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Electrical start-up for diesel fuel processing in a fuel-cell-based auxiliary power unit

Remzi Can Samsun [a,*], Carsten Krupp [a], Andreas Tschauder [a], Ralf Peters [a], Detlef Stolten [a,b]

[a] *Forschungszentrum Jülich GmbH, Electrochemical Process Engineering (IEK-3), 52425 Jülich, Germany*
[b] *Chair for Fuel Cells, RWTH Aachen University, 52072 Aachen, Germany*

HIGHLIGHTS

- Electrical start-up strategy for diesel fuel processing is reported.
- Start-up is optimized using transient computational fluid dynamics simulations.
- Reproduction of experimental results with high accuracy using dual-cell approach.
- Validation of internal steam production in the reformer via electrical wire.
- Start-up time of 9.5 min with 0.4 kW h energy input for a 28 kW_{th} fuel processor.

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ABSTRACT

As auxiliary power units in trucks and aircraft, fuel cell systems with a diesel and kerosene reforming capacity offer the dual benefit of reduced emissions and fuel consumption. In order to be commercially viable, these systems require a quick start-up time with low energy input. In pursuit of this end, this paper reports an electrical start-up strategy for diesel fuel processing. A transient computational fluid dynamics model is developed to optimize the start-up procedure of the fuel processor in the 28 kW_{th} power class. The temperature trend observed in the experiments is reproducible to a high degree of accuracy using a dual-cell approach in ANSYS Fluent. Starting from a basic strategy, different options are considered for accelerating system start-up. The start-up time is reduced from 22 min in the basic case to 9.5 min, at an energy consumption of 0.4 kW h. Furthermore, an electrical wire is installed in the reformer to test the steam generation during start-up. The experimental results reveal that the generation of steam at 450 °C is possible within seconds after water addition to the reformer. As a result, the fuel processor can be started in autothermal reformer mode using the electrical concept developed in this work.

1. Introduction

Fuel cell systems with the capacity to reform diesel and kerosene can yield emissions savings and reduce fuel consumption when used as auxiliary power units in trucks and aircraft. One of the challenges in developing these systems is the required start-up time. The U.S. Department of Energy defined the technical target for the start-up time from 20 °C as 30 min for 1 kW_e to 10 kW_e fuel cell APUs operating on standard ultra-low sulfur diesel fuel [1]. Apart from the quick start-up time, the start-up strategy should offer low energy consumption and the start-up components should only minimally increase the system volume and weight. Many research groups have published their work on optimizing the start-up strategy of fuel processing systems for mobile applications. The first such publications were based on gasoline fuel processing for automotive applications. For instance, Springmann et al. [2] carried out simulations based on 1D dynamic multiphase models of gasoline fuel processors for mobile fuel cell systems to analyze different start-up strategies. They utilized an electrically heatable monolith in the autothermal reformer (ATR) to reach the necessary ignition temperature for oxidation reactions from a cold start. By means of

* Corresponding author.
E-mail address: r.c.samsun@fz-juelich.de (R.C. Samsun).

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reactive heating, the system could be started in 2 min. Moreover, the start-up time could be further reduced when the high temperature shift (HTS) stage was heated electrically, enabling a start-up time of less than 1 min. Ahmed et al. [3] report on the design and fabrication of a gasoline fuel processor for automotive fuel cell systems with a rapid start-up capability. They start the reformer using a small amount of electrical energy to ignite the catalytic partial oxidation (CPOX) reaction with fuel and air. They then switched to ATR mode by commencing liquid water injection when the catalyst was warmed up. Afterwards, they used reactive heating with air injection to enable the controlled oxidation of hydrogen and carbon monoxide in the reformate in essential zones. The results of the simulation showed that the fuel processor could deliver 90% of the related hydrogen capacity within 90 s. The authors optimized the reactors using 3D computational fluid dynamics simulations to achieve operation conditions near to the design point. Goebel et al. [4] developed a gasoline fuel processor with two burners with direct steam generation via water injection into the burner exhaust. Using direct vaporization of water and hydrogen for catalyst light-off, the time required to achieve full power was 140 s. A fuel-lean start-up method without hydrogen was also demonstrated, with 190 s to full power. In more recent work, Ji et al. [5] developed a gasoline fuel processor for military APUs. The system was started using a start-up burner. Gasoline was ignited using a glow plug positioned behind the catalyst to minimize soot formation. Afterwards, the reactor was operated in CPOX mode, followed by ATR mode. Using the selected start-up strategy, the fuel processor was able to produce reformate with less than 0.5 vol% CO within 30–35 min.

Other research groups have optimized the start-up behavior of fuel processors using butane and propane. Santis-Alvarez et al. [6] investigated a hybrid start-up process for a self-sustained CPOX reformer for n-butane in intermediate-temperature micro-SOFC power plants. A resistance heater was embedded inside the catalytic reactor bed and was activated until the exothermic oxidative reaction was ignited. Lee et al. [7] optimized the start-up characteristics of a commercial propane steam reformer for a portable fuel cell system. They extended the start-up strategy based on external heating using the spark ignition of the catalytic combustor by introducing a slip stream of air into the reformate line at the inlet of the WGS reactor. Stutz et al. [8] present a novel start concept for a micro-solid oxide fuel cell (SOFC) system with the partial oxidation of butane. In comparison to a pure electrical start, they utilize the reformer or post-combustor as a catalytic reactor to convert butane and air combined with an electrically heated wire.

Ryi et al. [9] developed a microchannel fuel processor for methane steam reforming with an integrated hydrogen combustor to decrease start-up time. Chen et al. [10] explore the cold start-up of another methane fuel processor via modeling and experiments, conceptualizing start-up as an optimization problem and reducing the start-up time by a factor of 25% through mathematical changes in operation conditions, thereby achieving a start-up time of 28 min.

Yoon et al. [11] determine that catalyst degradation during the autothermal reforming of methanol dominates as a result of the abrupt spikes in temperature caused by fuel-lean processes during start-up. They also report that fuel-rich start-up processes show faster transient responses for hydrogen production because the fuel-lean process consumes hydrogen during the oxidation process.

Maximini et al. [12] develop a novel start-up strategy for their diesel steam reforming fuel processor for the APU application. According to their strategy, the reformer operation under oxidative steam reforming mode starts 15 min after system start-up and provides reformate for the reactive heating of the downstream water–gas shift (WGS) reactors. Steam reforming begins after approximately 23 min.

If an HT-PEFC is selected as the stack technology, the stack must also be heated during system start-up. Wang et al. [13] analyze the start-up process of HT-PEFCs via dynamic simulations for UPS application using a 3D physical model of a single cell. For their given cell configuration, they found that the combined cooling channel and reaction heating was optimal and capable of heating the cell faster than the other options. Andreasen et al. [14] analyze different heating strategies for air-cooled HT-PEFC stacks using a dynamic model. The experiments show that the fastest and most efficient way to heat the stack was using hot air. The heating-up time achieved using hot air was 6 min, in comparison to 1 h with electrical heating.

The most promising start-up strategies reported in the literature are based on starting the reforming reaction in CPOX mode to eliminate the need for steam during system start-up. Another promising concept recommended above requires the flow of hot burner gases through the reformer. In the case of an integrated HT-PEFC system with autothermal reforming of diesel fuel [15], which is the focus of this paper, these strategies cannot be used. To enable stable operation of the reformer, diesel, air and superheated steam are required at all times at their design values. In addition, the flow of hot burner gases through cold system components is not favored due to possible soot formation. In Ref. [16], the authors of the present work optimized the start-up strategy of a fuel processor for diesel and kerosene using a start-up burner and indirect use of hot off-gases from the burner. Furthermore, a commercial burner was selected and tested in Ref. [17] as a start-up burner for HT-PEFC systems with diesel reforming for APU application in trucks.

In this work, an alternative strategy is presented based on the electrical start-up of the fuel processor. With the help of transient computational fluid dynamics simulations, different optimization strategies are analyzed with a novel approach. The intention is to enable a quick system start without the need for additional components such as start-burners and heat exchangers, which are only necessary during start-up.

2. Approach and methodology

The basis for the start-up strategy in this work is an HT-PEFC system with autothermal reforming of diesel and kerosene. The main components of the fuel processor are an autothermal reformer, a two-stage water–gas shift reactor, a catalytic burner and a heat exchanger, all of which were designed for a thermal power of 28 kW. The HT-PEFC stack is cooled by a heat transfer fluid and was developed and tested in previous work [15,18]. The long-term stability of the reformer technology has been proven for 10,000 h using GTL kerosene and BTL diesel as fuels [19].

In the following, a new start-up concept is described. To optimize the start-up strategy based on the new concept, a transient model is developed to enable a dynamic, space-resolved analysis of the fuel processor components with respect to their geometric details.

2.1. Development of the start-up concept

The electrical start-up concept is based on the utilization of electrical heaters at essential locations in the fuel processor to heat process air during system start-up. In addition to the electrical heaters, an additional heating wire was located in the reformer's integrated heat exchanger. The main task of the heating wire is to evaporate steam during the start-up process to commence autothermal reforming. In the system's steady state operation mode, steam is prepared within the integrated heat exchangers of the reformer and catalytic burner utilizing process heat. At the fuel cell