation increases while energy loss decreases. Among the fuel cells, SOFCs are suitable, practical and logical option for steady energy generation. They are attractive thanks to their flexibility with respect to their consuming fuel, having high-temperature exhaust output, not having leakage issues due to solid electrolyte while can be combined with other cycles in order to increase the power stations output. In this paper, we survey prominent and up-to-date researches on introducing and application of SOFC hybrid systems.

2. The Overall Schematic of SOFCs

The fuel cell is a galvanic cell in which the chemical energy of fuel is turned into electricity through electrochemical processes. It has two electrodes where fuel and oxidant will be fed individually and the desired reactions occur. A conductive electrolyte is necessary to transfer the ions between electrodes, while electrons flow through an external circuit due to potential difference. The fuel cells usually take advantage of high-cost catalyzers, but SOFCs conduct the ions of oxygen within the Yttria-Stabilized Zirconia (YSZ) in the 800-1200 degrees centigrade span. The solid electrolyte helps to eliminate the need for evaporation and cycling which is vital for non-solid ordinary electrolyte. New designs of electrodes and usage of various ceramics other than YSZ which are capable of conducting the hydrogen ions possibly can decrease the operational temperature up to 600 º C.

The SOFCs are able to use different kinds of fuels which encompass hydrogen atoms in order to accomplish the mentioned above reactions. They do not need high cost catalyzers and the whole stack can be cheaper compared to other FCs. Other than NG, SOFCs can use liquid fuels such as gasoline, diesel and jet fuel, artificial fuels, derivative fuels from biomass and also ammonia even though some of the fuels might need some sort of external reforming [A7]. Fig. 1 illustrates the operation of an SOFC.

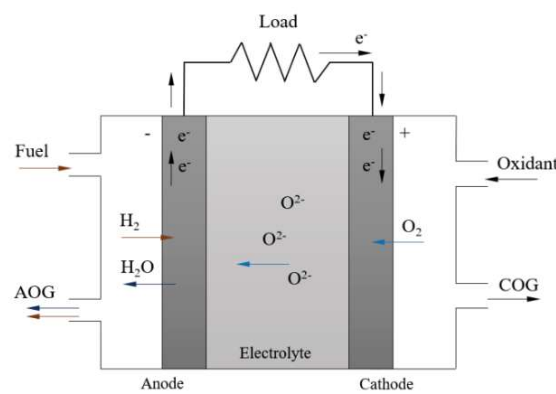

Fig. 1: Solid Oxide Fuel Cell [A6]

From the figure, the oxygen molecules in cathode reduce into oxygen ions which subsequently can flow through the electrolyte. The cathode gas (COG) cycles through FC into a heat converter (HEX) in order to reuse its own thermal energy. Within the anode, the oxygen ions oxidize fuels that has hydrogen, while electrons flow through an external circuit and produce electricity. As the electrons enter cathode, the cycle repeats. When the pure hydrogen is used, the only emission is water. If a fuel other than pure hydrogen is used, the emission will include a combination of AOG mixture of hydrogen, hydrocarbon, CO, CO_2 and water steam. SOFCs do not produce such critical environmental pollutants as nitrogen oxidant or sulfur oxidants; as a matter of fact, they also can COs very well while CO can poison other kinds of FC.

The chemical reaction within fuel cells is similar to those in batteries, but due to availability of fuel source they produce steadier electricity compared to batteries. The SOFC has an anti-leakage architecture. Also their processes outputs include lower pollutants. Some types of SOFCs can safely operate very long up to 80000h to generate DC electricity and 8000h for automobile applications. Operation of FCs generally and SOFCs especially does not involve any mobile devices, mechanical frictions or loud noises, and they have repair and maintenance cost which is equal to or lower compared to heat engines. FCs have quicker refueling time and higher specific energy than batteries; these characteristics, respectively, are attractive large and long distant transportation.
The internal combustion engines are a low cost and reliable option for distributed generation application from 1KW up to 10MW due to their puberty and higher mass production. For the span of electricity generation capacity, batteries and FCs have a long way in order to turn into steady energy sources. As the FC technologies of high efficiency grow continuously, hybridization with ICEs can provide more powerful and flexible generators of electricity for more integration of renewable energies and to be used for steady transportation vehicles [A8].

In practice, SOFCs needs auxiliary equipment including cooling pomp, oxidant cycling pomp (usually air), refueling pomp, electrical control devices and etc. in order to work properly. The air recycling pomp is the biggest energy consuming device that can use up to 10% of total output power stack of FCs. Other auxiliary devices consume noticeably lower energies. The efficiency of FC decreases as the electric current and thus power increases; thus, it is better off for an FC to operate at lower currents in order to increase its efficiency. However, from another viewpoint, operation at very low currents (and thus very low powers) decreases the operational efficiency due to electricity consumption of auxiliary equipment. SOFC are of different geometries such as plane, piped and integrated architecture, each with their own pros and cons with respect to cost, power density and manufacturing issues.

The piped geometry compared to plane has the following advantages: usage of a thin layer of electrolyte in the outer part of the pipe decreases the power loss resulted from polarization of the geometry; direct distribution of air and fuel causes fast reaction against load oscillation and provides steadier behavior versus refueling variations. On the other hand, the plane geometry thanks to lower manufacturing cost and simple production process provides high power density which is attractive and used within very FCs [A3,A8].
Depending whether the provided fuel is fed directly or not into the SOFC stack so that to be used in the chemical reactions, the SOFC's system configuration can be classified into direct fuel cell and processed fuel cell as illustrated in fig. 2.

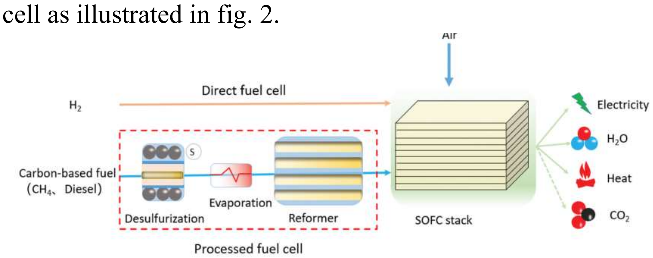

Fig. 2: Direct and Processed Fuel Cells [A4]

A direct fuel cell generally requires pure hydrogen to operate and is suitable for areas with hydrogen refueling stations. In contrast, a reformed fuel cell typically means that the fuel needs to be processed to produce hydrogen-rich gas, which is then supplied to the SOFC stack.

3. The SOFC-ICC Hybrid System

In order to increase efficiency of ICs, we must consider both restoration of chemical heat (fuel modification) and reduction of inefficiency related to the combustion reaction, which can be compensated for through combination with a more efficient energy converter device [A8].

On the other hand, the SOFC system efficiency, as driving force in automobiles, must be improved higher. The mentioned improvement is a key point related to restoration of energy and gas fuel in SOFC stack. In addition to ATGR, SOFC can be combined with other power systems so that a combined power system, that is, hybrid power system based on SOFC is provided as in fig. 3. This hybrid power system based on SOFC not only increases the system efficiency, but also adapts SOFC for usage within automobiles. The kay points of a SOFC-based hybrid power system for automobiles are: (1) the type of driving force device must be adaptable to SOFC, (2) the strategies of the energy system must be managed properly. A proper distribution strategy leads not only faster dynamic response, but also increases the system efficiency so that system would operate within optimal operational range, (3) start-up strategy; reducing the start-up time duration is pretty significant in the start-up strategy [A4].

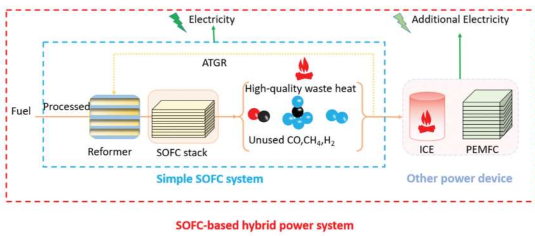

Fig. 3: SOFC-based Hybrid Power System

Within the SOFC-IC systems, the choice of ignition states is very import for ICE. Referring to the fuels' characteristics, the typical ignitions of ICE are Spark Ignition (SI) and Compression Ignition (CI).

The key SOFC design parameters for designing a suitable SOFC-ICE hybrid system are: (1) fuel consumption; a fraction of the input fuel from SOFC's anode remain without any reaction or it can constitute in undesired sideways reaction instead of electrochemical half-reaction; this fraction is defined with respect to the overall fuel. (2) Recycling Ratio (RR); parts of the output gases of anode/cathode output can be fed back into the fuel/air duct; this, in turn, improve the demand for additional air. (3) System Operation; this denotes combined effect of previous key points.

The SOFC system has advantages such as fuel flexibility, high energy density, is clean and efficient, noiseless and compressed; these properties make SOFCs a promising energy source for automobiles. For a simplified SOFC system, in order to increase the system efficiency, we can adopt ATGR policy, heat recycling, and configuring a hybrid system using ICE and PEMFC. The main essence of this strategy is to use energy and fuel for the anode gas so that to improve the system efficiency. At the moment, application of SOFC in automobiles is limited to usage as an APU for trucks; also, it can be used as a multiplier of operating range within the electric transportation vehicles. Nonetheless, there are still issues to be addressed in order to use SOFC in vehicles. A small time duration of start-up is very important in vehicles [9]. The start-up includes two steps: first those related to materials and second heating strategy. One of the criticized disadvantages of SOFC is its long start-up time which is resulted from high temperature of stack operation. The key point to shorten the start-up is applying optimization in SOFC materials so that it can be manufactured for medium or low temperatures. Furthermore, energy management is an important subject in SOFC-based power systems. For a simple SOFC system, the most important issue is energy management of the lost heat with high quality. ATGR and a suitable heating exchange design can recycle the lost heat completely and improve the system energy productivity. For SOFC-ICE and SOFC-PEMFC, two apparatuses are involved in output energy. Therefore, a practical energy distribution strategy is of great significance, while the internal wasted heat management must be taken into account, too.

5. Conclusion

Analysis of the present hybridization of a SOFC system with an insertion of a GT or ICE can provide noticeable progress in productivity, lower the greenhouse gas emissions and improve fuel consumption compared to traditional electricity generation systems. Generally speaking, the electrical efficiency of such systems spans over 50%-70% depending upon such factors as system design, parameter control and type of the fuel. The combined cycles that use ICE instead of GT are more reliable due to better load management, easier parameters management, lower cost and more extended applications. In order to speed up usage of SOFC for vehicles, cell, stack and system must be improved simultaneously. In this respect, the following items must be taken into account: 1) in the cell level, the first item is optimization of materials and development of SOFC for medium or low temperatures, as well as improved cell operation and increasing the power density; 2) in the stack level, development of reliable sealing materials for preventing gas leakage and designing suitable flowing flux stack ducts (whether for the same direction or cross directional); this, in turn, reduce the heat tension and gradient. 3) In the system level, the first item to optimize is system configuration; this includes ATGR, heat recycling and hybridization of power system with other approaches. The second one is related to development of specific devices for SOFC system such as blower, etc. Last, but not the least, study of the energy management strategies such as those related to start-up methods and energy distribution in steady state.

References

[A1] B. Feng , H. Xu , A .Wang , L .Gao , Y. Bi and X . Zhang , "A Comprehensive Review of Energy Regeneration and Conversion Technologies Based on Mechanical–Electric–Hydraulic Hybrid Energy Storage Systems in Vehicles" *Appl. Sci,* **Vol.** *13*, pp. 4152, 2023.

[A2] X. Lü , Y. Wu , J. Lian , Y. Zhang , C. Chen , P. Wang and L. Meng , "Energy management of hybrid electric vehicles: A review of energy optimization of fuel cell hybrid power system based on genetic algorithm" , *Energy Conversion And Management* , **Vol.** *205*, pp. 112474, 2020.

[A3] P. Kumar and O. Singh, "A review of solid oxide fuel cell-based hybrid cycles", *Energy Conservation*, **Vol.** *46*, pp. 8560-8589, 2022.

[A4] X. Qin, J. Cao, G. Geng, Y. Li, Y. Zheng, W. Zhang and B. Yu , "Solid oxide fuel cell system for automobiles" , *International Journal of Green Energy*, 2022

[A5] T. Reza , J. Yang , R. Wang , C. Xia , R. Raza , B. zhu and S. Yun , "Recent advance in physical description and material development for single component SOFC: A mini-review" , *Chemical Engineering Journal*, **Vol.** *444*, pp. 136533, 2022.

[A6]T. Gechev and P. "Punov , Combined Cycles of SOFC/ICE and SOFC/GT – a Brief Review", *13th International Scientific Conference on Aeronautics, Automotive and Railway Engineering and Technologies.* BulTrans, 2022.

[A7] S. Ma , M. Lin , T. Lin , T. Lin , X. Liao , F. marechal , J. Herle , Y. Yang , C. Dong and L. Wang , "Fuel cell-battery hybrid systems for mobility and off-grid applications , A review" , *Renewable and Sustainable Energy Reviews* , **Vol.** *135*, pp. 110119, 2021.

[A8] H. Chehrmonavari, A. Kakaee , S. Ehsan Hosseini, U. Desideri, G. Tsatsaronis, G. Floerchinger , R. Braun and A. Paykani , "Hybridizing solid oxide fuel cells with internal combustion engines for power and propulsion systems: A review" , *Renewable and Sustainable Energy Reviews*, **Vol.** *171*, pp. 112982, 2023.

[A9] M. Kandidayeni , J.P. Trovao , M. Soleymani , L. Boulon, "Towards health-aware energy management strategies in fuel cell hybrid electric vehicles : a review", *International journal of energy* , **Vol.** *47*, pp. 10021-10043, 2022.