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Heat exchanger design for autothermal reforming of diesel

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ABSTRACT

The increasing electrification of vehicles for passenger and heavy duty transport requires the deployment of efficient, low-emission power sources. Auxiliary Power Units (APUs) based on fuels cells offer an excellent solution, especially for supplying power during idling mode. For urban transport applications, gaseous hydrogen appears to be the best fuel option, whereas long-distance applications are better served by a liquid energy carrier. The autothermal reforming of liquid fuels such as diesel presents a simple and efficient method for producing hydrogen for fuel cell APUs. Heat integration for steam generation and air pre-warming are the key elements to a compact autothermal reformer design. With the aid of intense CFD simulations, a reformer construction was achieved with the high power density of 3.3 kW_{th}/l. Experimental validation indicates high hydrogen concentrations of between 32 and 36%, depending on diesel quality. In combination with already existing results, the newest autothermal reformer (ATR) generation enables the set-up of a complete APU system, fulfilling the U.S. Department of Energy (DOE) targets for fuel cell-based APUs.

Introduction

Autothermal reforming is a simple and efficient process for deriving hydrogen from liquid fuels. The so-called ‘short-lived’ hydrogen produced in this manner can be used in fuel cell-based auxiliary power units (APUs) for transport applications that are reliant on carbonaceous fuels, such as road freight transportation, railroad applications, maritime and inland water vessels and aviation [1]. These applications feature high and relatively constant energy demands. Due to their energy density, liquid fuels are the preferred option for propulsion in the transport sector. In order to simplify on-board systems and maintain the existing infrastructure, the same fuel used for propulsion should ideally also be capable of auxiliary power generation. Advanced auxiliary power units consist of a reformer with an integrated or additional gas clean-up stage, a fuel cell and a catalytic burner. These APUs are characterized by energy savings, modularity, low-noise operation, favourable behaviour at partial load and a potentially long service life. They are therefore likely to be an important element in the future energy economy, as is reflected by intensive international development activities in recent years [2]. With respect to fuel cells, several different types have been developed over

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the past few decades. Polymer electrolyte fuel cells (PEFCs, which operate at 60–95 °C) are preferred for mobile applications, whereas solid oxide fuel cells (SOFCs, which operate at 800–1000 °C) and molten carbonate fuel cells (MCFCs) are preferred for stationary applications, although SOFCs are also currently being investigated for use in APUs. More recently, the high-temperature PEFC, with working temperatures between 120 °C and 180 °C, is attracting more attention, particularly in conjunction with hydrogen produced by reforming. There are two development paths in fuel cell technology for transportation today, namely for public transport applications and heavy duty transport. The path discussed here focuses on highly energy-intensive transport applications, such as heavy duty transport by trucks [3–10] and passenger transport by aircraft [11–19]. Worldwide, the fuels used will most likely later shift from standard diesel to cleaner fuels such as those already used in light duty transportation applications. Heavy duty transportation will most likely make use of biofuels or synthetic fuels as a cleaner but scarcer resource in the long term, see Schemme et al. [20]. For these applications, the substitution of internal combustion engines or turbines for propulsion is not a consideration. Substantial energy savings can be made by decoupling on-board power supply from the propulsion unit and introducing an auxiliary power unit. As another major area for fuel cell applications, light duty transportation can make use of the on-board storage of hydrogen, as this would be more efficient than reforming carbonaceous fuels on-board.

APUs are widely used in aviation, but until now this has been exclusively on the basis of gas turbines that utilize kerosene. These systems are only employed on the ground and have electrical capacities of 150–400 kW_e as stated by Peters and Westenberger [17]. Fuel cell-based APUs provide electrical power independent of the drivetrain and can thus relieve the engine. An efficient power supply is thereby also available during the shutdown phases. This is particularly advantageous, since operating the engine to generate electricity using, as a rule, a very small partial load, is associated with a correspondingly low level of efficiency of, e.g., 4–11% in heavy goods vehicles as reported by Nehter et al. [8] and Rechenberger et al. [9,10]. The use of systems with particularly low pollutant and noise emissions therefore considerably improves the environmental impact of vehicles equipped with them. For example, in this way it would be possible to substantially improve the emissions profiles of airports and ports. Various studies of the application of fuel cells in the aviation sector have been conducted, with a multifunctional approach developed that means that, apart from utilizing the electric current generated, the water produced by the fuel cell and the resulting exhaust gases can best be used for tank inerting during aircraft descent, see Peters and Westenberger [17,18]. Tank inerting systems are now required in accordance with the latest aviation regulations for new aircraft designs. Classical PEFC fuel cells in the 50 kW_e power class are already available on the market, but can only be reliably operated with hydrogen. The combination of PEFCs and a reforming capacity is technologically complex and not yet mature. Currently, Airbus uses PEFC-type fuel cells that make use of stored liquid hydrogen. In the long term, however, a liquid energy carrier such as the fossil-based Jet A-1 or biokerosene for long-haul aircraft should be used, since the storage of large quantities of liquid hydrogen requires a modification of aircraft architecture and also leads to high energy losses in the energy conversion chain due to liquefaction. HT-PEFC system development is much more attractive with regard to heat and water management, but stack sizes are currently limited to 5–10 kW_e. Therefore, much current research on APU systems focuses on trucks and other small applications. More details about HT-PEFC system development concerning system design, the use of different fuels, hybridization and start-up components is provided by Samsun et al. [21–24].

Fig. 1 displays a sketch of a fuel cell system combining diesel fuel processing with two HT-PEFC stacks that yields a nominal electric power of 5 kW_e during reformate operation. The system design enables efficient electricity production and makes use of exhaust air for tank inerting, as well as a positive water balance, with condensed water being used during aircraft operation. A process analysis of stationary conditions by Peters and Samsun [25] revealed a system efficiency of up to 38.5%, a specific water production rate of 15 cl $kW_e^{-1}\,h^{-1}$ and an exhaust gas flow of 3.2 $m^3_N\,kW_e^{-1}\,h^{-1}$. These values must be interpreted as potential values, because the operating conditions chosen were the optimum values for achieving the high system efficiency. Table 1 shows the target values of APUs for aircraft and truck applications according to the literature [11–16,19,26]. There are fairly large differences in APU power between aircraft and truck applications. Annual aircraft production rates imply the production of approximately 500 units per year. The most challenging targets are the relatively high operation times of 15,000–40,000 h and the low costs of the complete APUs for a truck application of \$600 kW^{-1}. Mass-specific power and power density are an outcome of the design and construction process.

CFD modelling has been a key tool underpinning reformer construction [27–30]. Each new generation of reformers incorporates new insights from modelling and moves a step closer to meeting APU development targets, such as those set out by the DOE [26]. Important published results of the fuel processing group at IEK-3 include the elimination of by-products produced by the autothermal reforming of diesel [31], the development of operating strategies for fuel processing systems with a focus on water-gas shift reactor stability [32], electrical start-up for diesel fuel processing [22], the development of a novel reactor type for the autothermal reforming of diesel fuel and kerosene [33] and long-term stability [34]. The most important secondary reactions during the reforming process are those that lead to undesired carbon formation as reported by Peters and Rostrup-Nielsen [35,36]. Carbon deposits in a reformer lead to catalyst deactivation and must therefore be avoided. Heat integration is an important issue for achieving a compact design in terms of power density and mass-specific power, respectively.

Fuel evaporation and educt mixing

Chemical reactions

Hydrocarbon reforming is based either on steam reforming or on partial oxidation. Regarding the basic chemical reactions in

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