# SOLID OXIDE FUEL CELL COMBINED HEAT AND POWER PLANT OPERATED WITH DIESEL

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Abstract: *Solid Oxide Fuel Cells (SOFCs) are high efficient energy converter because they are able to convert chemically bound energy directly into electrical energy. In addition, SOFCs have a high fuel flexibility since they can not only be operated with hydrogen, but also with ammonia, biogas and other hydrocarbons. However, operating SOFCs with complex fuel mixtures such as conventional liquid fuels or biofuels bears several risks which can lead to early degradation of the SOFC. To reduce the risk, external fuel reforming and investigations on optimal operating conditions have to be conducted. Here we demonstrate the operation of an in house developed small scale SOFC combined heat and power (CHP) plant with standard Austrian diesel. The SOFC operation was monitored and characterized by applying temperature measurements, continuous gas analysis, electrochemical impedance spectroscopy and voltage and current measurements. These results may be useful to demonstrate the potential of SOFCs for future applications such as energy supply of greenhouses. The in house developed SOFC CHP system can be used for further investigations regarding the fuel flexibility and long term behavior.*

*Key words:* *solid oxide fuel cell (SOFC), combined heat and power plant, system development*

## 1. INTRODUCTION

During the transmission of the electric power supply from fossil fuels, to sustainable energy sources, it shows up that for some applications, fuels with high gravimetric energy density are necessary. Such applications can be aircraft (Santarelli et al., 2010), ships (Nehter et al., 2017) or isolated areas such as islands, or rural areas and agriculture facilities (DePippo & Peppley, 2019). Isolated areas have often only limited access to different kind of power grids but still need heat and electric energy supply. For these purposes, liquid synthetic- and bio- fuels are necessary. In addition, the fuels should be converted with high efficiencies and without emitting pollutants such as $NO_x$. One energy converter with potential high efficiencies due to direct electrochemical conversion of chemical bound energy is the solid oxide fuel cell (SOFC) (Song, 2002). Due to the operating principle of the SOFC, oxygen ion conduction and high operating temperatures, a variety of fuels can be applied to the SOFC. Possible fuels are hydrogen, ammonia (Stoeckl et al., 2020), biogas (Gandiglio et al., 2020) or liquid hydrocarbons (Bae et al., 2009). However, to use hydrocarbons, often a fuel pre-treatment is required since direct utilization of hydrocarbons in the fuel cell can lead to early performance loss of the SOFC due to carbon deposition. To minimize this risk, a fuel pre-treatment such as reforming can be used (Li et al., 2023). During reforming, hydrocarbons get mixed with other substances and converted in a hydrocarbon rich syngas. Depending on the substance mixed with the hydrocarbon, different reforming strategies exist. Most important reactions for the following work are the endothermal steam reforming reaction, the exothermal partial oxidation with air and its combination, in the following referred to as auto thermal reforming (Rostrup-Nielsen, 1993). Till now, only limited work is available about monitoring and efficiency analysis of diesel operated SOFCs (Kleinohl et al., 2014; Lawrence & Boltze, 2006). Further, most of diesel operated systems are built as auxiliary power units (APU) instead of combined heat and power supply units (Rechberger et al., 2013; Reissig et al., 2015). Here we report about characterization tests of an in house developed diesel operated heat and power SOFC system. We additionally applied a variety of monitoring measurements to investigate the behavior of a SOFC which is operated with liquid fuels. This could help us in future to optimize such systems and gain knowledge about the system- and electrochemical behavior.

## 2. METHODS

In this section, the in house developed combined heat and power SOFC system, which is operated with diesel as fuel, and its main components are described. The system consists of a (i) fuel supply line, (ii) a steam supply, (iii) an air supply, (v) a diesel mixing and evaporation chamber, (vi) a reformer, (vii) the SOFC stack, (viii) a catalytic burner, (ix) a gas water heat exchanger and (x) a control cabinet. The fuel supply line pumps a controllable fuel flow rate from a fuel tank via a nozzle in the mixing and evaporation chamber. In addition to fuel, at least steam is added to the mixing chamber to generate a mixture suitable for steam reforming. If auto-thermal reforming should be conducted, air is also added to the mixing chamber. The air supply line further supplies the SOFC air electrode, the catalytic burner and additional aggregates such as the pneumatic needle valve from the steam supply line and cooling units. The air flow rates for the reformer, SOFC and catalytic burner are controlled by mass flow controllers. The mixing and evaporation chamber is heated to 400 °C. The reformer consists of four parallel tubes which are filled with an inert bulk, Pt based catalyst pellets and commercial Ni catalysts (Höber et al., 2022). The control temperature of the reformer is 780 °C. The SOFC stack consisting of 30 anode supported cells is placed downstream of the reformer and supplied with the reformer outlet-gas and pre-heated air. The air and the reformer outlet gas are additionally heated in the furnace where the SOFC stack is placed, to reach the SOFC operating temperature of 750 °C. Downstream of the SOFC, the gases from the SOFC fuel electrode and air electrode are mixed and let into the catalytic burner. The catalytic burner is filled with Pt based catalyst pellets and is cooled with an additional controlled air supply. The gas water heat exchanger is placed downstream of the catalytic burner and is used to heat up water for external heating circuits.

The system is operated during the presented test results with diesel and steam flows or with diesel steam and air flows on the fuel side, to achieve steam reforming or auto-thermal reforming conditions respectively.

## 3. RESULTS

The flow rates and the electrical power output of the SOFC are shown over time in Figure 1 for the two tested operating conditions. A constant diesel and water flowrate is set for both operating conditions. The stack air supply was constant at 55 slpm except for a short duration while operating with diesel, steam and air mixtures, where it was increased to 60 slpm. To achieve diesel, steam and air mixtures, an additional air flow (reformer air) was added in the mixing chamber, upstream of the reformer, to the fuel line. We observed that operation with diesel and steam mixtures led to higher electrical power outputs of the system compared to operation with diesel, steam and air mixtures. This is the case because to reform the diesel and steam mixtures, external heating is required due to the observed endothermal diesel steam reforming reactions. The externally provided heat combined with the reforming process leads to an increased heating value of the gas mixture at the reformer outlet (equal to SOFC inlet) compared to the reformer inlet. By mixing air to the diesel and steam mixture upstream of the reformer, additional exothermal reactions from partial oxidation of the fuel are observed. These exothermal reactions lead to a decrease in external heat demand. Hence, diesel, steam and air mixtures can be beneficial to increase the heat output of the system. We observed, that the electrical efficiency is mainly dependent on the ratio of fuel flow to electrical power output. By adjusting the fuel flow to the actual electrical demand, no to only small efficiency losses can be achieved, allowing high efficient operation also in partial load conditions. The electrical power output of the SOFC can be varied between 0 W and an upper power output limit of the SOFC. The upper power output limit is determined by a voltage limit of 0.7 V per single cell to avoid re-oxidation of the Ni in the SOFCs fuel electrode. This would result in 21 V for the presented system. Due to inhomogeneity's in temperature and gas distribution, which could lead to local differences of the voltage, it was observed that a SOFC stack voltage of more than 21 V should be maintained to extend the system lifetime.

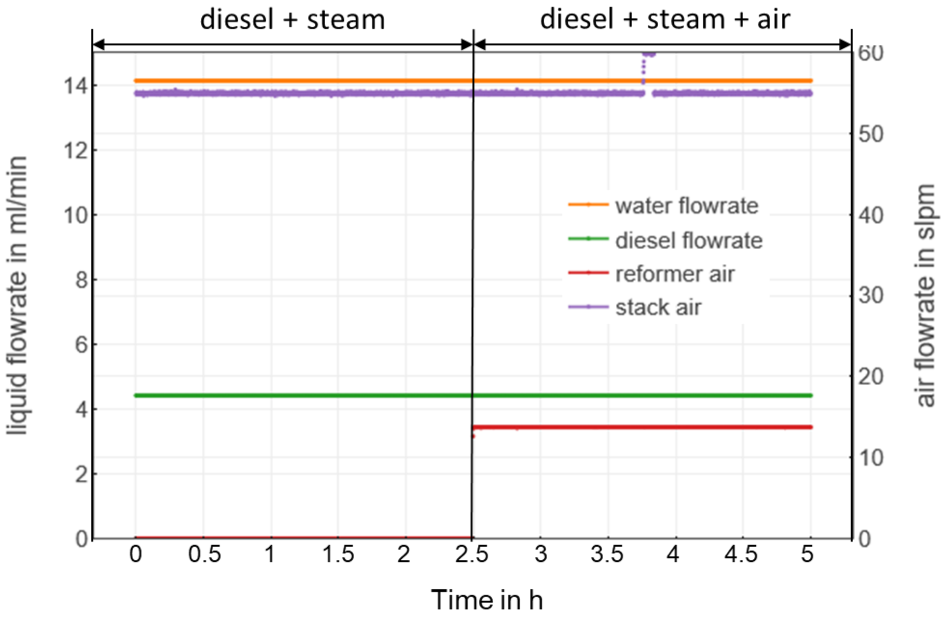

*Figure 1: SOFC relevant flow rates and SOFC electrical power output over time.*

## 4. DISCUSSION

Within the results section, we compared operation with diesel and steam mixtures and operation with diesel, steam and air mixtures of the developed diesel driven SOFC system. The partial load in terms of electric energy output is only limited by the lower voltage limit of the stack which is found to be above 21 V and can else be adjusted as needed.

## 5. CONCLUSIONS

In this work, a characterization experiment of a system able to utilize diesel in SOFCs is shown. The system consists of several components including fuel pre-treatment where diesel, water and air mixtures are reformed to a hydrogen rich gas mixture. System operation with diesel and steam mixtures and with diesel, steam and air mixtures were discussed. The overall high efficiency potential including partial load conditions show the potential of SOFC applications not only for hydrogen or methane based fuels but also for liquid fuels such as diesel or bio-diesel. The developed system can be used to further investigate SOFC operation with different liquid fuels and optimize operating conditions. Such SOFC systems could in future be used for areas where the high gravimetric energy density of liquid fuels is necessary and high electric energy efficiencies or coupled heat and electric power supply is needed.

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