Abstract

In the face of ongoing climate change and the depletion of fossil fuel reserves, fuel cell technology has emerged as an attractive method for generating electricity and heat. The single-step conversion of the fuel chemical energy in fuel cells offers higher efficiency compared to combustion processes while simultaneously reducing carbon dioxide and harmful gas emissions into the atmosphere. This technology plays a crucial role in the energy transition, combining high efficiency with exceptional fuel flexibility. It can utilize a wide range of energy carriers, including gaseous fuels like hydrogen and methane, as well as liquid fuels such as methanol and formic acid.

The current fuel infrastructure is not designed to accommodate hydrogen, making synthetic liquid fuels an appealing alternative for accelerating the widespread adoption of fuel cell technology. These fuels can serve as storage for renewable energy and as carriers for carbon dioxide captured from the atmosphere. Among them, liquid formic acid stands out as a particularly promising option. Compared to methanol, another commonly used fuel in this field, formic acid is safer for both the environment and users. Moreover, in its pure form, formic acid stores 26% more energy than hydrogen compressed to 700 bar and has a higher flash point than gasoline. These properties make it a viable candidate for integration with the adapted existing fuel infrastructure to enable its distribution.

Mass transport in fuel cells primarily occurs through diffusion due to the laminar flow regime of reactants in the interconnector channels. In fuel cells powered by liquid fuels, this challenge is further pronounced by the significantly lower diffusion coefficients of reactants in the liquid phase compared to the gas phase. As a result, higher voltage losses associated with mass transport occur, leading to reduced overall fuel cell performance.

The aim of this doctoral dissertation is to enhance mass transport and ensure uniform reactant distribution in a direct formic acid fuel cell (DFAFC) by designing novel geometries for reactant distribution systems and developing a theoretical model of the DFAFC to analyse the sensitivity of the current-voltage characteristics to specific process conditions such as fuel concentration and system temperature and material parameters such as exchange current density and equivalent resistance of the cell. Achieving these objectives requires a comprehensive approach that combines numerical modeling methods (CFD – computational fluid dynamics) in the

design of new distribution systems with experimental validation of DFAFC performance using demonstration setups, followed by the calibration of the theoretical model.

The research outcomes of this doctoral dissertation contribute to advancing knowledge in the design of efficient reactant distribution systems for fuel cells, particularly those powered by liquid fuels, such as DFAFC. A particularly important scientific aspect is determining the impact of local flow turbulisation and uniform fuel distribution on DFAFC performance. The scientific value of the work is further enhanced by demonstrating the applicability of residence time distribution analysis in evaluating mixing conditions within fuel cells. A novel aspect of the study includes the quantitative and qualitative analysis of two-phase flow on the anode side in an original transparent fuel cell, conducted through imaging studies. Additionally, the theoretical DFAFC model developed in this study provides a better understanding of the influence of process conditions and material parameters on voltage loss in a DFAFC.

The results obtained contribute to improving the efficiency of DFAFCs, which is of both cognitive and practical significance in the context of promoting alternative energy sources. The proposed geometric solutions are characterized by their universality and potential applicability to other electrochemical technologies utilizing flow microreactors, such as electrolyzers and flow batteries.

Keywords: DFAFC, formic acid, mass transport, reagent distribution systems, interconnector, CFD modelling, theoretical model, two-phase flow