



# Conceptual design of a novel ammonia-fuelled portable solid oxide fuel cell system

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## ABSTRACT

A novel portable electric power generation system, fuelled by ammonia, is introduced and its performance is evaluated. In this system, a solid oxide fuel cell (SOFC) stack that consists of anode-supported planar cells with Ni–YSZ anode, YSZ electrolyte and YSZ–LSM cathode is used to generate electric power. The small size, simplicity, and high electrical efficiency are the main advantages of this environmentally friendly system. The results predicted through computer simulation of this system confirm that the first-law efficiency of 41.1% with the system operating voltage of 25.6 V is attainable for a 100 W portable system, operated at the cell voltage of 0.73 V and fuel utilization ratio of 80%. In these operating conditions, an ammonia cylinder with a capacity of 0.8 l is sufficient to sustain full-load operation of the portable system for 9 h and 34 min. The effect of the cell operating voltage at different fuel utilization ratios on the number of cells required in the SOFC stack, the first- and second-law efficiencies, the system operating voltage, the excess air, the heat transfer from the SOFC stack, and the duration of operation of the portable system with a cylinder of ammonia fuel, are also studied through a detailed sensitivity analysis. Overall, the ammonia-fuelled SOFC system introduced in this paper exhibits an appropriate performance for portable power generation applications.

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## 1. Introduction

Solid oxide fuel cells (SOFCs) are power generation devices that can convert chemical energy of a variety of fuels, such as hydrogen, hydrocarbons, ammonia, and biomass, into electrical energy with high efficiency and low environmental impact. The SOFCs are suitable for power generation from a few watts to many megawatts in distributed and centralized applications. The portable application of SOFCs has been recently increased [1–3]; however, selecting a proper fuel is a crucial step for its commercialization. Such a fuel should be cheap, safe, and easy to store and transport. Hydrogen is both expensive and difficult to store and transport [4]. To use hydrocarbon fuels, a fuel processor to prevent carbon deposition over the anode catalyst and a gas clean-up system to separate sulfur compounds from the fuel are usually required [5,6]; hence, the size and cost of the portable system increases. For the following reasons, ammonia can be considered as an adequate substitute for hydrogen and hydrocarbon fuels for portable application of SOFC-based power generation systems [7–10]:

- At ambient temperature and pressure of around 10 atm, the gaseous ammonia is liquefied and its density increases by approximately 850 times, which makes it a cost-effective fuel for transportation and storage. In this condition, the volumetric energy density of the ammonia is comparable with that of gasoline or methanol [11].
- Ammonia can be produced in massive quantities at a cost as competitive as hydrocarbon fuels [7], and its cost per volume of stored energy is approximately 3 times less than that of hydrogen [12].
- Ammonia is safer than hydrogen and hydrocarbon fuels because it does not burn in air under normal conditions, and as such is considered non-flammable when transported. If ammonia is released into the atmosphere, it dissipates rapidly and because of its distinct smell, can easily be detected by the human nose [13].
- According to the results of fuel maps developed for SOFCs, ammonia is a suitable fuel for electric power generation with high maximum voltage and electrical efficiency [14,15].

Of course, ammonia is corrosive [16]. If it is directly fed to an oxygen ion conducting SOFC, the anode catalyst is rapidly destroyed. This problem can be solved by decomposing ammonia into its constituent elements, i.e. nitrogen and hydrogen, before feeding it to the SOFC stack in the portable system. The corrosion problem of

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### Nomenclature

$C_p$	heat capacity at constant pressure ( $\text{kJ kg}^{-1} \text{K}^{-1}$ )
$\dot{E}_x$	exergy (W)
$k$	heat capacity ratio
LHV	lower heating value ( $\text{kJ kg}^{-1}$ )
$\dot{m}$	mass flow rate ( $\text{kg s}^{-1}$ )
$p$	pressure (Pa)
$T$	temperature (K)
$U_f$	fuel utilization ratio (%)
$\dot{W}$	electric power (W)

### Greek letters

$\eta$	efficiency
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### Subscripts

I	first law of thermodynamic
II	second law of thermodynamic

ammonia in other components of a portable system can also be solved by selecting a suitable alloy with an appropriate thickness for these components [17].

Introducing and conceptually designing a novel ammonia-fuelled portable power generation system using the oxygen ion conducting SOFC are the purposes of this study.

## 2. System description

The configuration of the portable SOFC system is shown in Fig. 1. The system is mainly comprised of an oxygen ion conducting SOFC stack to produce DC electricity; liquid ammonia and water cylinders, enough for a specified-duration of operation of the portable system; an air blower to supply air to the SOFC stack and to overcome the pressure drop in the system; a heat exchanger to increase the temperature of air, water and ammonia before entering the SOFC stack; and a catalytic burner to convert the chemical energy of the unutilized fuel in the SOFC stack to heat. In contrast to hydrocarbon-fuelled SOFC systems, a clean-up component to remove sulfur compounds from the fuel is not required. Even if the hydrogen required to produce ammonia is obtained from fossil or renewable fuels, the sulfur compounds are removed from the feedstock in the first step of the ammonia production process, because sulfur compounds deactivate catalysts used in this process [18].

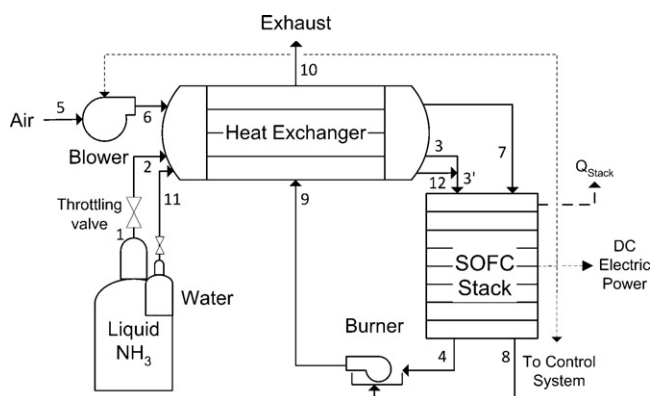


Fig. 1. Configuration of the introduced ammonia-fuelled portable SOFC system.

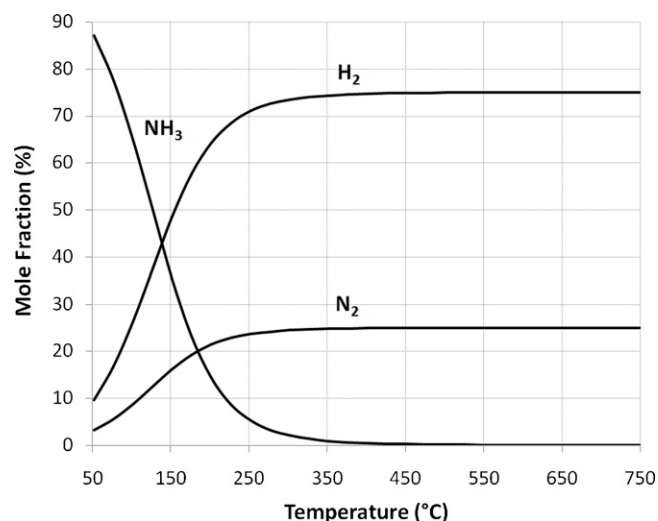
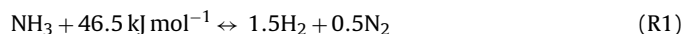


Fig. 2. Mole fraction of ammonia, hydrogen and nitrogen in thermodynamic equilibrium at different temperatures.

## 3. Process description

The pressurized liquid ammonia in the small cylinder is vaporized using a throttle valve. Although direct utilization of the vaporized ammonia in proton conducting SOFCs is possible [19–25], the ammonia content of the inlet fuel to an oxygen ion conducting SOFC should be kept as low as possible to prevent the corrosion problem. In the portable SOFC system illustrated in Fig. 1, the vaporized ammonia enters a heat exchanger where its temperature increases to around 700 °C. By increasing the temperature, the ammonia begins to decompose into its constituent elements, i.e. hydrogen and nitrogen, through the following endothermic reaction [26]:



To predict the composition of the ammonia at the outlet of the heat exchanger, a thermodynamic equilibrium-based study was performed, and the result is shown in Fig. 2. As shown in this figure, for temperatures higher than 450 °C, more than 99% of the ammonia can be decomposed into its constituent elements; however, the rate of the decomposition reaction is slow at this temperature [27]. The amount of ammonia at the inlet of the SOFC stack can reach less than 250 ppm in equilibrium at a temperature of 700 °C. It is assumed that the ammonia decomposition reaction is fast enough at this temperature compared to the residence time of ammonia in the heat exchanger. Because iron acts as a suitable catalyst for the ammonia decomposition reaction [28,29], an iron porous body can be also inserted in the ammonia's paths in the heat exchanger to increase the rate of the reaction. In this condition, the outlet fuel from the heat exchanger will be in thermodynamic equilibrium.

The temperatures of the outlet water from the water cylinder and the pressurized air in the blower also increase to 700 °C in the heat exchanger. The water vapour at 700 °C is then mixed with the decomposed ammonia and a suitable fuel for the SOFC stack is prepared. The fuel and air enter the SOFC stack where the electric power, heat and water vapour are generated due to the electrochemical reaction of hydrogen and oxygen. Ma et al. [7] investigated the possibility of nitric oxide formation in a variety of ammonia conversion rates and temperatures in SOFCs. They found that the amount of nitric oxide is not detectable even at 800 °C. Therefore, nitric oxide is not expected to be formed in the SOFC stack of the ammonia-fuelled portable system. The outlet fuel and air from the SOFC stack enter a catalytic burner where the chemical energy of

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