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A REVIEW OF THE NUMERICAL STUDIES ON PLANAR AND TUBULAR SOLID OXIDE FUEL CELLS WITHIN FOUR EU PROJECTS OF THE 7th FRAMEWORK PROGRAMME

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Dedicated to Professor Andrzej Burghardt on the occasion of his 90th birthday

The paper addresses the issues of quantification and understanding of Solid Oxide Fuel Cells (SOFC) based on numerical modelling carried out under four European, EU, research projects from the 7FP within the Fuel Cell and Hydrogen Joint Undertaking, FCH JU, activities. It is a short review of the main projects' achievements. The goal was to develop numerical analyses at a single cell and stack level. This information was integrated into a system model that was capable of predicting fuel cell phenomena and their effect on the system behaviour. Numerical results were analysed and favourably compared to experimental results obtained from the project partners. At the single SOFC level, a static model of the SOFC cell was developed to calculate output voltage and current density as functions of fuel utilisation, operational pressure and temperature. At the stack level, by improving fuel cell configuration inside the stack and optimising the operation conditions, thermal stresses were decreased and the lifetime of fuel cell systems increased. At the system level, different layouts have been evaluated at the steady-state and by dynamic simulations. Results showed that increasing the operation temperature and pressure improves the overall performance, while changes of the inlet gas compositions improve fuel cell performance.

Keywords: Solid Oxide Fuel Cell, stack, fuel cell system, Computational Fluid Dynamics, CFD, Finite Element Method, FEM, modelling, process simulation

1. KEY OBJECTIVES OF THE PROJECTS

The projects were focused on Solid Oxide Fuel Cells (SOFCs) for transport (SUAV, SAPIENS and SAFARI projects) and residential (STAGE-SOFC project) applications in the energy micro-range (W~kW). The SUAV project aimed at developing microtubular SOFC (mSOFC) technology and a system, which was hybridized with a battery to power an Unmanned Aerial Vehicle, UAV. The SAPIENS project explored fuel cell stacks used in a Recreation Vehicle, RV, while the SAFARI project set up a step development of the microtubular and planar SOFC stacks for truck cab power system. The primary objective of the STAGE-SOFC project was to develop, construct and test a serial connection of an exothermal Catalytic Partial Oxidation, CPO_x, stage with an endothermal steam reforming stage of a SOFC based Combined Heat and Power, CHP, system.

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Each of the projects was conducted by a consortium of European Research and Development, R&D, institutions and companies with high expertise and long experience in the SOFC field. The involved industry project partners possessed advanced production capabilities to develop new improved electrolyte membrane and electrode materials as well as assembling and testing of SOFC stacks and systems. The West Pomeranian University of Technology, Szczecin, ZUT, team was one of the R&D partners and was responsible for fuel cell and system performance characterisation by numerical modelling. The main objective of the numerical analysis was achievement of improved understanding of the SOFC phenomena under chosen operating conditions. A joint analysis by Computational Fluid Dynamics, CFD, and Finite Element Method, FEM, was carried out. The commercial software: ANSYS Academic Research CFD and Mechanical was used in parallel to process simulations using also Aspen TECH and MATLAB Simulink. These diagnostics tools were recognised as fundamental for safe, efficient operation of fuel cells to improve reliability and durability.

In the present work, a short review of the main projects' achievements is presented. The models have been developed at the West Pomeranian University of Technology, Szczecin and were validated with empirical results from literature or available experimental data obtained from the project partners. Parameter studies were conducted for two types of microtubular and planar Solid Oxide Fuel Cells. The effects of cell geometry, temperature, pressure and inlet gas composition on the SOFC performance were studied accounting also for thermal stresses inside the cells.

2. CHALLENGES ADDRESSED

New requirements towards modern trucks, recreation vehicles and unmanned aerial vehicles along with an increasing pressure to lower fuel consumption, level of pollution and noise emission have significantly affected the need to find a new and clean technology. Over the past years, a huge effort was undertaken to substitute conventional power units by fuel cells, especially Solid Oxide Fuel Cells, SOFCs (Coplan et al., 2008; Dincer and Acar, 2015; Hou et al., 2018; Fernandes et al., 2018). SOFCs have attracted special attention due to the fact that they are produced from ceramic materials and thus they can be used in a wide range of industries starting from propulsion systems for transport applications to combined heat and power generation systems (Choundhury et al., 2013; McPhail et al., 2017). Therefore, the heating/chilling system based on SOFC technology was recognised as a potential attractive application in a modern truck. The units were fuelled by Liquefied Natural Gas, LNG. Thus, the challenge of the SAFARI project was to develop the SOFC auxiliary road truck installation in order to make the technology ready to demonstrate lower cost and emission than diesel trucks. Two different types of fuel cells were considered in the project.

Whilst much effort and resources were devoted to cell and stack issues, less attention has been paid to the balance of plant. Components and sub-systems such as fuel processing, heat and thermal management and fluid supply are as fundamental to successful commercialisation of fuel cell systems as the cell or stack. Therefore, this was the main reason and basic idea, which led the ZUT team to be considered within the STAGE-SOFC project. The serial connection of an exothermal CPO_x reformer with endothermic steam reformer combines the benefits of a simple and robust CPO_x layout with high efficiencies achievable using the steam reforming process. The main advantage of the STAGE-SOFC concept was using only natural gas and air as inputs.

Development of the balance of plant was also an important consideration within the SUAV project due to the fact that weight and volume were limited and restricted for an airborne application. In addition, stringent safety requirements had to be fulfilled. The varying power demands of a mini-UAV over a flight mission also required improvement of the understanding of degradation mechanism resulting from thermal stresses on the SOFC construction that take place during the operation of the SOFC at high temperature. Therefore, it was particularly challenging to deliver a system under several constraints.

3. TECHNICAL APPROACHES APPLIED

The projects addressed the following aspects: model improvement and analysis of the SOFC performance in comparison to the measurement data obtained from the project partners. Usually the projects were comprised of three major steps. First, the single cell was modelled and deep knowledge of the fuel cell performance was collected. Hydrodynamics, heat transfer and thermo-electrochemical processes occurring at the Membrane-Electrode-Assembly, MEA, were taken into account for the single fuel cell. Local heat flux values along the electrochemically active surface of the SOFCs were applied during the second phase that included SOFC stack simulations. This allowed to evaluate thermal and mechanical conditions inside the stacks. Analyses of the residual stresses developed during manufacturing processes of the fuel cells were carried out. Thermal stresses occurring during operation for an assembly consisting only of the fuel cells or of the fuel cells and sealants, manifolds and external housing were also analysed. The third phase consisted of system modelling and suggestions for optimising the systems based on the obtained numerical results. The performed analysis allowed to assess technical feasibility of the fuel cell technology in real systems. The projects aimed at improving the efficiency of SOFC and technical development of the stationary/transport fuel cell applications. The projects also led to deepening the knowledge of SOFC phenomena and mechanisms.

Two different Solid Oxide Fuel Cell designs were analysed. The first one was based on a microtubular concept (Pianko-Oprych et al., 2015a, b, c), while the other one on a planar design (Pianko-Oprych et al., 2016a,b; Pianko-Oprych et al., 2017b). The planar design demonstrated higher power density than the microtubular design, but the microtubular design was found to be more suitable for non-stationary power generation small systems. SOFC designs comprised basically three main components such as anode, cathode and electrolyte. The anode supported microtubular Solid Oxide Fuel Cells included Nickel Yttria Stabilized Zirconia (Ni-YSZ) anodes, Yttria Stabilized Zirconia (YSZ) electrolytes and Lanthanum Strontium Cobalt Ferrite (LSCF) cathodes. The planar SOFC geometry was divided into separate layers: cathodic bipolar plate, air channel, LSM (Strontium-doped Lanthanum Manganite) cathode, YSZ (Yttria-Stabilized Zirconia) electrolyte, Ni-YSZ cermet anode, fuel channel and anodic bipolar plate. Mechanical properties of both types of SOFCs are presented in Tables 1–3.

Table 1. Mechanical properties of mSOFC layer materials (Pianko-Oprych et al., 2015a, b, c)

Property	mSOFC material		
Material	Anode (Ni-YSZ)	Electrolyte (YSZ)	Cathode (LSCF)
CTE$\times 10^6$ [1/K]	12.2	10.3	13
E [GPa]	57	215 at 298 K 185 at 1073 K	161
ν [-]	0.28	0.32/0.313	0.32
ρ [kg/m^3]	4500	6050	6820
λ [W/mK]	1.83	2.2	1.31
C_p [J/kgK]	500	600	470
Tensile yield strength [MPa]	115	332/256	155
Compressive strength [MPa]	100	1000	100
Stress free temperature [K]	1473	1473	1323

Table 2. Mechanical properties of mSOFC stack materials used in the FEM simulations (Pianko-Oprych et al., 2015a, b, c)

Property	mSOFC material		
	Manifolds and seals (Macor machinable glass ceramic)	Housing & air distributor (Hastelloy X)	Housing & air distributor (Inconel X 750)
CTE $\times 10^6$ [1/K]	12.3	15.6	9.3
E [GPa]	66.9*/40.5**	205/153***	213.7/127.5***
ν [–]	0.29	0.32*	0.29
ρ[kg/m^3]	2520	8220	8280
λ[W/(m·K)]	1.46*/1.25**	9.1/27.2****	12.0/23.65***
C_p [J/kgK]	790*	486/699***	431/716***
Ultimate tensile strength [MPa]	94*/41**	767/310***	758.4/241.3***
Tensile yield strength [MPa]	–	379/194***	320.6/189.6***
Compressive strength [MPa]	345 (to 900)	–	1175.5#

*at 25 °C; **at 800 °C; ***sheet at 25 °C/871 °C; ****at 21 °C/816 °C; #at 704 °C

Table 3. The physical parameters of the planar SOFC materials (Zinko et al., 2016)

Material Property	Ni-YSZ anode	YSZ electrolyte	LSM cathode	Crofer 22 APU bipolar plate/ current colector
CTE $\times 10^6$ [1/K]	12.2	10.3	11.7	10.3–12.7 (473–1273 K)
Young's modulus [GPa]	57	215 / 185 (298 / 1073 K)	35	214–44 (298–1073 K)
Poisson's ratio [–]	0.28	0.32 / 0.313	0.36	0.29
Density [kg/m^3]	7740	6000	5300	7700
Thermal conductivity [W/(m·K)]	6	2.7	10	24
Specific heat [J/(kg K)]	600	400	607	660
Tensile yield strength [MPa]	115	332 / 256	155	291
Compressive strength [MPa]	100	1000	100	345
Stress free temperature [K]	1623	1623	1473	–

The complex phenomena in SOFC, including flow, heat transfer, mass transfer, electrochemical and chemical reactions have been implemented in the modelling work by appropriate mathematical models to provide prediction of the overall performance. Within the presented studies the macroscopic approaches like Finite Element Method and Finite Volume Method were applied similar to other authors (Andersson et al., 2010; Colpan et al., 2008). Mass and heat transfer in fuel cells were coupled to charge transfer, which was governed by the Ohm's law. For momentum conservation, the Navier-Stokes equation and Darcy's law were used for flow in the channels and the porous electrodes, respectively. The Butler-Volmer equation was used for the electrochemical reactions. The electrochemical kinetics acted as source terms or boundary conditions and affected the governing equations of momentum, heat and mass transport. 3D models provided profiles of the local current densities, the solid/gas temperatures and all kind of the overpotentials, which were of great significance for the safe operation (Bao et al., 2018).

4. MAIN ACHIEVEMENTS

The main operation variables in the performed analysis were temperature, current density and fuel cell configurations inside the microtubular and planar SOFC stacks. By varying these parameters, the interactions between main factors became identifiable. Figure 1 depicts the mass fraction distributions respectively of

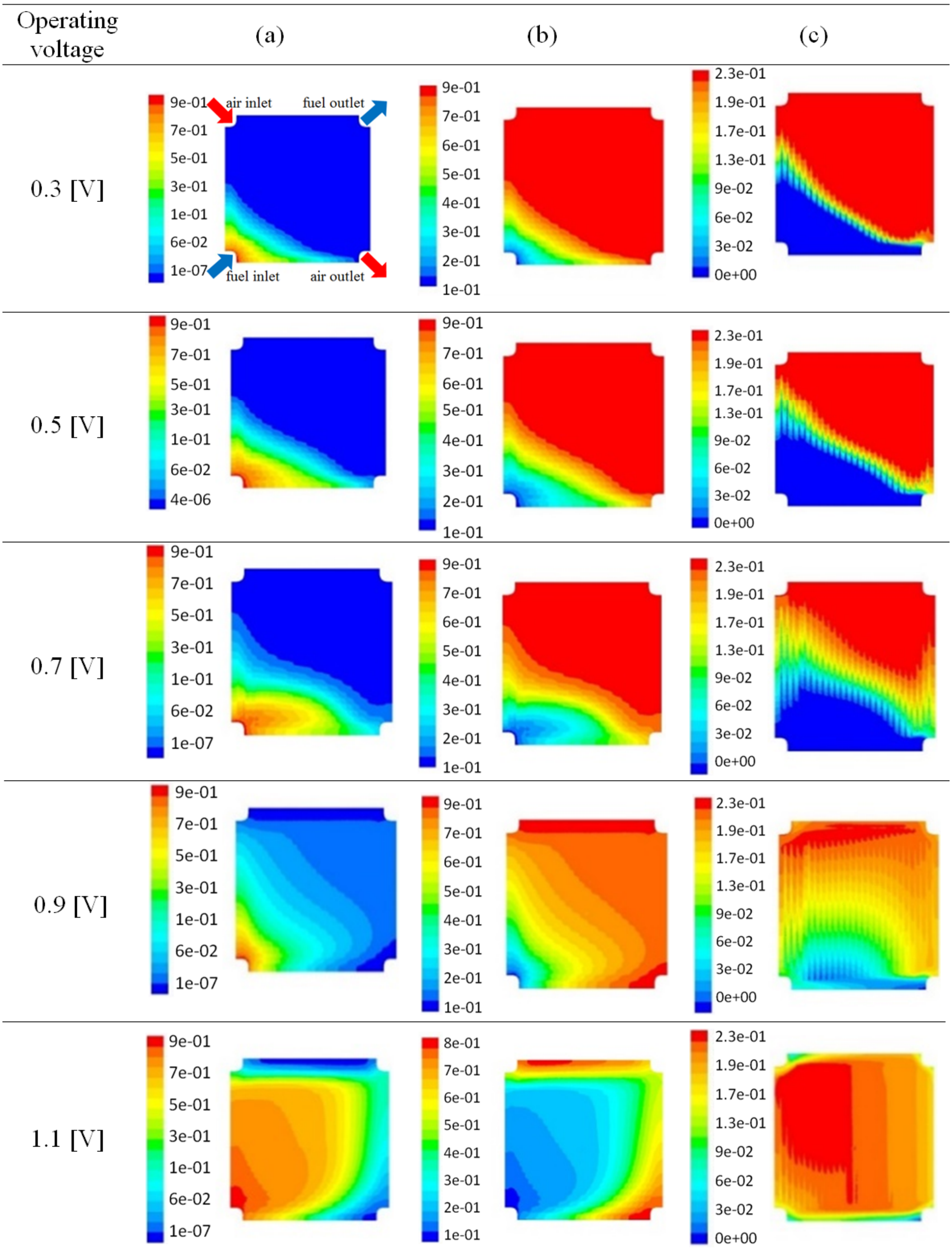

Fig. 1. Species distributions at the electrolyte [kg/kg]: a) mass fraction of hydrogen, b) mass fraction of water, c) mass fraction of oxygen (Pianko-Oprych et al., 2016a)

hydrogen (a), water (b) and oxygen (c) at the electrolyte layer on the anode side for the single planar SOFC considered within the SAFARI project. The mass fraction of hydrogen significantly changes diagonally between the fuel inlet and outlet, which can be seen in the distributions of Fig. 1a from the bottom left corner to the upper right corner.

A comparison of the calculated voltage vs. power curves with the experimental results (Bossel, 2012) is presented in Fig. 2. The CFD results correspond quite well with the experimental ones for the operating voltage range of 0.7, 0.9 and 1.1 V, respectively, while at lower voltage values of 0.3 and 0.5 V significant gradients in the electrical current were noticed.

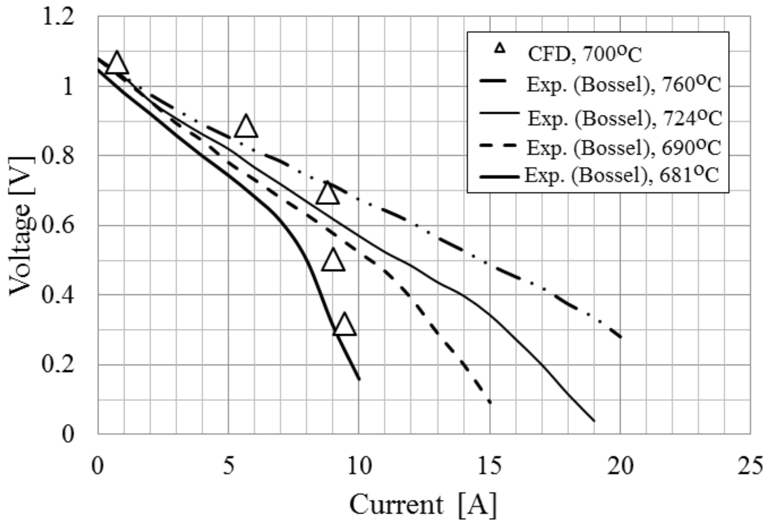

Fig. 2. Voltage [V] vs. current density [A] curve for the single planar SOFC (pSOFC) at the temperature of 700 °C and for pure hydrogen (Pianko-Oprych et al., 2017a)

High hydrogen utilisation was observed for the cell voltage decreasing from 0.7 V, which may be a potential cause for the deviations from the experimental results. Areas of the highest current density appear in Fig. 3 in the same regions where the highest formation rates were shown in Fig. 1.

In addition, temperature distributions were analysed to obtain full information at the single cell level. The lowest temperature was found near the fuel outlet at the upper right corner as can be seen in Fig. 3b. The most surprising finding was that the highest temperature of the fuel was at the region of the air outlet at the lower right corner as well as in the region, where the formation rate of the products was maximum. The average temperature difference between the fuel inlet and outlet was equal to 150 °C, with 230 °C for the air. Hence, the temperature distributions were characterised by high non-uniformity, which may cause local thermal stresses and lead to fuel cell damage, which was tested later as well.

A deeper understanding of heat transfer was needed at the stack level. Therefore, further CFD analysis was carried out. The simulation results of the temperature distribution for SOFC stacks with 48 microtubular and 16 planar cells are shown in Fig. 4b, c. The geometry of the two stacks with numerical meshes is presented in Fig. 4a. For the planar SOFC stacks, maximum temperatures were reached in the areas close to the outlet surface both in the fuel and air channels. The average temperature in the fuel channels of the 16 planar SOFC stack was equal to 1026 K for the first fuel cell and 1029 K for the 16th, while for the air channel 1039 K and 1031 K were obtained for the 1st and 16th fuel cells, respectively. The data was obtained for the inlet air velocity of 1.5 m/s. For the 48 microtubular SOFC stack, the maximum wall temperature difference between the middle fuel cell tube, located in the first row in the axis of the stack, and the corner tube located at the periphery part of the housing was equal to 95 K, for the inlet air velocity of 2 m/s and in a short distance from the air distributor situated inside the stack.

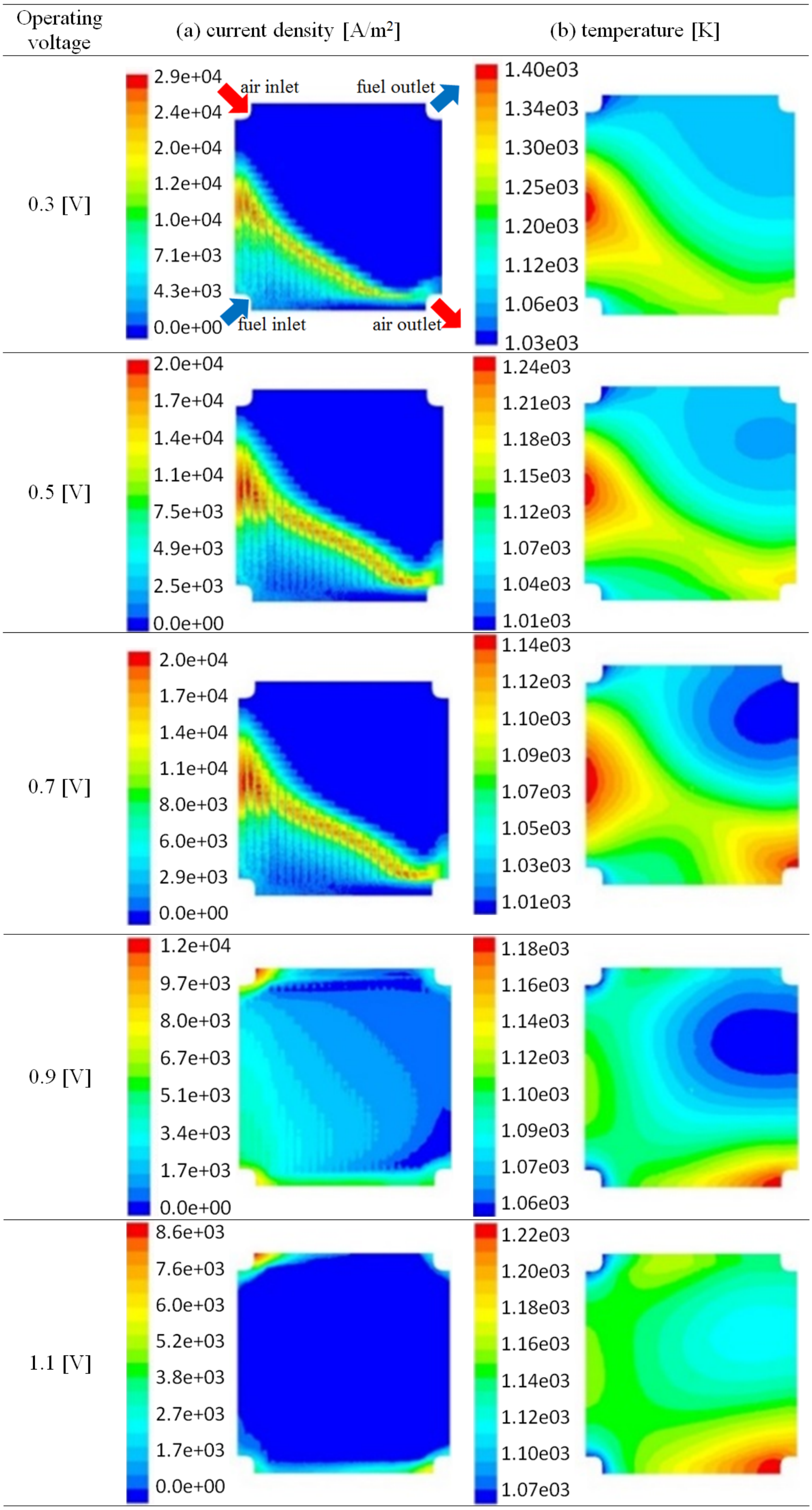

Fig. 3. Distributions of: a) current density [A/m^2] at the electrolyte from the cathode side and b) temperature [K] at the electrolyte from the anode side (Pianko-Oprych et al., 2017a)

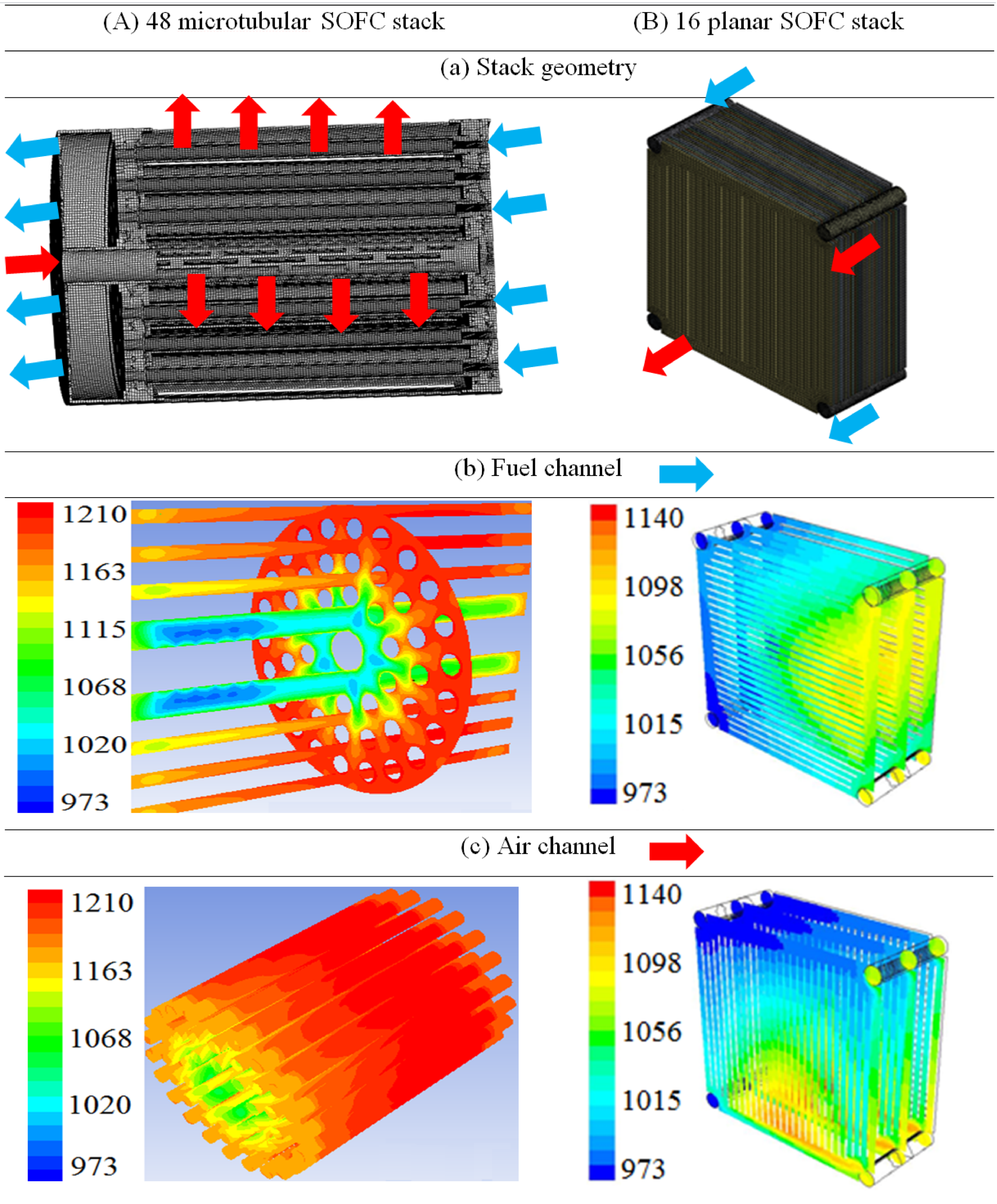

Fig. 4. 48 microtubular (A) and 16 planar SOFC stacks (B) with the numerical meshes as well as temperature distributions for fuel channel (b) and air channel (c) stacks

The main significance of the SUAV and SAFARI project results was development of the numerical approach that enables to predict thermal stresses in both types of fuel cells based on the CFD and FEM methods (Pianko-Oprych et al., 2015a, b, c; Pianko-Oprych et al., 2016b). Figure 5 presents the total stress profiles, including the residual stresses as well as those resulting from operational temperature distributions in the anode, electrolyte and cathode layers. For both types of fuel cells the highest stress was noticed in the electrolyte and it was equal to 290 MPa and 670 MPa for the 48 mSOFC and 16 pSOFC stacks, respectively.

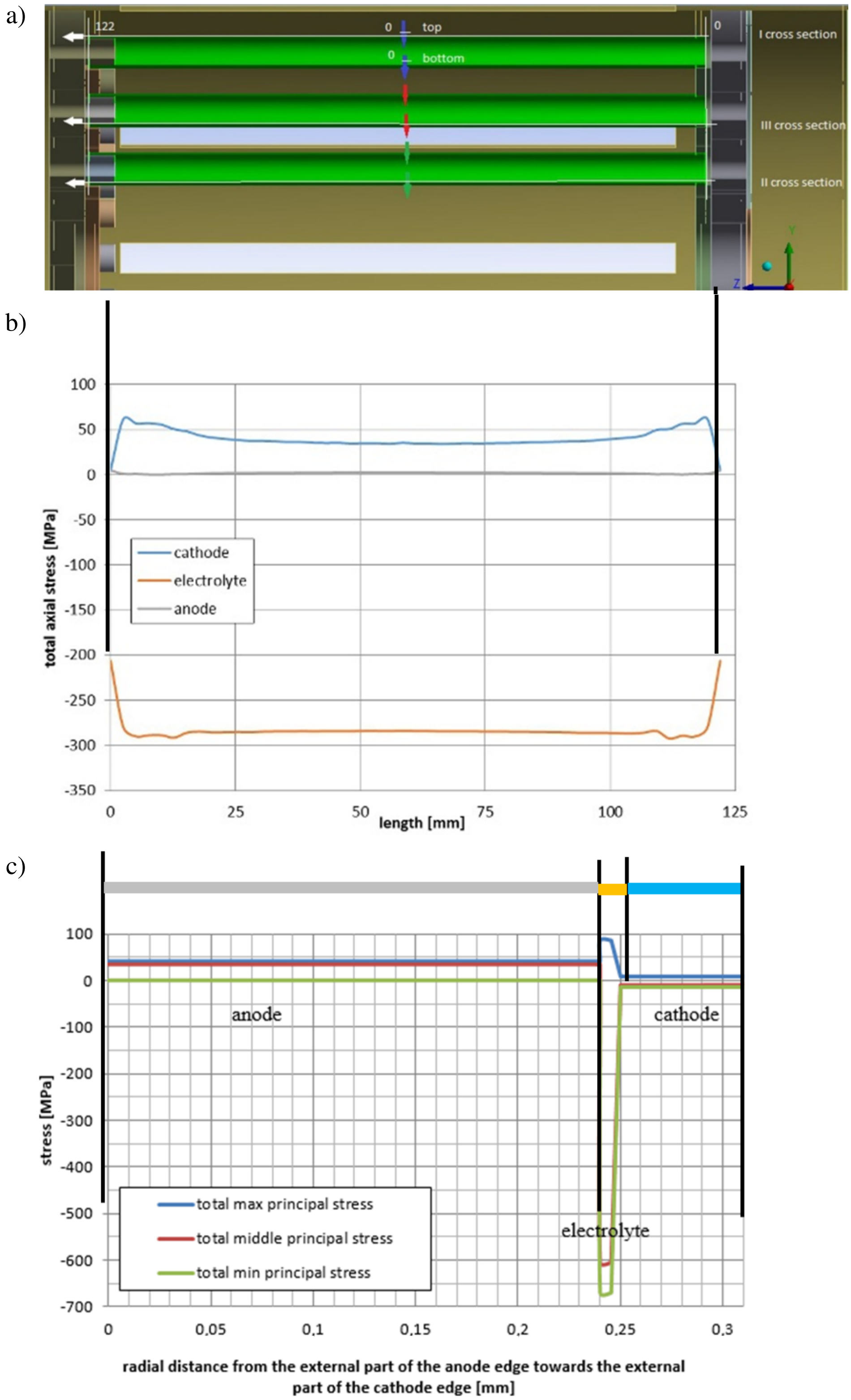

Fig. 5. a) Geometry of mSOFC stack with cross-sections and total stress distributions, b) in the anode, electrolyte and cathode along the horizontal centre lines of each layer for I cross section of the mSOFC, c) along the vertical centre line in the centre point of the pSOFC (Pianko-Oprych et al., 2015c; 2016b)

Further FEM simulations were performed at the single cell level for a planar, single SOFC that runs with hydrogen at the operating cell voltage of 0.3, 0.7 and 1.1 V, respectively. Similar tests were conducted at the stack level for the microtubular SOFC stack consisting of 48 fuel cells, rings and shells. FEM results for a single SOFC are presented in Figs. 6 and 7.

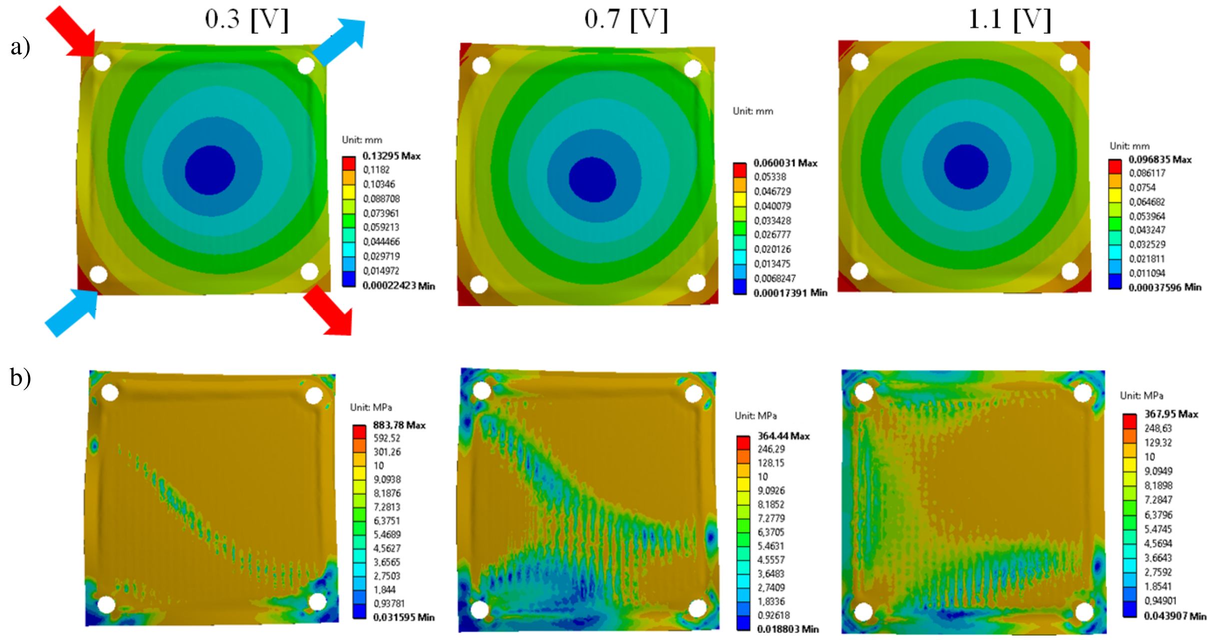

Fig. 6. Operating distributions of: a) total displacement [mm], b) von Mises stress [MPa] for the single planar SOFC (Pianko-Oprych et al., 2016b)

At the single cell level, total displacement for the planar SOFC was lowest of 0.06 mm at the cell voltage of 0.7 V, while at voltage of 1.1 V it was equal to 0.09 mm. The highest total displacement was noticed at the cell voltage of 0.3 V and was equal to 0.13 mm (Fig. 6a). Figure 6b shows that the lowest von Mises stress for the planar SOFC was equal to 364 MPa for 0.7 V, while the maximum of 0.3 V was 884 MPa. It is interesting to note that at the cell voltage of 1.1 V the von Mises stress was only slightly higher than the value calculated for 0.7 V and was equal to 368 MPa.

In addition, it was noticed that the temperature distributions (Fig. 3b) were characterised by high non-uniformity, which resulted in local thermal stresses and can lead to fuel cell damage. Thus, both gradients of the operating temperature and the manufacturing process temperatures of the MEA layers for the planar SOFC were taken into account during the thermal stresses generation. It was found in the numerical investigation that the residual stress due to the manufacturing process had a major impact on thermal stress distributions and the highest total stress value of −670 MPa was obtained in the electrolyte layer (Fig. 5). Based on a joint analysis, carried out using the CFD and FEM techniques, potential failure

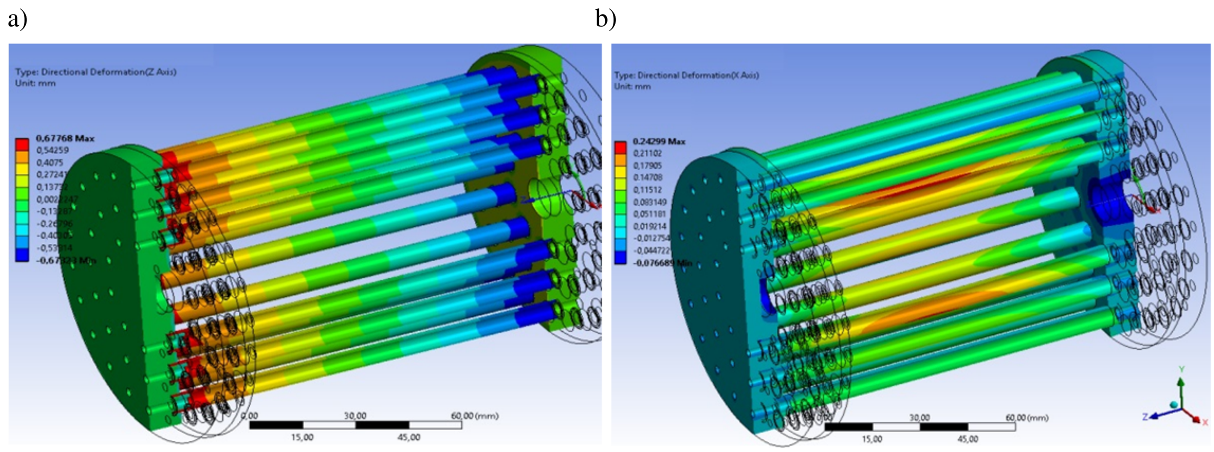

Fig. 7. Distribution of: a) an axial deformation [mm], b) a radial deformation [mm] of the fuel cell surfaces in the 48 mSOFC stack

locations in the planar SOFC were predicted. The obtained stress distributions provide helpful guidance in the optimisation of the new planar SOFC design.

At the stack level, the axial deformation of the fuel cell surfaces for the mSOFC stack design was equal to 0.67 mm, while the radial deformation was equal to 0.24 mm (Fig. 7).

Finally, to evaluate the thermo-mechanical resistance of the 48 mSOFC stack with a supporting structure, the distribution of von Misses stress is presented in Fig. 8. The maximum axial and equivalent von Mises stresses were equal to 537 MPa and 1427 MPa, respectively. The greatest stresses arose in the supporting structure of the housing. However, the majority of the fuel cells were exposed to the von Mises stress of up to 125 MPa (Fig. 8b).

a) b)

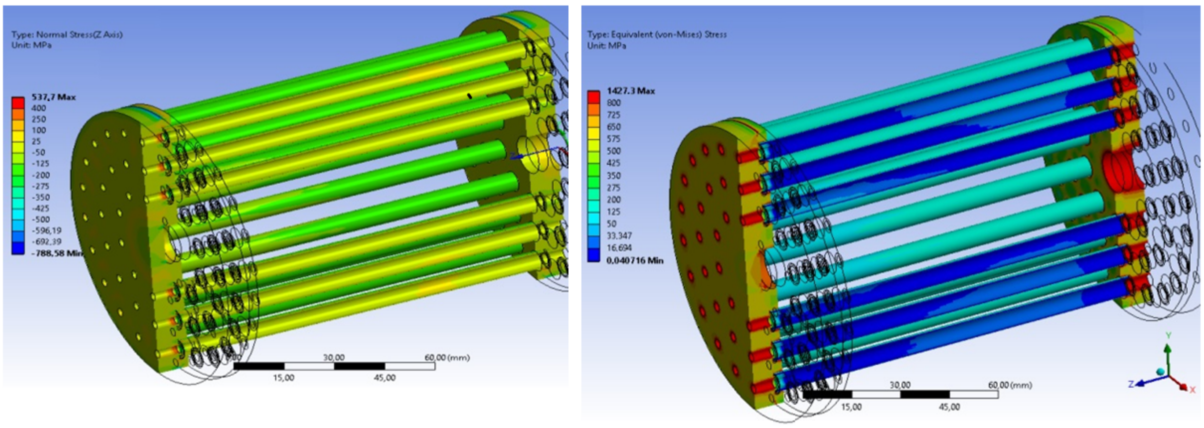

Fig. 8. Distribution of: a) an axial von Mises stress [MPa], b) an equivalent von Mises stress [MPa] for the 48 mSOFC stack

A noticeable increase in the stress values was observed in the contact areas of the supporting structure and manifolds with fuel cells, which confirms the need to change the structure. The areas of the highest values of the stress were determined in the 48 mSOFC stack as those requiring special attention (Pianko-Oprych et al., 2015b), which was one of the main findings in the SUAV project.

Finally, according to project's outputs at the single and stack level, regarding the fuel cell structure resistance to damage even at high temperature gradients, priority was given to reaching high fuel utilisation and high electrical efficiency under different load at the system level. Assessment and advanced simulations of the SOFC based power energy systems were performed by the ZUT team within the SAFARI and STAGE-SOFC projects.

Performance of two system types with one or two-staged SOFC stacks was calculated using numerical models in Aspen Plus^{TM} and MATLAB Simulink, respectively. In the SAFARI project, the system model was fuelled by methane with separate models for anode and cathode for microtubular SOFC stack. Methane reforming, based on a Catalytic Partial Oxidation (CPO_x) reformer, was investigated and the results are shown in Fig. 9 (Pianko-Oprych and Palus, 2017). The cell voltage was estimated based on the model proposed in the literature (Ameri and Mohammadi, 2013; Campanari, 2001; Zhang et al., 2005). A parametric study was also conducted to estimate effects of pressure and temperature on the overall fuel cell performance as presented in Fig. 10. An increase of the stack temperature causes the power increase in the full range of the current density. Within given temperature values: 795 °C, 820 °C, 845 °C, a higher voltage was observed in the case of fuel delivery at an increased pressure of 3.105 bar.

In the STAGE-SOFC project a more complex model of power generation system, based on two serially connected SOFC stacks with two different types of reformer, was developed in MATLAB Simulink

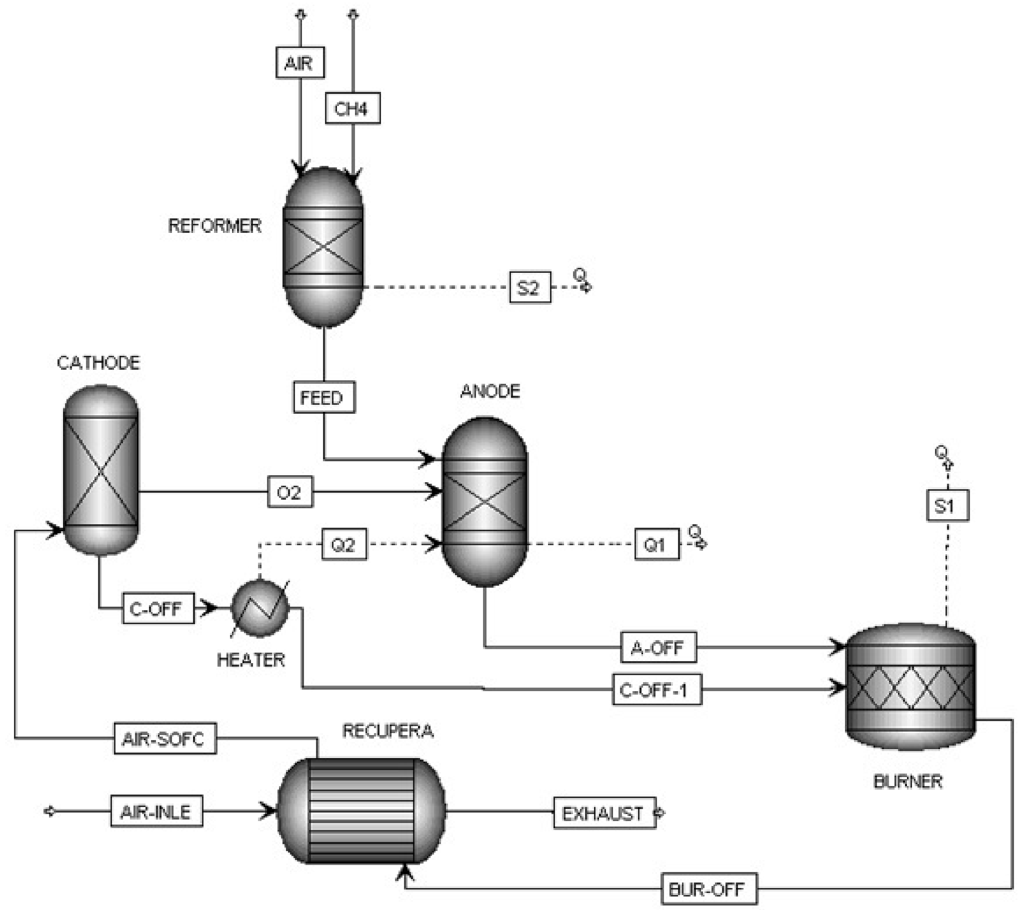

Fig. 9. Aspen Plus^{TM} flowsheet of SOFC power system model of 100 W considered in the SAFARI project (Pianko-Oprych and Palus, 2017)

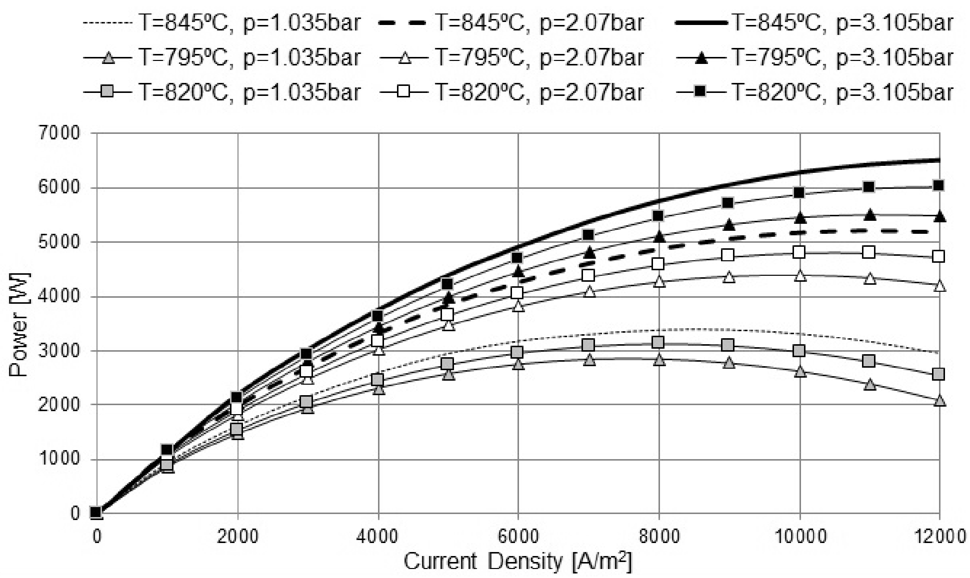

Fig. 10. Current density vs. power for three levels of pressure and temperature for SAFARI power system

(Pianko-Oprych and Hosseini, 2017) and Aspen Dynamics. The developed system models included Catalytic Partial Oxidation and Steam Reformers for methane reforming. A schematic view of the models in MATLAB Simulink and Aspen Dynamics are presented in Fig. 11.

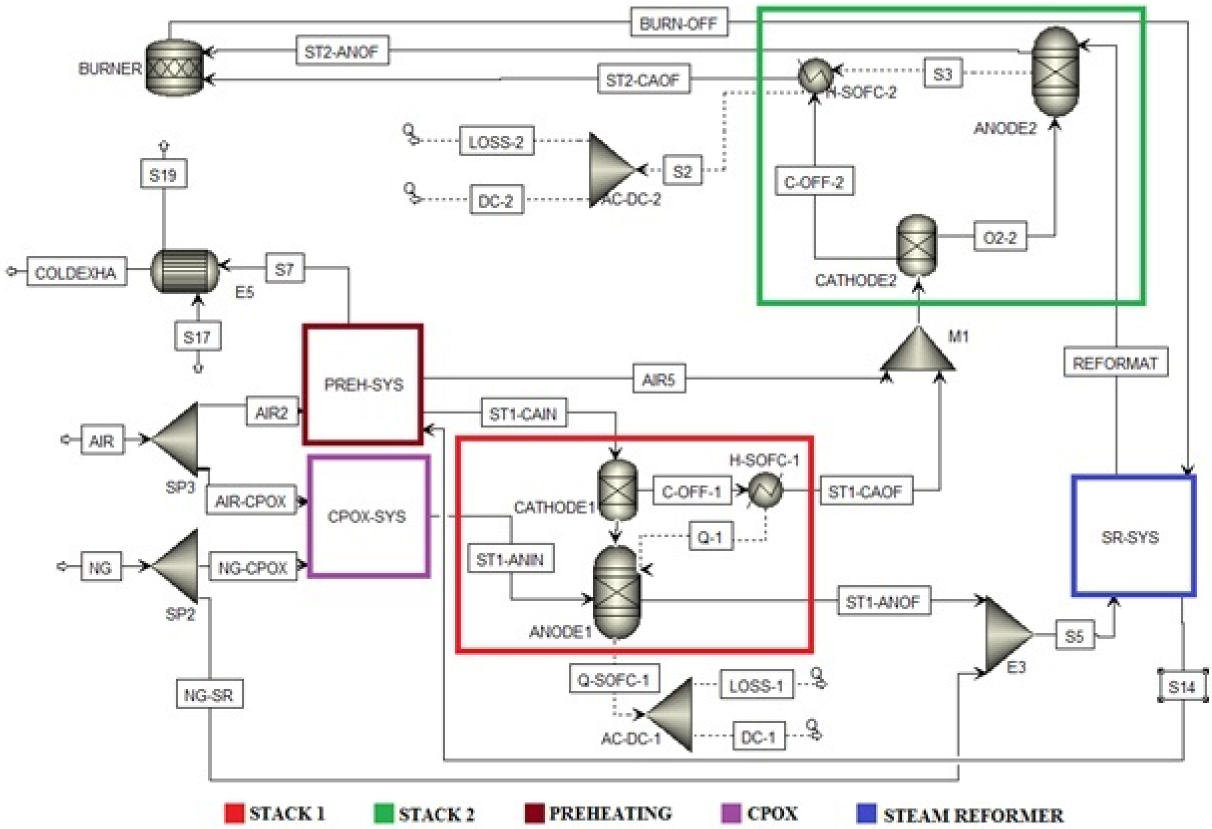

Fig. 11. Aspen Dynamics model for the SOFC power system considered in the STAGE-SOFC project

The temperature of the CPO_x reformer was a function of the lambda number in both models and it was a key parameter in determining the composition of CPO_x outlet flow rate. One of the most important issues in system lifetime and efficiency is the stack operating temperature. Therefore, particular attention was paid to the analysis of the transient response of the system under different operating conditions such as the start-up time or different 47% and 100% load conditions. The model prediction results for 100% load were very close to project partner data, while under the 47% load the differences were higher by about 7–8%. It was probably the result of the lack of knowledge of the correct porosity and tortuosity of the electrodes values. Nevertheless, good agreement in prediction using Aspen Dynamics of the current for both stacks was achieved as can be seen in Table 4.

It was shown that a combination of two different reforming processes and two SOFC stacks with a different number of fuel cells within the Combined and Heat Power system, CHP, can operate feasibly and allows to increase the output power of the system.

Moreover, the second advantage of using Aspen, that should be underlined here in particular in dynamic simulations, is that it can be used to investigate the values of operating parameters at any point in the system over time. The user can change any parameter value (i.e. temperature, pressure, efficiency) or connect additional blocks (control subsystem, other subsystem types of fuel reforming) and then compare data to find an optimal solution. Due to the fact that simulations are based on mathematical models, limitations depend mainly on the user's skills /knowledge. Theoretically, simulations of the considered SOFC based power generation system over 1000 °C are possible from a mathematical point of view, but in practice, too high temperatures may cause damage of fuel cells due to the stresses induced by differences in mechanical and thermal properties of the SOFC materials. Therefore, the user settings are of great importance and the user of the process simulator tool is responsible for a correct and critical interpretation of numerical results.

Table 4. Model results for 100% load compared to project partner data at operating temperature of 830 °C and fuel utilisation of 75%

Data:	Dimensions	Project partner data	Aspen	Standard deviation [%]
SOFC STACK No. 1 (90 cells)				
Efficiency DC-AC	[–]	95%	95%	
Temperature	[°C]	830	830	
FU	[–]	75%	75%	
P_el_DC	[W]	2425	2473	−1.98%
U_cell	[V]	0.70	0.71	−1.17%
U_stack	[V]	62.67	63.74	−1.70%
I_stack	[A]	38.70	38.78	–0.21%
SOFC STACK No. 2 (240 cells)				
Efficiency DC-AC	[–]	95%	95%	
Temperature	[°C]	830	830	
FU	[–]	75%	75%	
P_el_DC	[W]	4797	4557	5.00%
U_cell	[V]	0.77	0.73	5.74%
U_stack	[V]	183.80	174.19	5.23%
I_stack	[A]	26.10	26.16	–0.23%

5. SUMMARY

The projects aimed at a better understanding of the fuel cell behaviour as a function of operating parameters, mainly temperature and current density. This was typically the first step towards developing a new SOFC design within four EU projects, where the ZUT team was involved. Simulations were conducted and evaluation was performed with validation by experimental data delivered by the project partners. The modelling results were very beneficial for the projects' partners and can help prolong fuel cell lifetimes. The most sensitive region for thermal stress was identified for microtubular and planar SOFCs with respect to temperature gradients. The obtained results indicated that identification of the temperature gradients within cross sections of the fuel cell is possible with the 3D model and with appropriate boundary conditions. It was predicted that there were substantial temperature gradients along the cell length and the cross section of the cell.

The CFD and process simulators were recognised as excellent diagnostic tools that improve reliability and durability of fuel cells for their safe, effective and efficient operation. The CFD modelling results indicated that for the proposed microtubular and planar SOFC designs, reasonably uniform distributions of current density over the active fuel cell area were achieved. However, it was also pointed out that the design of the planar SOFC could be further improved by modification of the cross section of side channels. Using MATLAB Simulink and Aspen TECH software, successfully discretised models for the microtubular and planar SOFC stacks and other major components such as steam and CPO_x reformers or burners were achieved. Each model of the individual component was discretised in the principal flow direction to resolve physical and chemical processes such as heat transfer, chemical reaction and ion flow. The developed models were designed for specific operation conditions. However, the operation of a SOFC based system includes different discrete states such as a start-up, standby, warm up, shut down and also switch between different control modes. Thus, further control strategies should be studied particularly for the SOFC power generation system with fuel recirculation, where critical events can be considered, control strategies can be developed and adverse operating states can be avoided.

In parallel, broad dissemination activities were carried out and they had a high focus in the projects. The consortium acknowledged the importance of promoting the development of fuel cell technologies for sustainable and efficient utilisation of hydrogen as an energy carrier.

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SYMBOLS

CFD	Computational Fluid Dynamics
CHP	Combined Heat and Power
CPO_x	Catalytic Partial Oxidation
CTE (TEC)	Coefficient of Thermal Expansion (Thermal Expansion Coefficient)
FEM	Finite Element Method
FU	fuel utilisation
LNG	Liquefied Natural Gas
LSCF	Lanthanum Strontium Cobalt Ferrite
LSM	Strontium-doped Lanthanum Manganite
MEA	Membrane-Electrode-Assembly
Ni-YSZ	Nickel Yttria Stabilized Zirconia
PEMFC	Proton Exchange Membrane Fuel Cell
RV	Recreation Vehicle
R&D	Research and Development
RT	Room Temperature
SOFC	Solid Oxide Fuel Cell
UAV	Unmanned Aerial Vehicle
YSZ	Yttria Stabilized Zirconia
c_p	heat capacity, J/(kg·K)
E	Young's modulus, GPa
I	current, A
I_stack	stack current, A
p	pressure, Pa
P_el_DC	power, W
t	time, s
T	temperature, K
U_cell	cell voltage, V
U_stack	stack voltage, V

v	velocity, m/s
V_{OC}	open circuit voltage, V

Greek symbols

λ	thermal conductivity, W/mK
μ	dynamic viscosity, Pa·s
ρ	density, kg/m^3
ν	Poisson's ratio

Subscripts

m	micro
p	planar
t	tubular

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