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Experimental study of homogeneous charge compression ignition engine operation fuelled by emulated solid oxide fuel cell anode off-gas

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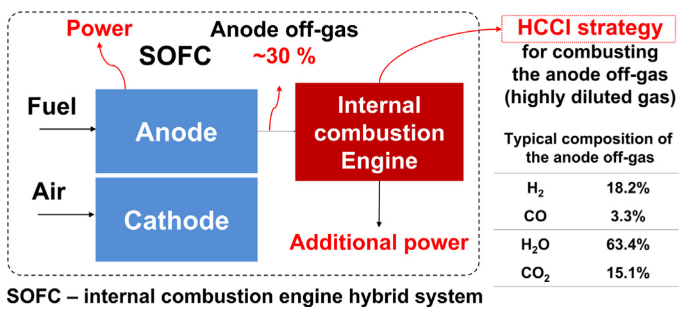
HIGHLIGHTS

- Engine operation in the hybrid system is experimentally analysed for the first time.
- HCCI engine is experimented while varying the operating conditions of the system.
- HCCI engine yields a significant amount of power while emitting very low NO_x emission.
- It has been found how each system control parameter affects HCCI engine operation.
- System operating conditions enabling successful HCCI engine operation are identified.

GRAPHICAL ABSTRACT

Schematic of solid oxide fuel cell – homogenous charge compression ignition engine hybrid system.



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ABSTRACT

A solid oxide fuel cell (SOFC) hybrid system is a system that combines an SOFC with an additional power generation device to increase the efficiency of the system. The SOFC–gas turbine hybrid system has been primarily investigated for SOFC hybrid systems. However, the current power generation capacity of an SOFC is less than several MWs; for this generation capacity, an internal combustion engine is generally more efficient and economical than a gas turbine. Focusing on this point, recently, the concept of an SOFC–internal combustion engine hybrid system was proposed. However, the operation of this system has not been experimentally studied yet. In this paper, as the first step in an experimental investigation of the hybrid system, an experimental study on the operation of an internal combustion engine fuelled by SOFC anode off-gas was conducted. To successfully combust the SOFC anode off-gas, which includes a large amount of diluents (H_2O and CO_2), the homogeneous charge compression ignition (HCCI) method was selected instead of spark ignition as the combustion strategy of the internal combustion engine in the hybrid system. For the HCCI engine experiments, a single-cylinder HCCI engine and experimental equipment for emulating SOFC anode off-gas were constructed. Various HCCI engine experiments were performed while varying several system control parameters, e.g., the fuel utilization factor of an SOFC, which primarily affects the composition and flow rate of the engine intake gas. The experiments indicated that, in general system operating condition, HCCI engine operation yields a significant amount of power (w/25–30% gross indicated efficiency) and produces significantly low NO_x emissions (< 5 ppm @ O_2 15%) under stable HCCI combustion (< 5% COV $IMEP_g$, which is the coefficient of variance of the gross indicated mean effective pressure). Considering that the experiment was performed using a small single-cylinder engine, these experimental results reveal that the use of an HCCI engine as the bottoming cycle in an SOFC

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hybrid system is promising. In addition, it has been found how each system control parameter affects HCCI engine operation. It was confirmed that HCCI engine operation was not always stable in all system operating conditions. System operating conditions that induce an exceedingly low engine load (< 1.8 bar $IMEP_g$, which is the gross indicated mean effective pressure) should be avoided as it decreases the stability of engine operation. Additionally, system operating conditions that make an engine intake gas with excessive dilution (fuel molar fraction < 0.125) should be avoided to decrease the amount of unburned CO emission and maintain a CO combustion efficiency higher than 90%.

1. Introduction

The use of solid oxide fuel cells (SOFCs) in future power generation systems is attracting significant attention due to their advantages, including high efficiency, fuel flexibility, and the ability to operate without an expensive catalyst, such as Pt [1]. To achieve the full commercialization of SOFCs, studies are being actively conducted to increase the efficiency of SOFCs. Research on SOFC hybrid systems, which improve the power generation efficiency by combining an SOFC with an additional power generation device, has revealed that a hybrid system can be a powerful tool for increasing efficiency.

Thus far, SOFC–gas turbine (GT) hybrid systems have been primarily investigated for SOFC hybrid systems [2]. The gas turbine in the SOFC–GT hybrid system utilizes the heat and chemical energy of SOFC anode off-gas to produce additional power. The SOFC–GT hybrid system has been explored using various approaches, such as numerical simulations [3–8], experiments [9,10], hardware-based simulations [11–13], and thermos-economic analyses [14]. These studies have analysed the various aspects of an SOFC–GT hybrid system, such as system configuration [8,15], operation characteristics [3,5], full and part-load operation [4,6], fuel flexibility [7,13], and the control of the system [11,12]. Particularly, the experimental studies directly verified the actual feasibility of system operation [9,10]. Siemens Power Corporation has developed a 220 kW-class pressurized SOFC–GT hybrid system, which has operated for approximately 2900 hours and achieves an efficiency of 53% [9]. Mitsubishi Heavy Industries has also developed a 220 kW-class pressurized SOFC–GT hybrid system and has reported an operating time of more than 3000 hours and an achieved efficiency of 52% [10].

However, the current power generation capacity of an SOFC is typically below several MWs; for this generation capacity, internal combustion engines (ICEs) are more frequently employed than GTs as ICEs are generally more efficient and economical than GTs at this generation capacity [16,17]. Therefore, it is expected that an ICE may have the potential to be used as a bottoming cycle of an SOFC. Focusing on this point, recently, the concept of an SOFC–ICE hybrid system was proposed and registered for US and Korean patents [18].

This patented concept has another significance: it proposes the application of homogeneous charge compression ignition (HCCI) as the combustion strategy of the ICE in an SOFC–ICE hybrid system. The inventors claimed that spark ignition, which is the combustion strategy extensively employed in ICEs fuelled by gaseous fuels, is not appropriate for the ICE of an SOFC–ICE hybrid system due to the high dilution level of the fuel of an ICE, i.e., the SOFC anode off-gas. In the presence of a large amount of diluent in the fuel of an ICE, the flame propagation speed, which is an important parameter of the spark ignition method, is significantly reduced, and proper combustion is unlikely to occur unless additional fuel is provided for the ICE [19,20]. For reference, an exemplary composition of SOFC anode off-gas in a typical SOFC operating condition with natural gas is shown in Table 1. The amount of diluent is approximately four times the amount of fuel. For this reason, the HCCI combustion strategy, which is known to be capable of adequately combusting highly diluted gas, achieving high efficiency, and producing low NO_x emissions, is proposed as the combustion strategy for the ICE in the SOFC–ICE hybrid system [21].

Researches on SOFC–HCCI engine hybrid system have also been conducted [22–24]. For example, Park et al. conducted a thermos-economics analysis to compare the SOFC–HCCI engine hybrid system with the SOFC–GT hybrid system in terms of energy efficiency, total cost, and environmental impacts [22]. The analysis revealed that, for 100 kW-class system, the SOFC–HCCI engine hybrid system is considered to be superior to the SOFC–GT hybrid system in terms of not only energy efficiency but also economic aspects. Lee et al. similarly compared the SOFC–HCCI engine hybrid system with SOFC–GT hybrid system in terms by conducting exergoeconomic evaluation and a similar conclusion was reached [23]. Kang et al. constructed a dynamic model of an SOFC–ICE hybrid system and analysed the transient behaviour of the SOFC–ICE hybrid system during the increase of load [24]. The study showed the first research work on the transient behaviour of SOFC–HCCI engine hybrid system and the model developed in the study can be utilized for developing control strategies of the system.

However, unlike the case of the SOFC–GT hybrid system, the studies of the SOFC–HCCI engine hybrid system have been conducted only through simulation and thermos-economics analysis; an experimental study on this system has not been conducted yet. Therefore, it is necessary to experimentally verify the feasibility of actual system operation and study the system operation characteristics in various operating conditions.

To experimentally investigate the entire hybrid system, since the SOFC and HCCI engines continuously provide feedback to each other in the hybrid system, a complete understanding of the operation of the HCCI engine in the hybrid system is essential. In particular, it is essential to analyse how the HCCI engine will operate under various system operating conditions; however, such analysis has not been performed. Although the studies on the operation of HCCI engine fuelled by syngas have been conducted, from these studies, it is difficult to predict how the HCCI engine would operate depending on the system operating conditions of the SOFC–HCCI engine hybrid system. This is because, in most of these studies, the temperature of syngas was lowered for the clean-up and the most of H_2O was separated so that the SOFC anode off-gas generally has a higher temperature and a larger amount of H_2O than those of syngas in these studies [25,26]. In recent years, researches have been conducted on the use of syngas as fuel for HCCI engines, without lowering the temperature for clean-up [27,28]. The temperature of the gas studied in these studies is relatively close to that of the SOFC anode off-gas. However, still the SOFC anode off-gas has much larger amount of H_2O than that of syngas in these studies because H_2O is input into the hybrid system for reforming natural gas

Table 1
Composition of SOFC anode off-gas (for SOFC fuel utilization factor of 70% and steam-to-carbon ratio of 2.5).

H_2	18.2%	Fuel	21.5%
CO	3.3%		
H_2O	63.4%	Diluent	78.5%
CO_2	15.1%		