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Modeling, state estimation and nonlinear model predictive control of cathode exhaust gas mass flow for PEM fuel cells

M. Schultze*, J. Horn

Institute of Control Engineering, Department of Electrical Engineering, Helmut-Schmidt-University/University of the Federal Armed Forces Hamburg, Holstenhofweg 85, 22043 Hamburg, Germany

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ABSTRACT

Polymer electrolyte membrane fuel cells are efficient energy converters and provide electrical energy, water and oxygen depleted air with a low oxygen content as exhaust gas if fed with air. Due to their low emission of greenhouse gases and noise they are investigated as replacement for auxiliary power units currently used for electrical power supply on aircraft. Oxygen depleted air, called ODA-gas, with an oxygen concentration of 10–11% and a low humidity can be used for tank-inerting on aircraft. A challenging task is controlling the fuel cell system for generation of dehumidified ODA-gas mass flow while simultaneously keeping bounds and gradients on control inputs. This task is attacked by a nonlinear model predictive control. Not all system states can be measured and some states measured exhibit a significant time delay. A nonlinear state estimation strategy builds the entire system state and compensates for the delay. The nonlinear model predictive control and the state estimation are derived from the system model, which is presented. Simulation and experimental results are shown.

1. Introduction

The use of electrically powered systems has been growing in civil aircraft during the last decades (McLoughlin, 2009). On aircraft electrical power supply during ground operation is done by an auxiliary power unit (APU) that significantly emits CO_2, NO_x and noise. Polymer electrolyte membrane (PEM) fuel cells are very efficient energy converters, suitable for dynamic applications and offer the potential of drastically reducing these emissions. Therefore, PEM fuel cells are studied as replacement of an aircraft's APU. In addition to supply of electrical energy, PEM fuel cells deliver water and oxygen depleted exhaust gas if provided with air. They are suitable for supply of electrical power, of water and of oxygen depleted air (ODA-gas) for tank-inerting on aircraft during ground operation as well as during flight. This multifunctional use on aircraft offers a great benefit as size of current systems for power and water supply as well as tank-inerting can be drastically reduced, which offers great savings on total aircraft weight. The multifunctional fuel cell system (MFFCS) and its functions on aircraft are shown in Fig. 1. For tank-inerting the MFFCS must provide ODA-gas with an oxygen content of 10–11% (Aviation Rulemaking Advisory Committee, 1998; Kallo et al., 2010) to prevent ignition of fuel vapors and a low humidity to prevent icing and contamination inside the tanks (Tomlinson, Barker, Venn, Hickson & Lam, 2011). PEM fuel cell systems have been studied for electrical power supply of autonomous robots (Niemeyer, 2009) or for automotive applications (Karnik, Sun, Stefanopoulou & Buckland, 2009; Pukrushpan, Stefanopoulou & Peng, 2004). Operation of PEM fuel cells for inerting is a novel research topic and has not yet been studied in detail.

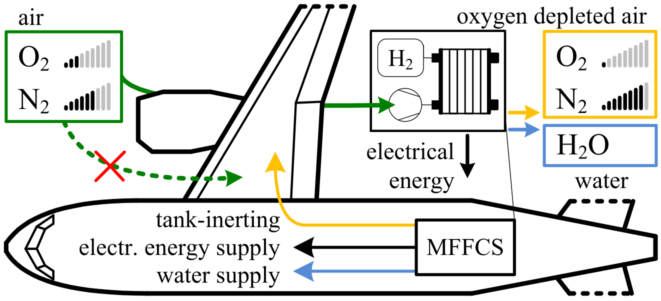

Fig. 1. Multifunctional fuel cell system (MFFCS) for electrical power supply, water supply and tank-inerting on a civil aircraft.

Proper fuel cell system operation such as keeping the membrane well hydrated and to proper supply fuel and air as oxygen carrier is a central aspect (Borup et al., 2007; Pukrushpan et al., 2004). In the

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* Corresponding author.
E-mail addresses: martin.schultze@hsu-hh.de (M. Schultze), joachim.horn@hsu-hh.de (J. Horn).
URL: http://www.hsu-hh.de (J. Horn).

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multifunctional context, controlling the fuel cell system for ODA-gas mass flow further requires satisfaction of limitations on stack current, its gradient and exhaust gas dehumidifier cooling temperature. Due to its inherent capability of incorporating constraints model predictive control is an advantageous approach as compared to classical control techniques. Model predictive control (MPC) has already been successfully applied to fuel cell systems for a time-optimal warm-up (Müller, Stefanopoulou & Guzzella, 2007), an optimal load-sharing between fuel cell and short-term energy storage (Vahidi, Stefanopoulou & Peng, 2004, 2006) or for electrical power supply (Niemeyer, 2009). Nonlinear Model Predictive Control (NMPC) of a MFFCS for exhaust gas is a novel topic. NMPC requires the current system state, which is gained by a nonlinear state estimation strategy based on the Sigma-Point-Kalman-Filter. NMPC strategies designed for the entire system (Schultze & Horn, 2013a) or assuming an underlying state estimation (Schultze, Hähnel & Horn, 2014) are part of previous work. Previous works have not presented the entire process of developing a NMPC for a MFFCS. This paper presents all steps in synthesis of the NMPC for exhaust gas mass flow, state estimation strategy and modeling of a MFFCS. The entire system model is presented in Section 2. This entire model is used for the design of the state estimation strategy presented in Section 3 and was used in designing the underlying fuel cell stack cooling temperature controller. The state estimation strategy supplies the NMPC with the entire state vector. Exploiting the underlying temperature control, the NMPC presented in Section 4 is based on a subset of the entire system model to save computational time. Simulation and experimental results are shown. The NMPC is compared to basic controls to show the advantages of this novel control strategy.

2. Multifunctional fuel cell system model

The flow of electrical energy from the MFFCS, additional short time energy storages and the main aircraft generators to the electrical consumers would be managed by an electrical power management strategy (PM). The PM is not scope of this work. In the following it is assumed that the PM applies a fuel cell stack current as requested. Moreover, the PM is assumed to react ideally and immediately. As a simplification, the electric load in Fig. 2 represents the PM and the aircraft's electric system.

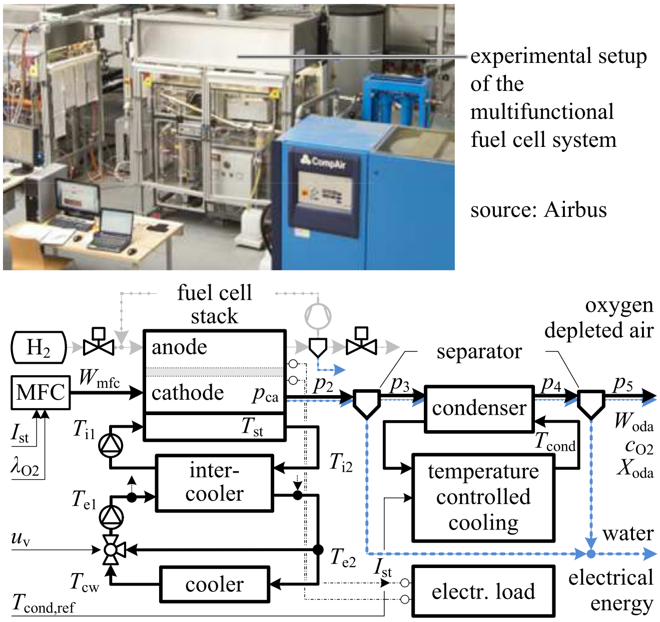
Fig. 2 shows the experimental setup and a schematic of the multifunctional fuel cell system. The MFFCS fuel cell stack has an anode recirculation loop for efficient hydrogen use. The polymer membrane inside the stack separates the cathode and anode volumes. The membrane is electrically not conductible, however, allows for water and proton transport. Its thinness facilitates high water diffusivity and hence promotes a stack-internal membrane humidification. Stack cooling temperature is limited by manufacturer specifications, so that the stack does not dry out or experiences flooding. Supply of air and fuel, especially during transients, must be kept to minimize the risk of oxygen and fuel starvation. Limitation of stack current rate decreases these risks as well as the risk of dynamic voltage losses and therefore protects against stack damage. The stack cooling system consists of two cooling loops that are coupled by an intercooler. Cooler and cooling valve are in the external loop. Exhaust gas dehumidification is performed by water separators and a condenser that is connected to a temperature-controlled cooling unit. The fuel cell stack is electrically connected to a controllable ohmic electric load. System inputs are stack current I_{st}, stoichiometry λ_{O_2}, condenser cooling reference temperature $T_{cond,ref}$ and cooling valve position u_v. ODA-gas mass flow and O_2 content are measured by a hot-wire anemometer and a lambda probe. Relative humidity, temperature and pressure measurements determine ODA-gas humidity.

The system model described in the following is derived from the nonlinear model (Schultze & Horn, 2013b) and is part of previous research (Schultze & Horn, 2013c). The model consists of ordinary differential equations, has 11 states and covers the MFFCS shown in Fig. 2. Air is modeled consisting of 21% (vol.) oxygen (O_2) and 79% nitrogen (N_2). Electrochemical as well as electric processes are very fast as compared to gas-transport and thermal processes and are modeled as static. The underlying stack cooling temperature control as well as the system's high thermal mass cause the thermal process to have only little influence on the gas-dynamic process. Gas dynamics are therefore considered being decoupled from thermal dynamics. Fig. 3 shows the entire system model structure. Due to a long pipe exhaust gas transport from the stack to the mass flow sensor underlies a significant transport delay. In the following, the delay is not stated explicitly. For the model, delayed measurements are derived by delaying the corresponding values by T_d.

2.1. Gas dynamics

The gas dynamics model describes the behavior of ODA-gas mass flow and its oxygen content.

The vector of inputs $\underline{u}_g = [I_{st}, \lambda_{O_2}]^T$ to the gas dynamics model comprises stack current I_{st} and stoichiometry λ_{O_2}. Feed air W_{mfc} is provided by a controlled valve (MFC), which is modeled as a


experimental setup of the multifunctional fuel cell system

source: Airbus

Fig. 2. Experimental setup and schematic of the multifunctional fuel cell system (MFFCS) with fuel cell stack, controllable electric load, stack cooling system and exhaust gas dehumidification.

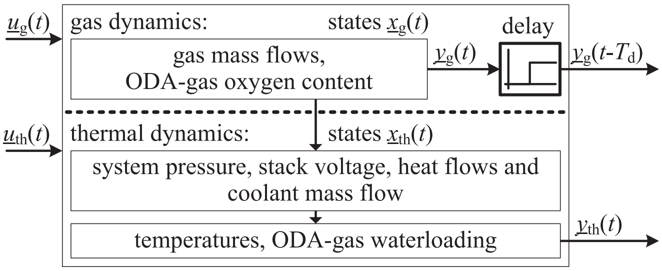


Fig. 3. Main structure of the multifunctional fuel cell system (MFFCS) model: gas dynamics and thermal dynamics.