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An integrated diesel fuel processing system with thermal start-up for fuel cells

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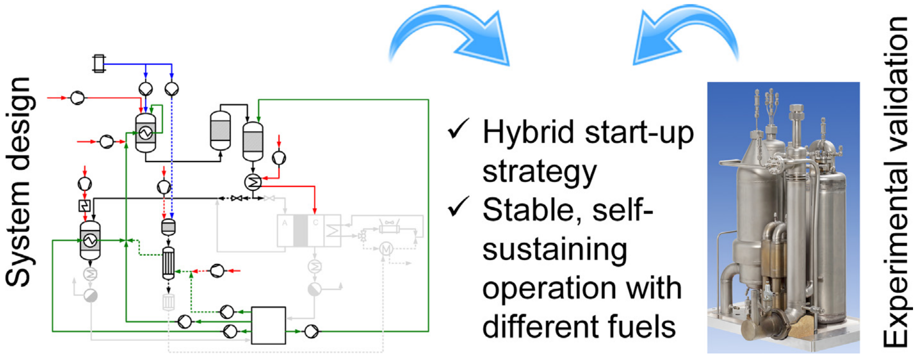
HIGHLIGHTS

- Design of a diesel fuel processor for 5 kW_e fuel-cell-based auxiliary power unit.
- Hybrid start-up strategy using a diesel burner assisted by a glow plug.
- Self-sustaining system operation at full load in 27 min from cold start.
- Target carbon monoxide level achieved with different kerosene and diesel fuels.
- Operation periods between 4 and 24 h with start/stop/regeneration cycles.

GRAPHICAL ABSTRACT



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ABSTRACT

A diesel fuel processor for high temperature polymer electrolyte fuel cells in the 5 kW_e power class was developed and tested. Emphasis was placed on a quick and sustainable start-up. Furthermore, operational conditions were identified that would achieve the desired reformate quality for the fuel cell anode. A thermal start-up strategy using a commercial diesel burner was developed and further optimized, resulting in a hybrid strategy with the help of a glow plug. With this strategy, self-sustaining operation of the fuel processor at full load was achieved in 27 min and the resulting reformate was of sufficient quality to operate the fuel cell in 31 min. The experimental plan includes operation periods of between 4 and 24 h with start/stop/regeneration cycles representing the daily operation of an auxiliary power unit at maximum load. With all fuels used, the target carbon monoxide concentration of 1% at the anode inlet (wet reformate) was achieved. Significant deviations from the design parameters were necessary to demonstrate a stable system performance with desulfurized Jet A-1 and to achieve the target carbon monoxide concentration with premium diesel. These results bring diesel fuel processing for auxiliary power units closer to real application, offering experimentally-validated solutions for start-up and stable operation under realistic conditions with different fuels on a systems level.

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Nomenclature

APU	auxiliary power unit
ATR	autothermal reformer/reforming
CAB	catalytic burner
CPOX	catalytic partial oxidation
DOE	department of energy
FTIR	Fourier-transform infrared spectroscopy
GHSV	gas hourly space velocity
HC kerosene	desulfurized Jet A-1
HEX	heat exchanger
HT-PEFC	high-temperature polymer-electrolyte fuel cell
HTS	high-temperature shift
HVO	hydrotreated vegetable oil
LTS	low-temperature shift
MCFC	molten carbonate fuel cell
PEFC	polymer electrolyte fuel cell
PEM	polymer electrolyte membrane
PROX	preferential CO oxidation
SOFC	solid oxide fuel cell
SR	steam reforming
UPS	uninterruptible power system
WGS	water-gas shift reactor/reaction
WHSC	world harmonized stationary cycle

Abbreviations and indices

e	electrical
λ	stoichiometry
N	standard conditions

1. Introduction

A diesel-based fuel cell auxiliary power unit (APU) enables a highly efficient power supply for heavy duty vehicles. The applied catalytic burner allows for low emission operation with no particles, NOx or soot. The availability of a global infrastructure for diesel and kerosene-type jet fuel, in conjunction with the high energy density of these liquid fuels, further motivates the development of such systems today. If diesel fuel is produced regeneratively, using hydrogen from wind electrolysis and carbon dioxide from industrial processes in the future, as is entailed by the Power-to-Fuel concept [1], the proposed route will become even more attractive.

Specchia [2] states that aside from the benefits of lower fuel consumption and CO$_2$ emissions, such systems can deliver electrical energy for applications on-board vehicles at any time, even when the engine is switched-off, as they function independent of engine operation. APUs can even be used as back-up and uninterruptible power systems (UPS) for the mobile telecommunication industry and military purposes. Zhou et al. [3] conducted a comprehensive analysis of the application of an SOFC-APU on different trucks in Northeast China. Meanwhile, Peters and Samsun [4] analyzed different fuel cell systems for multifunctional aircraft applications, reporting that kerosene-based systems are the superior choice for medium- to long-range missions. Rahman et al. [5] note that fuel cell APUs can substantially reduce both the fuel consumption of trucks and the emission of pollutants, but that an absence of appropriate fuels, higher unit production expenses and the integration of the units with other on-board truck systems are major challenges. Shancita et al. [6] considered alternative idling reduction technologies and compared their performances in reducing fuel consumption and exhaust emissions. The main disadvantage of the fuel cell technology was determined to be the unavailability of suitable fuel; however this fact was based on rather old information from 2006 and 2008. Meanwhile, significant progress has been achieved with diesel fuel processing on a systems level. Rechberger et al. reported on the first European SOFC APU in a heavy duty truck [7]. These achieved 2500 km and an APU efficiency of 29% [8]. Pregelj et al. demonstrated a laboratory system for a PEFC-based diesel APU as a proof of concept [9], supported by a case study of the impact of fuel cell and battery size on overall system performance [10]. Nehter et al. [11] published their first results from an SOFC/diesel-based fuel cell APU for emissions reduction in ships, where they demonstrated 55% efficiency with their prototype system. Jeong et al. [12], meanwhile, achieved the coupled operation of an SOFC with an integrated diesel fuel processor for 1000 h at a degradation rate of 4% per 1000 h.

Apart from the complexity of the complete fuel processor and its integration into the complete fuel cell system, the reforming process itself still presents a challenge. Recent works mostly focus on autothermal (ATR) or steam reforming (SR) as the diesel reforming route of choice.

Cozzolino and Triboli [13] present an in-depth analysis of the influence of various operating parameters for an ATR-based diesel processor in a modeling study. Dong et al. [14] analyze a 1 kW SOFC system with an ATR of different fuels, including diesel and Jet A, and achieve 40% system efficiency with Jet A and self-sustaining operation. Walluk et al. [15] report the optimum anode off-gas recycle ratio to be 45% in an SOFC system based on an ATR of diesel with 65% fuel utilization in order to maximize reforming efficiency. Lindström et al. [16] opt for ATR as the reforming route in order to circumvent the heat transfer problem in catalytic SR and report significantly higher efficiencies than early generation diesel reformers. Karatzas et al. [17] report RhPt/CeO$_2$–ZrO$_2$ to be the most active catalyst for the ATR of diesel. Furthermore, Creaser et al. [18] develop a model that successfully describes the key operating features of a 5 kW$_e$-scale diesel ATR with an engineered monolith-supported Rh-based catalyst. Ekdunge [19] report on the diesel ATR on the path to commercialization. In full-scale ATR experiments, Gonzales et al. [20] observe a maximum hydrogen concentration of 42 vol% and a fuel conversion of 98% using FT diesel. With European standard diesel, they note a 92% conversion [21]. Liu and Hong [22] examine new catalyst formulations, such as Nickel phosphide, grown on ceria and Gd-doped ceria and the resulting supported catalysts for the ATR of diesel. Lee et al. [23] apply Ni-Al-based catalysts to the ATR of n-dodecane and obtain 90% conversion. Jung et al. [24] use various promoters to improve Ni-Al-based reforming catalysts for the ATR of dodecane. Recently, Choi et al. [25] observe excellent catalytic activity amongst Rh/Al-Ce-Zr-based catalysts for diesel ATR and no carbon deposition on the catalyst surface. Pasel et al. [26] demonstrate 10,000 h of ATR operation with diesel and kerosene fuels and more than 98.2% conversion at the end of the experiment, but also present a highly integrated novel ATR prototype [27]. Meißner et al. [28] report on constructive and operational measures to generating a high quality reformate for PEFC from commercial diesel at a conversion rate greater than 99.95%.

For the most part, low conversions and poor long-term stability are reported with the steam reforming of diesel, whereas the utilization of micro reactors offers new perspectives for this route. Much research has been conducted on catalysts. Vita et al. [29] investigate the activity and stability of Pt/CeO$_2$ catalysts towards the SR of n-dodecane and report stable activity for 50 h. Using a Rh/CeO$_2$ catalyst, they achieved stable performance in a sulfur-free condition, but observe catalyst deactivation in the presence of sulfur [30]. Fauteux-Lefebvre et al. [31] undertake the SR of commercial diesel for more than 15 h at high gas hourly space velocities with an overall conversion of 85%. In terms of a catalyst study, Kim et al. [32] investigate the SR of n-dodecane over Ni–YSZ/KTO and observe a stable performance at a space velocity of 20,000 h^{-1}. However, at 30,000 h^{-1} they observe nickel deactivation due to pyrolytic carbon. Mundhwa et al. [33] develop two