Article :

Numerical analysis on the anode active thickness using quasi-three-dimensional solid oxide fuel cell model

Journal :

International Journal of Hydrogen Energy

Related equation :

Equation (6) in page 4 of the article.

$$0 = \frac{\partial}{\partial x} \left(\lambda_{\rm s} \frac{\partial T_{\rm s}}{\partial x} \right) + \frac{\partial}{\partial z} \left(\lambda_{\rm s} \frac{\partial T_{\rm s}}{\partial z} \right) + Q \tag{1}$$

where λ_s is the solid phase thermal conductivity, T_s is the solid phase temperature, and Q is the heat generation.



Figure 1: Schematic view of (a) cell unit of a solid oxide fuel cell (SOFC) and (b) mesh layers for quasi-3D SOFC model [1].

The equation (1) is utilized exclusively in the top separator mesh layer, bottom separator mesh layer, and positive-electrolyte-negative assembly (PEN) & electric insulator mesh layer, as illustrated in Figure 1. The general expression for the first law of thermodynamics can be expressed as equation (2) and further expanded as in equation (3).

$$E_{\rm in} - E_{\rm out} = \Delta E_{\rm system} \tag{2}$$

$$(Q_{\rm in} - Q_{\rm out}) + (W_{\rm in} - W_{\rm out}) + (E_{\rm mass,in} - E_{\rm mass,out}) = \Delta U + \Delta K E + \Delta P E$$
(3)

Taking into account the separator layers and PEN & electric insulator shown in Figure 1(a), the net energy transfer by work and mass is zero. Additionally, since the system is stationary, there is no change in either the kinetic or potential energies. This can be expressed using the following equation:

$$Q_{\rm in} - Q_{\rm out} = \Delta U \tag{4}$$

$$0 = Q_{\rm out} - Q_{\rm in} + mc\Delta T_{\rm s} \tag{5}$$

Compare equation (1) with equation (5) give

$$\frac{\partial}{\partial x} \left(\lambda_{\rm s} \frac{\partial T_{\rm s}}{\partial x} \right) + \frac{\partial}{\partial z} \left(\lambda_{\rm s} \frac{\partial T_{\rm s}}{\partial z} \right) + Q = Q_{\rm out} - Q_{\rm in} + mc\Delta T_{\rm s} \tag{6}$$

The first and second terms on the left-hand side of equation (6) represent the heat conduction flux in the xand z-directions, respectively, within the separators and PEN & electric insulator. On the other hand, the third term on the left-hand side of equation (5) represent the heat that is generated within the considered volume of analysis.

Reference:

[1] W.C. Tan, E.A. Lim, H. Abd Rahman, A. Abdul Samat, C.S. Oon, Numerical analysis on the anode active thickness using quasi-three-dimensional solid oxide fuel cell model, Int. J. Hydrogen Energy. (2023). https://doi.org/10.1016/J.IJHYDENE.2023.01.361.

Please note that the article used in this example cannot be used again in assignment 2. Additionally, the way in which you discuss the equation or formula will depend on your creativity and approach to the material. To assist you with incorporating figures or diagrams into your report, please refer to the above example which demonstrates how to properly insert a figure or diagram and provide a detailed explanation within the paragraph.

INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (XXXX) XXX



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Numerical analysis on the anode active thickness using quasi-three-dimensional solid oxide fuel cell model

Wee Choon Tan ^{a,b,*}, Eng Aik Lim ^c, Hamimah Abd Rahman ^d, Abdullah Abdul Samat ^{a,e}, Cheen Sean Oon ^f

^a Faculty of Mechanical Engineering & Technology, Universiti Malaysia Perlis, Pauh Putra Campus, 02600 Arau, Perlis, Malaysia

^b Thermofluids & Energy Research Group, Universiti Malaysia Perlis, Pauh Putra Campus, 02600 Arau, Perlis, Malaysia

^c Institute of Engineering Mathematic, Universiti Malaysia Perlis, 02600 Arau, Perlis, Malaysia

^d Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, Malaysia

^e Centre of Excellent Unmanned Aerial Systems (COEUAS), Universiti Malaysia Perlis, 01000 Kangar, Perlis, Malaysia

^f School of Engineering, Monash University of Malaysia, 47500 Subang Jaya, Selangor, Malaysia

HIGHLIGHTS

- Attenuation factor of charge transfer current density is derived.
- Concentration loss is derived from the dusty-gas model by considering local losses.
- Root of attenuation factor is determined by the Newton Raphson method.
- \bullet Effect of anode thickness between 5 and 1000 μm towards active thickness is studied.
- Sufficiently thick electrode is required for the quasi-3D SOFC model.

ARTICLE INFO

Article history: Received 9 December 2022 Received in revised form 29 January 2023

GRAPHICAL ABSTRACT



ABSTRACT

A quasi-three-dimensional solid oxide fuel cell (SOFC) model reduces the computational cost by strategically ignoring the thinnest direction in an SOFC by incorporating a charge-transfer current density model to represent its active thickness in electrodes to represent its complex phenomenon in an electrode. Therefore, high accuracy of this charge-transfer

* Corresponding author. Faculty of Mechanical Engineering & Technology, Universiti Malaysia Perlis, Pauh Putra Campus, 02600 Arau, Perlis, Malaysia.

E-mail address: tweechoon@unimap.edu.my (W.C. Tan). https://doi.org/10.1016/j.jjhydene.2023.01.361

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ARTICLE IN PRESS

INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (XXXX) XXX

Accepted 30 January 2023 Available online xxx

Keywords:

Dusty-gas model Concentration loss Charge-transfer current density Attenuation factor current density model is required. The concentration loss is mathematically related to the charge-transfer current density based on the dusty-gas model together with activation and ohmic losses in this work. The numerical results from this study are validated with the experimental results. The influence of anode's thickness towards anode active thickness is studied with the anode thickness of 5, 10, 50, 100, 500 and 1000 μ m. It is found that the quasi-three-dimensional SOFC model is capable of analysing SOFC with a sufficiently thick electrode. Also, a thick electrode and a high average current density result in a thin active thickness.

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Nomenclature		Р	total pressure (Pa)
ASR	area-specific resistance	Q	heat generation term ($W \cdot m^{-3}$)
DGM	dusty-gas model	r	average radius of pore (m)
FM	Fick's model	R	ideal gas constant (J \cdot mol $^{-1}\cdot$ K $^{-1}$)
GDC	gadolinia-doped ceria	S_{Y_i}	mass transport source term for species i
H_2	hydrogen		$(kg \cdot m^{-3} \cdot s^{-1})$
H ₂ O	steam	S_ϕ	charge transport source term (V·m ⁻³)
LSCF	lanthanum strontium cobalt ferrite	$T_{\rm in}$	inlet temperature (K)
LSV	lanthanum strontium vanadate	$T_{\rm f}$	fluid phase temperature (K)
No	nitrogen	Ts	solid phase temperature (K)
Ni	nickel	и	x-velocity component (m \cdot s $^{-1}$)
0.	oxvgen	u _{in}	inlet x-velocity component (m·s ⁻¹)
DFN	nositive-electrolyte-negative assembly	U	velocity (m·s ⁻¹)
SIMPLE	semi-implicit method for the pressure-linked	vi	diffusion volume of gas species i (m ³ ·kg ⁻¹ ·mol ⁻¹)
DIMI LL	equations	ω	diffusion volume of gas species i (m $^3 \cdot kg^{-1} \cdot mol^{-1}$)u
SOFC	solid oxide fuel cell		z-velocity component (m·s ⁻¹)
VS7	vttria-stabilized zirconia	x _i	molar fraction of gas species i (–)
152	surface area of norous materials (m^2)	Yi	mass fraction of gas species i $(-)$
C C	heat canacity (I.k σ^{-1} . K^{-1})	[i]	coefficient of gas species in a mixture in Eqs.
Deff	effective binary diffusion coefficient (m^2, e^{-1})		(14)–(18) (s·m ⁻²)
D _{ij} Deff	effective molecular diffusion coefficient of	α	symmetric coefficient in Butler-Volmer-like
D _{i,m}	multicomponent $a_{1} c^{-1}$		equation (–)
Deff	offective Knudson diffusion coefficient of and	ε	porosity (–)
$D_{K,i}$	energies i $(m^2 e^{-1})$	$\eta_{\rm conc}$	concentration loss (V)
f	iportio coefficient ()	η_{total}	total voltage loss (V)
J	$\frac{1}{10000000000000000000000000000000000$	λ	attenuation factor (–)
r h	raraday's constant ($C \cdot mol^{-1}$)	$\lambda_{\rm f}^{\rm eff}$	fluid phase effective thermal conductivity
n h	unickness of electrode (m)		$(W \cdot m^{-1} \cdot K^{-1})$
n _{sf}	porous interfacial neat transfer coefficient $(W_{m})^{-1} = (W_{m})^{-1}$	λs	solid phase thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
	$(W \cdot M^{-1} \cdot K^{-1})$	μ	viscosity (Pa·s)
1 ₀	exchange current density (A \cdot m ⁻²)	ρ	density $(kg \cdot m^{-3})$
l _{ct}	charge-transfer current density $(A \cdot m^{-2})$	σ_{ionic}^{eff}	effective ionic conductivity (S \cdot m ⁻¹)
1	current density $(A \cdot m^{-2})$	σ_{e}^{eff}	effective solid phase conductivity $(S \cdot m^{-1})$
K	permeability (m ²)	τ	tortuosity factor (–)
M _i	molecular mass of gas species i (kg·mol ⁻¹)	φ	electric potential (V)
Ni	molar flux of gas species i (mol \cdot m ⁻² \cdot s ⁻¹)	т	

Introduction

Solid oxide fuel cell (SOFC) converts chemical energy within supplied reactants to electrical energy through electrochemical processes. The efficiency of an SOFC depends on the transport of mass and species in fuel and air channels of a cell and porous medium within electrodes, transport of charge carriers in a cell, heat transfer within a cell and interaction with the environment. SOFCs are divided into anode-, cathode- and electrolyte-supported SOFCs accordingly to the thickest layer of either anode, cathode or electrolyte within a cell to provide sufficient mechanical strength. Both the anode- and cathode-supported SOFCs have the advantage of high ionic conductivity, which enable high efficiency of a cell.

The anode thickness of an anode-supported SOFC is thicker than an electrolyte-supported SOFC or cathodesupported SOFC to provide sufficient strength to the cell. Anode-supported cell offers better performance by reducing the ohmic loss in a thick electrolyte of an electrolytesupported cell. Furthermore, this anode-supported cell offers higher stability than the cathode-supported cell. Therefore, anode-supported cell gains high attention for the range of intermediate- and high-temperature SOFC. Anode-supported SOFC has a common drawback of a high anodic concentration loss, especially at high current density operation. Several strategies are proposed to overcome such disadvantage, like multiplying layers of anode [1] to have high porosity near the surface of an anode to promote better gas species transport and high reaction sites density to encourage higher electrochemical reaction rate as well as the phase inversion fabrication method [2,3] to improve the transportation of gas species. Recently with a focus on low-temperature SOFC, a porous metal layer is introduced to provide mechanical strength to the cell [4-6]. Anode thickness for a metal-support SOFC has greatly reduced to a significant thin around 100 nm.

The active thickness of an electrode represents the locations where the half-reaction of the electrochemical reaction takes place within the electrode during operation. Due to the limitation of available physical devices to measure the charge transport within the relatively thin electrode of an SOFC, such studies of the active thickness were conducted through numerical analysis [7–9]. Zheng et al. [9] found that the active thickness depends on activation loss, ohmic loss and concentration loss within an electrode. Also, a high ratio of both activation to ohmic losses is found to contribute to a large active thickness. Note that, the activation loss is under the consideration of the effect of concentration loss. Zheng et al. [9] report the 400 µm thickness anode has an active thickness between 4.5 and 8.1 µm under 99% of the electrochemical reaction. Then, Ge et al. [10] descript that the 23 µm thick lanthanum strontium vanadate (LSV)-yttria-stabilized zirconia (YSZ) anode has an active thickness of 5–20 µm under 99% of the reaction. Andersson et al. [11] state 6.2 µm of the active thickness (under 90% of the reaction) for a 415 μ m thick nickel (Ni)-YSZ anode under operation temperature of 1010 K. Kishimoto et al. [12] study the 3D microstructure of an infiltrated Ni-gadolinia-doped ceria (GDC) anode. The active thickness of infiltrated Ni-GDC anode has an active thickness of ~10 μ m. In summary, the anode active thickness that represents the thickness of the anode involved in the electrochemical reaction is below 20 µm.

A quasi-3D SOFC model was previously developed and used for the analysis of intermediate-temperature direct-internal-reforming SOFC [13]. A porous material is assumed to be inserted in the passages as a current collector in this quasi-3D SOFC model to reduce the computation time. The electrochemical reaction is assumed to take place at the electrodeelectrolyte interfaces. Later, Onaka et al. [14] considered the influence of both activation and ohmic losses within an electrode during the development of a charge-transfer distribution model, which explains the electrochemical reaction rate within an electrode. This update enables the electrochemical reaction to be extended further from the electrodeelectrolyte interface in the quasi-3D SOFC model. Although the attenuation factor in the charge-transfer distribution model is determined as the minimum total voltage losses in the electrode, the contribution concentration loss is neglected in the work of Onaka et al. [14]. It is due to the considered concentration loss only focusing on the partial pressure of gas species within the channels and at the electrode-electrolyte interface, which is determined by Fick's model by Chan et al. [15].

The numerical analysis allows researchers to understand the complex phenomena in SOFCs. A quasi-3D SOFC model with real microstructure information was developed in the authors' group to study the effect of cell aspect ratio on cell performance [16] and the effects of the air-flow configuration in a short stack [17]. Recently, some researchers apply artificial intelligence technology to study the complex phenomena in SOFCs. Liu et al. [18] study the correlation between microstructures with five effective properties like effective elastic modulus, Poisson's ratio, shear modulus, coefficient of thermal expansion and triple-phase boundary length density using deep learning model. Xu et al. [19] combine deep learning with multi-physics simulation to achieve optimisation for the performance of an SOFC. In this work, the concentration loss together with activation and ohmic losses in the electrode is considered in the charge-transfer distribution model. The gas species transport within electrodes is modelled by the dusty-gas model (DGM) to address its relationship with the charge-transfer distribution within an electrode. Also, the active thickness of an SOFC is analysed using the updated quasi-3D SOFC model with the DGM.

Modelling method

A cell unit as shown in Fig. 1(a) consists of top and bottom separators, fuel and air channels, and a positive-electrolyte-negative assembly (PEN) is considered in this study. Each component has only one mesh on the y-axis. Note that both fuel and air channels consist of solid- and fluid-phase meshes as shown in Fig. 1(b). Additionally, two layers of mesh located



Fig. 1 — Schematic view of (a) cell unit and (b) mesh layers for quasi-3D SOFC model.

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at the top and bottom of the cell unit are introduced as boundary layers. Hence, a cell unit with a dimension of $89.0 \times 3.40 \times 60.0 \text{ mm}^3$ consists of $101 \times 9 \times 71$ meshes in the quasi-3D SOFC model. The cell has an effective area of $80.0 \times 60.0 \text{ mm}^2$. The electrochemical reaction is no longer limited to occur at the anode-electrolyte interface but extended toward its surface accordingly to its charge-transfer distribution. Details of the quasi-3D SOFC model have already been described in our previous reports [16,17], therefore only essential equations are summarized below.

Governing equations

The numerical analysis was based on conservation equations of mass, momentum, species, and energy.

Mass conservation:

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho w)}{\partial z} = \sum S_{Y_i}$$
(1)

Momentum conservation:

$$\begin{bmatrix} \frac{\partial}{\partial x} \left(\frac{\rho u u}{\varepsilon} \right) + \frac{\partial}{\partial z} \left(\frac{\rho w u}{\varepsilon} \right) \end{bmatrix} = -\varepsilon \frac{\partial P}{\partial x} + \frac{\partial}{\partial x} \left(\mu \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial z} \left(\mu \frac{\partial u}{\partial z} \right) + \frac{1}{3} \frac{\partial}{\partial x} \left(\mu \frac{\partial u}{\partial x} \right) - \frac{2}{3} \frac{\partial}{\partial x} \left(\mu \frac{\partial w}{\partial z} \right) + \frac{\partial}{\partial z} \left(\mu \frac{\partial w}{\partial x} \right) - \varepsilon \frac{\mu}{K} u - \varepsilon \frac{\rho f}{\sqrt{K}} |U| u$$
(2)

$$\begin{bmatrix} \frac{\partial}{\partial \mathbf{x}} \left(\frac{\rho u w}{\varepsilon}\right) + \frac{\partial}{\partial z} \left(\frac{\rho w w}{\varepsilon}\right) \end{bmatrix} = -\varepsilon \frac{\partial P}{\partial z} + \frac{\partial}{\partial x} \left(\mu \frac{\partial w}{\partial x}\right) + \frac{\partial}{\partial z} \left(\mu \frac{\partial w}{\partial z}\right) \\ + \frac{1}{3} \frac{\partial}{\partial z} \left(\mu \frac{\partial w}{\partial z}\right) - \frac{2}{3} \frac{\partial}{\partial z} \left(\mu \frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial x} \left(\mu \frac{\partial u}{\partial z}\right) - \varepsilon \frac{\mu}{K} w - \varepsilon \frac{\rho f}{\sqrt{K}} |\mathbf{U}| w$$
(3)

Energy conservation:

(fluid phase in the channels filled with metal foam)

$$\frac{\partial (\rho C_{p} u T_{f})}{\partial x} + \frac{\partial (\rho C_{p} w T_{f})}{\partial z} = \frac{\partial}{\partial x} \left(\lambda_{f}^{eff} \frac{\partial T_{f}}{\partial x} \right) + \frac{\partial}{\partial z} \left(\lambda_{f}^{eff} \frac{\partial T_{f}}{\partial z} \right) + h_{sf} a_{sf} (T_{s} - T_{f})$$
(4)

(solid phase in the channels filled with metal foam)

$$0 = \frac{\partial}{\partial x} \left(\lambda_{s}^{eff} \frac{\partial T_{s}}{\partial x} \right) + \frac{\partial}{\partial z} \left(\lambda_{s}^{eff} \frac{\partial T_{s}}{\partial z} \right) + h_{sf} a_{sf} (T_{f} - T_{s})$$
(5)

(solid phases in the separator and the cell)

$$0 = \frac{\partial}{\partial x} \left(\lambda_{s} \frac{\partial T_{s}}{\partial x} \right) + \frac{\partial}{\partial z} \left(\lambda_{s} \frac{\partial T_{s}}{\partial z} \right) + Q$$
(6)

Species conservation:

$$\frac{\partial}{\partial \mathbf{x}}(\rho \mathbf{u} \mathbf{Y}_{i}) + \frac{\partial}{\partial z}(\rho \mathbf{w} \mathbf{Y}_{i}) = \frac{\partial}{\partial \mathbf{x}}\left(\rho D_{i,m}^{\text{eff}} \frac{\partial \mathbf{Y}_{i}}{\partial \mathbf{x}}\right) + \frac{\partial}{\partial z}\left(\rho D_{i,m}^{\text{eff}} \frac{\partial \mathbf{Y}_{i}}{\partial z}\right) + S_{\mathbf{Y}_{i}}$$
(7)

Charge conservation

$$\frac{\partial}{\partial x} \left(\sigma_{s}^{\text{eff}} \frac{\partial \phi}{\partial x} \right) + \frac{\partial}{\partial y} \left(\sigma_{s}^{\text{eff}} \frac{\partial \phi}{\partial y} \right) + \frac{\partial}{\partial z} \left(\sigma_{s}^{\text{eff}} \frac{\partial \phi}{\partial z} \right) = S_{\phi}$$
(8)

Both fuel and gas channels are filled with metal foam, which acts as a current collector in the equivalent circuit model [13]. The developed model adopts the geometric parameters representing the porous metal foam in the channels from Bhattacharya et al. [20] and Calmidi and Mahajan [21]. The validation of the developed quasi-3D SOFC model with the updated DGM within electrodes was conducted in our previous works [22]. An in-house Fortran code is developed and run with a laptop that is equipped with an Intel i5 processor 1.7 GHz and 12 GB RAM.

Dusty-gas model

Dusty-gas model (DGM) is implemented for the transport of reactants and product in the porous anode. DGM can be expressed as follows [23]:

$$\frac{N_{i}}{D_{K,i}^{eff}} + \sum_{i \neq j} \frac{\mathbf{x}_{j} N_{i} - \mathbf{x}_{i} N_{j}}{D_{ij}^{eff}} = -\frac{P}{RT_{s}} \nabla \mathbf{x}_{i} - \frac{\mathbf{x}_{i}}{RT_{s}} \left(1 + \frac{KP}{\mu D_{K,i}^{eff}} \right) \nabla P,$$
(9)

$$\nabla P = -\frac{\sum_{\substack{D \in H \\ D_{K,i}}}^{N_i}}{\frac{1}{RT_s} + \frac{K}{\mu} \sum x_i D_{K,i}^{eff}}$$
(10)

$$D_{K,i}^{\text{eff}} = \frac{2}{3} \left(\frac{8RT_{\text{s}}}{\pi M_{i}}\right)^{\frac{1}{2}} \overline{r}$$
(11)

where x_i , N_i and M_i are the mole fraction, the molar flux and the molecular mass of gas species, respectively. μ , R, T_s and P are the viscosity, gas constant, temperature and total pressure of the gas mixture. ∇P is the pressure gradient. \bar{r} is the average radius of the pore in an electrode. $D_{K,i}^{eff}$ is the effective Knudsen diffusion of gas species, which is related to the porosity and tortuosity factor of the pore phase of the porous medium. The permeability constant in the porous medium K and the effective binary gas diffusion D_{ij}^{eff} are described in Eqs (12) and (13) [24].

$$K = \frac{\varepsilon^3 \overline{r}^2}{18\tau (1-\varepsilon)^2},$$
(12)

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$$D_{ij}^{\text{eff}} = \frac{\tau}{\varepsilon} \cdot \frac{0.01013 T_{\text{s}}^{1.75} \left(\frac{1}{10^3 M_i} + \frac{1}{10^3 M_j} \right)^{0.5}}{P \left[\left(\sum v_i \right)^{1/3} + \left(\sum v_j \right)^{1/3} \right]^2} .$$
(13)

where τ and ϵ are the tortuosity factor and the volume fraction of the pore phase within an electrode, respectively. v_i is the diffusion volume of gas species. The mole fraction gradient of the gas mixture of $H_2 - H_2O - N_2$ within an anode and gas mixture of $O_2 - N_2$ within a cathode can be given similar to the work of Vural et al. [25] as:

Anode:

$$\frac{d}{dy}(\mathbf{x}_{\mathrm{H}_2}) = \frac{\mathrm{RT}_{\mathrm{s}}}{\mathrm{P}} \cdot \frac{\int_{o}^{y} i_{\mathrm{ct}} \, dy}{2\mathrm{F}} \cdot [\mathbf{H}_2] \tag{14}$$

$$\frac{d}{dy}(\mathbf{x}_{\mathrm{H}_{2}\mathrm{O}}) = \frac{\mathrm{R}T_{\mathrm{s}}}{P} \cdot \frac{\int_{0}^{y} i_{\mathrm{ct}} \, dy}{2F} \cdot [\mathbf{H}_{2}\mathbf{O}]$$
(15)

$$\frac{d}{dy}(\mathbf{x}_{N_2}) = \frac{RT_s}{P} \cdot \frac{\int_o^y i_{ct} \, dy}{2F} \cdot [\mathbf{N}_2]$$
(16)

Cathode:

$$\frac{d}{dy}(\mathbf{x}_{O_2}) = \frac{RT_s}{P} \cdot \frac{\int_o^y i_{ct} \, dy}{4F} \cdot [\mathbf{O}_2]$$
(17)

$$\frac{d}{dy}(\mathbf{x}_{N_2}) = \frac{RT_s}{P} \cdot \frac{\int_o^y \mathbf{i}_{ct} \, dy}{4F} \cdot [\mathbf{N}_2]$$
(18)

where the coefficient of $[H_2]$, $[H_2O]$ and $[N_2]$ in the mixture of $H_2 - H_2O - N_2$ within an anode can be given as follow:

$$\begin{split} [\mathbf{H_2}] = & \frac{x_{H_2} \left(1 + \frac{KP}{\mu D_{KH_2}^{\text{eff}}}\right) \left(\frac{1}{D_{KH_2}^{\text{eff}}} - \frac{1}{D_{KH_2O}^{\text{eff}}}\right)}{\left[1 + \left(\frac{x_{H_2}}{D_{KH_2O}^{\text{eff}}} + \frac{x_{H_2O}}{D_{KH_2O}^{\text{eff}}}\right) \frac{KP}{\mu}\right]} \\ & - \left(\frac{x_{H_2} + x_{H_2O}}{D_{H_2-H_2O}^{\text{eff}}} + \frac{x_{N_2}}{D_{H_2-N_2}^{\text{eff}}} + \frac{1}{D_{KH_2O}^{\text{eff}}}\right) \end{split}$$
(17a)

$$\begin{split} [\mathbf{H}_{2}\mathbf{O}] = & \frac{\mathbf{x}_{H_{2}O} \left(1 + \frac{KP}{\mu D_{KH_{2}}^{\text{eff}}}\right) \left(\frac{1}{D_{KH_{2}}^{\text{eff}}} - \frac{1}{D_{KH_{2}O}^{\text{eff}}}\right)}{\left[1 + \left(\frac{x_{H_{2}}}{D_{KH_{2}}^{\text{eff}}} + \frac{x_{H_{2}O}}{D_{KH_{2}O}^{\text{eff}}} + \frac{x_{H_{2}O}}{D_{K,H_{2}O}^{\text{eff}}}\right) \frac{KP}{\mu}\right]} \\ & - \left(\frac{\mathbf{x}_{H_{2}} + \mathbf{x}_{H_{2}O}}{D_{H_{2}O-H_{2}}^{\text{eff}}} + \frac{\mathbf{x}_{N_{2}}}{D_{H_{2}O-N_{2}}^{\text{eff}}} + \frac{1}{D_{K,H_{2}O}^{\text{eff}}}\right) \end{split}$$
(18a)

$$[\mathbf{N}_{2}] = \frac{\mathbf{x}_{N_{2}} \left(1 + \frac{\mathbf{KP}}{\mu D_{k}^{\text{eff}}}\right) \left(\frac{1}{D_{kH_{2}}^{\text{eff}}} - \frac{1}{D_{kH_{2}}^{\text{eff}}}\right)}{\left[1 + \left(\frac{\mathbf{x}_{N_{2}}}{D_{kH_{2}}^{\text{eff}}} + \frac{\mathbf{x}_{N_{2}}}{D_{kH_{2}}^{\text{eff}}}\right) \frac{\mathbf{KP}}{D_{kH_{2}}^{\text{eff}}}\right]} - \left(\frac{\mathbf{x}_{N_{2}}}{D_{N_{2}-H_{2}}^{\text{eff}}} - \frac{\mathbf{x}_{N_{2}}}{D_{N_{2}-H_{2}}^{\text{eff}}}\right)$$
(19)

The coefficient of $[O_2]$ and $[N_2]$ in the gas mixture of $O_2 - N_2$ within a cathode can be given as follow:

$$[\mathbf{O}_{2}] = \frac{\mathbf{x}_{O_{2}} \left(1 + \frac{\mathbf{KP}}{\mu D_{KO_{2}}^{\text{eff}}}\right) \left(\frac{1}{D_{KO_{2}}^{\text{eff}}}\right)}{\left[1 + \left(\frac{\mathbf{x}_{O_{2}}}{D_{KO_{2}}^{\text{eff}}} + \frac{\mathbf{x}_{N_{2}}}{D_{KN_{2}}^{\text{eff}}}\right) \frac{\mathbf{KP}}{\mu}\right]} - \left(\frac{\mathbf{x}_{N_{2}}}{D_{O_{2}-N_{2}}^{\text{eff}}} + \frac{1}{D_{KO_{2}}^{\text{eff}}}\right)$$
(20)

$$[\mathbf{N}_{2}] = \frac{\mathbf{X}_{N_{2}} \left(1 + \frac{\mathbf{KP}}{\mu D_{\mathrm{KN}_{2}}^{\mathrm{eff}}}\right) \left(\frac{1}{D_{\mathrm{KO}_{2}}^{\mathrm{eff}}}\right)}{\left[1 + \left(\frac{\mathbf{x}_{0}}{D_{\mathrm{KO}_{2}}^{\mathrm{eff}}} + \frac{\mathbf{x}_{N_{2}}}{D_{\mathrm{KN}_{2}}^{\mathrm{eff}}}\right) \frac{\mathbf{KP}}{\mu}\right]} + \left(\frac{\mathbf{X}_{N_{2}}}{D_{N_{2}-O_{2}}^{\mathrm{eff}}}\right)$$
(21)

Concentration loss

The concentration loss within an electrode with the thickness of *h* can be given as follow:

$$\eta_{\rm conc} = \frac{\int_0^h i_{\rm ct} \eta_{\rm conc, local} \, dy}{\int_0^h i_{\rm ct} \, dy} = \frac{\int_0^h i_{\rm ct} \eta_{\rm conc, local} \, dy}{I}$$
(22)

Also, the local concentration loss at y distance from the electrode-electrolyte interface can be given as follow:

$$\begin{split} \eta_{\text{conc,local,ano}} &= -\frac{RT_{s}}{2F} ln \left[\frac{x_{H_{2}O}}{x_{H_{2}}} \cdot \frac{x_{H_{2}}(y)}{x_{H_{2}O}(y)} \right] = -\frac{RT_{s}}{2F} \\ & ln \left[\frac{x_{H_{2}O}}{x_{H_{2}}} \cdot \frac{x_{H_{2}} + (h_{\text{ano}} - y)\frac{d}{dy}(x_{H_{2}})}{x_{H_{2}O} + (h_{\text{ano}} - y)\frac{d}{dy}(x_{H_{2}O})} \right] \end{split}$$
(23)

$$\eta_{\text{conc,local,cat}} = -\frac{RT_s}{4F} \ln\left[\frac{x_{O_2}(y)}{x_{O_2}}\right] = -\frac{RT_s}{4F} \ln\left[\frac{x_{O_2} + (h_{\text{cat}} - y)\frac{d}{dy}(x_{O_2})}{x_{O_2}}\right]$$
(24)

Then, the concentration loss can be expressed accordingly to Eq. (22) by considering the local concentration loss at y distance from the electrode-electrolyte interface in Eqs. (23) and (24) with the mole fraction gradient of the gas mixture as given in Eqs. (14)-(18) as follows:

$$\begin{split} \eta_{\text{conc,ano}} &= \frac{1}{I} \int_{0}^{h_{\text{ano}}} i_{\text{ct}} \\ & \left[-\frac{RT_{\text{s}}}{2F} \ln \left(\frac{x_{\text{H}_{2}} x_{\text{H}_{2}\text{O}} + h_{\text{ano}} \frac{RT_{\text{s}}I}{2FP}}{x_{\text{H}_{2}\text{O}}[\text{H}_{2}] - y \frac{RT_{\text{s}}I}{2FP}} x_{\text{H}_{2}\text{O}}[\text{H}_{2}]}{x_{\text{H}_{2}} x_{\text{H}_{2}\text{O}} + h_{\text{ano}} \frac{RT_{\text{s}}I}{2FP}} x_{\text{H}_{2}\text{O}}[\text{H}_{2}] - y \frac{RT_{\text{s}}I}{2FP}} x_{\text{H}_{2}}[\text{H}_{2}\text{O}]} \right) \right] dy \end{split}$$

$$(25)$$

$$\eta_{\text{conc,cat}} = \frac{1}{I} \int_{0}^{h_{\text{cat}}} i_{\text{ct}} \left[-\frac{RT_{\text{s}}}{4F} \ln \left(\frac{x_{\text{O}_2} + h_{\text{cat}} \frac{RT_{\text{s}}I}{4FP} [O_2] - y \frac{RT_{\text{s}}I}{2FP} [O_2]}{x_{\text{O}_2}} \right) \right] dy$$
(26)

The charge-transfer current density $i_{\rm ct}$ is expressed as follow [26]:

$$i_{ct} = \lambda I \exp(-\lambda y)$$
 (27)

Equations (25) and (26) can be rewrite as follow:

$$\eta_{\text{conc,ano}} = \frac{1}{\lambda I} \cdot \frac{RT_{s}}{2F} \int_{i_{ct}(0)}^{i_{ct}(h_{ano})} \int_{i_{ct}(0)}^{i_{ct}(h_{ano})} \ln\left(\frac{x_{H_{2}}x_{H_{2}O} + h_{ano}\frac{RT_{s}I}{2FP}}{x_{H_{2}O}[H_{2}] + \frac{1}{\lambda}\frac{RT_{s}I}{2FP}} x_{H_{2}O}[H_{2}]\ln(\frac{i_{ct}}{\lambda I})}{x_{H_{2}}x_{H_{2}O} + h_{ano}\frac{RT_{s}I}{2FP}} x_{H_{2}}[H_{2}O] + \frac{1}{\lambda}\frac{RT_{s}I}{2FP}} x_{H_{2}}[H_{2}O]\ln(\frac{i_{ct}}{\lambda I})}\right) di_{ct}$$
(28)

$$\eta_{\text{conc,cat}} = \frac{1}{\lambda I} \cdot \frac{RT_s}{4F} \int_{i_{\text{ct}}(0)}^{i_{\text{ct}}(h_{\text{cat}})} \ln\left(\frac{x_{O_2} + h_{\text{cat}} \frac{RT_s I}{4FP}[O_2] - \frac{1}{\lambda} \frac{RT_s I}{2FP}[O_2] \ln\left(\frac{i_{\text{ct}}}{\lambda I}\right)}{x_{O_2}}\right) di_{\text{ct}}$$
(29)

Lastly, the concentration loss can be given as follow:

$$\eta_{\text{conc,ano}} = -\frac{RT_s}{2F} \ln\left(\frac{x_{H_2}x_{H_2O} + h_{\text{ano}}\frac{RT_sI}{2FP}x_{H_2O}[\mathbf{H}_2]}{x_{H_2O} + h_{\text{ano}}\frac{RT_sI}{2FP}x_{H_2}[\mathbf{H}_2O]}\right) + \frac{RT_s}{2F} \exp\left(-\frac{x_{H_2}x_{H_2O} + h_{\text{ano}}\frac{RT_sI}{2FP}x_{H_2O}[\mathbf{H}_2]}{\frac{RT_sI}{2FP}x_{H_2O}[\mathbf{H}_2]}\lambda\right) \text{Ei}\left(\frac{x_{H_2}x_{H_2O} + h_{\text{ano}}\frac{RT_sI}{2FP}x_{H_2O}[\mathbf{H}_2]}{\frac{RT_sI}{2FP}x_{H_2O}[\mathbf{H}_2]}\lambda\right) - \frac{RT_s}{2F} \exp\left(-\frac{x_{H_2}x_{H_2O} + h_{\text{ano}}\frac{RT_sI}{2FP}x_{H_2}[\mathbf{H}_2O]}{\frac{RT_sI}{2FP}x_{H_2}[\mathbf{H}_2O]}\lambda\right) \text{Ei}\left(\frac{x_{H_2}x_{H_2O} + h_{\text{ano}}\frac{RT_sI}{2FP}x_{H_2O}[\mathbf{H}_2]}{\frac{RT_sI}{2FP}x_{H_2O}[\mathbf{H}_2]}\lambda\right)$$
(30)
$$\eta_{\text{conc,cat}} = -\frac{RT_s}{4F} \ln\left(\frac{x_{O_2} + h_{\text{cat}}\frac{RT_sI}{4FP}[\mathbf{O}_2]}{x_{O_2}}\right) + \frac{RT_s}{4F} \exp\left(-\frac{x_{O_2} + h_{\text{cat}}\frac{RT_sI}{4FP}[\mathbf{O}_2]}{\frac{RT_sI}{4FP}[\mathbf{O}_2]}\lambda\right) \text{Ei}\left(\frac{x_{O_2} + h_{\text{cat}}\frac{RT_sI}{4FP}[\mathbf{O}_2]}{\frac{RT_sI}{4FP}[\mathbf{O}_2]}\lambda\right)$$
(31)

Ei in Eqs. (30) and (31) is the exponential integral, which is defined as a definite integral of the ratio between an exponential function and its argument. With the DGM for the transport of mass and species within an electrode, the concentration loss is found also be influenced by the charge-transfer distribution.

Attenuation factor λ

The concentration loss as expressed in Eqs. (30) and (31) are considered together with the activation and ohmic losses based on the work of Onaka et al. [14] as the total voltage losses as follow:

$$\eta_{\text{total,ano}} = \left\{ \frac{2i_{0,\text{ano}}RT_{\text{s}}}{\lambda I \alpha F} + \frac{RT_{\text{s}}}{\alpha F} \sinh^{-1}\left(\frac{\lambda I}{2i_{0,\text{ano}}}\right) - \frac{2i_{0,\text{ano}}RT_{\text{s}}}{\lambda I \alpha F} \sqrt{\left(\frac{I}{2i_{0,\text{ano}}}\right)^{2} \lambda^{2} + 1} \right\} + \left\{ \frac{I}{2\sigma_{\text{ionic,ano}}^{\text{eff}} \lambda} \right\} + \left\{ -\frac{RT_{\text{s}}}{2F} \ln\left(\frac{x_{\text{H}_{2}} x_{\text{H}_{2}\text{O}} + h_{\text{ano}} \frac{RT_{\text{s}}I}{2FP} x_{\text{H}_{2}}[\mathbf{H}_{2}\mathbf{O}]}{x_{\text{H}_{2}} x_{\text{H}_{2}\mathbf{O}} + h_{\text{ano}} \frac{RT_{\text{s}}I}{2FP} x_{\text{H}_{2}\mathbf{O}}[\mathbf{H}_{2}]} \right\} + \left\{ \frac{RT_{\text{s}}}{2F} \exp\left(-\frac{x_{\text{H}_{2}} x_{\text{H}_{2}\mathbf{O}} + h_{\text{ano}} \frac{RT_{\text{s}}I}{2FP} x_{\text{H}_{2}\mathbf{O}}[\mathbf{H}_{2}]}{\frac{RT_{\text{s}}I}{2FP} x_{\text{H}_{2}\mathbf{O}}[\mathbf{H}_{2}]} \lambda \right\} \text{Ei}\left(\frac{x_{\text{H}_{2}} x_{\text{H}_{2}\mathbf{O}} + h_{\text{ano}} \frac{RT_{\text{s}}I}{2FP} x_{\text{H}_{2}\mathbf{O}}[\mathbf{H}_{2}]}{\frac{RT_{\text{s}}I}{2FP} x_{\text{H}_{2}\mathbf{O}}[\mathbf{H}_{2}]} \lambda \right) - \frac{RT_{\text{s}}}{2F} \exp\left(-\frac{x_{\text{H}_{2}} x_{\text{H}_{2}\mathbf{O}} + h_{\text{ano}} \frac{RT_{\text{s}}I}{2FP} x_{\text{H}_{2}}[\mathbf{H}_{2}\mathbf{O}]}{\frac{RT_{\text{s}}I}{2FP} x_{\text{H}_{2}\mathbf{O}}[\mathbf{H}_{2}]} \lambda \right) \text{Ei}\left(\frac{x_{\text{H}_{2}} x_{\text{H}_{2}\mathbf{O}}[\mathbf{H}_{2}]}{\frac{RT_{\text{s}}I}{2FP} x_{\text{H}_{2}\mathbf{O}}[\mathbf{H}_{2}]} \lambda \right) + \frac{RT_{\text{s}}I_{\text{$$

$$\eta_{\text{total,cat}} = \left\{\frac{RT_s\lambda I}{4.4Fi_{0,\text{cat}}}\right\} + \left\{\frac{I}{2\sigma_{\text{ionic,cat}}^{\text{eff}}\lambda}\right\} + \left\{-\frac{RT_s}{4F}\ln\left(\frac{x_{O_2} + h_{\text{cat}}\frac{RT_sI}{4FP}[\mathbf{O}_2]}{x_{O_2}}\right) + \frac{RT_s}{4F}\exp\left(-\frac{x_{O_2} + h_{\text{cat}}\frac{RT_sI}{4FP}[\mathbf{O}_2]}{\frac{RT_sI}{4FP}[\mathbf{O}_2]}\lambda\right) \text{Ei}\left(\frac{x_{O_2} + h_{\text{cat}}\frac{RT_sI}{4FP}[\mathbf{O}_2]}{\frac{RT_sI}{4FP}[\mathbf{O}_2]}\lambda\right)\right\} = 0$$
(33)

The value of the minimum total voltage loss is obtained at the condition of $d\eta_{total}/d\lambda = 0$, and it is given by

YSZ) anode, YSZ electrolyte, gadolinium-doped ceria (GDC) barrier layer, lanthanum strontium cobalt ferrite (LSCF) – GDC

$$\left\{ \frac{\mathrm{RT}_{\mathrm{s}}}{\alpha F} \left(\frac{2i_{0,\mathrm{ano}}}{I\lambda^{2}} \right) \left[\sqrt{\left(\frac{\mathrm{I}}{2i_{0,\mathrm{ano}}} \right)^{2} \lambda^{2} + 1} - 1 \right] \right\} + \left\{ -\frac{\mathrm{I}}{2\sigma_{\mathrm{ionic,ano}}^{\mathrm{eff}} \lambda^{2}} \right\} + \left\{ \frac{\mathrm{RT}_{\mathrm{s}}}{2F} \cdot \frac{x_{\mathrm{H}_{2}} x_{\mathrm{H}_{2}\mathrm{O}} + h_{\mathrm{ano}} \frac{\mathrm{RT}_{\mathrm{s}}\mathrm{I}}{2\mathrm{FP}}}{\mathrm{RT}_{\mathrm{s}}\mathrm{I}_{\mathrm{s}}}\mathrm{I}_{\mathrm{s}}\mathrm{I}_{\mathrm{s}}\mathrm{I}_{\mathrm{s}}\mathrm{I}_{\mathrm{s}}}\mathrm{I}_{\mathrm{s}}\mathrm{I}_{\mathrm{s}}\mathrm{I}_{\mathrm{s}}\mathrm{I}_{\mathrm{s}}}\mathrm{I}_{\mathrm{s}}\mathrm{I}_{\mathrm{s}}\mathrm{I}_{\mathrm{s}}\mathrm{I}_{\mathrm{s}}}\mathrm{I}_{\mathrm{s}}\mathrm{I}_{\mathrm{s}}\mathrm{I}_{\mathrm{s}}\mathrm{I}_{\mathrm{s}}}\mathrm{I}_{\mathrm{s}}\mathrm{I}_{\mathrm{s}}\mathrm{I}_{\mathrm{s}}}\mathrm{I}_{\mathrm{s}}\mathrm{I}_{\mathrm{s}$$

$$\left\{\frac{RT_{s}I}{4.4Fi_{0,cat}}\right\} + \left\{-\frac{I}{2\sigma_{ionic,cat}^{eff}}\lambda^{2}\right\} + \left\{-\frac{RT_{s}}{4F} \cdot \frac{x_{O_{2}} + h_{cat}\frac{RT_{s}I}{4FP}[\mathbf{O}_{2}]}{\frac{RT_{s}I}{4FP}[\mathbf{O}_{2}]} \cdot \exp\left(-\frac{x_{O_{2}} + h_{cat}\frac{RT_{s}I}{4FP}[\mathbf{O}_{2}]}{\frac{RT_{s}I}{4FP}[\mathbf{O}_{2}]}\lambda\right) Ei\left(\frac{x_{O_{2}} + h_{cat}\frac{RT_{s}I}{4FP}[\mathbf{O}_{2}]}{\frac{RT_{s}I}{4FP}[\mathbf{O}_{2}]}\lambda\right)\right\} = 0$$
(35)

The first and second terms in the left-hand side of Eqs. (34) and (35) are the term $d\eta/d\lambda$ from the activation and ohmic losses, respectively. Recall that the coefficient of [H₂] and [H₂O] in the mixture of H₂ – H₂O – N₂ within an anode in Eqs. (17a) and (18a) and the coefficient of [O₂] in the mixture of O₂ – N₂ within a cathode in Eq. (20) is not influenced by the attenuation factor λ . The root of λ in Eqs. (34) and (35) for anode and cathode are determined by Newton Raphson method. Miyawaki et al. [26] proposed that the attenuation factor λ must be a positive value. Also, a small λ indicates a relatively homogeneous distribution of the electrochemical reaction in an electrode. On the other hand, a large λ indicates the electrochemical reaction mostly takes place in the vicinity of the electrode-electrolyte interface.

Microstructure information

The validation of the developed numerical model is conducted with the real microstructure which is manufactured by SOL-IDpower S.p.A. with nickel – yttria-stabilized zirconia (Ni-

Table 1 – Microstructure of commercial Ni-YSZ/YSZ/GDC/ LSCF-GDC/LSCF SOFC.								
Parameters	Anode [27]	Cathode [28]						
Average diameter of pore phase [µm]	0.566	1.01						
Volume fraction of pore phase [-]	0.251	0.410						
Volume fraction of ionic phase [–]								
YSZ(anode), GDC/LSCF(cathode)	0.383	0.260/0.330						
Tortuosity factor of pore phase [–]	20.1	2.24						
Tortuosity factor of ionic phase [–]								
YSZ(anode), GDC/LSCF(cathode)	2.44	20.3/4.29						
Volumetric density of triple-phase	4.97×10^{5}	· _						
boundary line [m/m³]								
Volumetric density of double-phase	-	$6.67 imes 10^6$						
boundary line [m²/m³]								

function layer of cathode and LSCF current collector layer of LSCF. The cell has an effective area of 80 mm \times 60 mm with a thickness of 240, 8, 4, and 50 μm for the anode, electrolyte, GDC barrier layer, and cathode layer, respectively. The details of the microstructure are given in Table 1.

The effective anode thickness is studied with the same cell's microstructure. Fig. 2(a) shows the annual research articles in solid oxide fuel cells after 1999.1% of the research articles within the recent 5 years: refs [29-50] in 2022, refs [51-73] in 2021, refs [19,74-92] in 2020, refs. [93-111] in 2019 and refs [112-128] in 2018. Are randomly considered to summarise the involved thickness of the anode and it is summarized in Fig. 2(b). The distribution of the anode thicknesses that are found in the research articles, is given by the round dot on the left-hand side in Fig. 2(b). On the other hand, the box chart on the right-hand side illustrates how the anode thicknesses are spread. It is found that the minimum and the maximum anode thickness are 0.15 and 2140 µm, respectively. The distribution has the lower and upper quartiles of 55 and 680 μm, respectively, which are represented by the box. The square within the box indicates the mean value of anode thickness, which has a value of 460.05 $\mu m.$ As a result, the considered anode thickness in this study is 5, 10, 50, 100, 500 and 1000 µm.

Calculation conditions

The numerical analysis is conducted with the volumetric flow rates of 0.5 and 3.0 L/min in the standard state with mole fraction ratios of 0.600: 0.020: 0.380 for hydrogen (H₂): steam (H₂O): nitrogen (N₂) and 0.210:0.790 for oxygen (O₂):N₂ are supplied to the fuel and air channel, respectively. The outlet pressure of both the fuel and air mixture is maintained at the atmospheric pressure.

The boundary conditions for the validation with the experimental [16] are given in Table 2. Note that the electric



Fig. 2 – Annual research article publication of SOFC (a) between 1999 and 2022, (b) anode thickness that is reported by 1% of research articles (92 articles) of SOFC between 2018 and 2022.

Table 2 – Boundary conditions.									
	и	W	T _f	Ts	Yi	π			
Inlet	$u = u_{in}$	w = 0	$T_{\rm f} = T_{\rm in}$	$\frac{\partial T_s}{\partial x} = 0$	$Y_i = Y_{i, \ in}$	$\frac{\partial \phi}{\partial x} = 0$			
Outlet	$\frac{\partial u}{\partial x} = 0$	$\frac{\partial w}{\partial x} = 0$	$\frac{\partial T_{f}}{\partial x} = 0$	$\frac{\partial T_s}{\partial x} = 0$	$rac{\partial \mathbf{Y}_i}{\partial \mathbf{x}} = 0$	$\frac{\partial \phi}{\partial x} = 0$			
Wall	<i>u</i> = 0	w = 0	$\frac{\partial T_f}{\partial z}=0$	$T_s = T_{in}$	$\frac{\partial Y_i}{\partial z} = 0$	$\frac{\partial \phi}{\partial z} = 0$			

potential difference between the top and bottom separators is the terminal voltage of the cell unit and is iteratively tuned to achieve a pre-determined average current density. The pressure fields in the fuel and air channels are solved by the semiimplicit method for the pressure-linked equations (SIMPLE) algorithm, while its outlet is set at 1 atm. During the analysis of the effect of the anode active thickness, the boundary condition of the T_s at walls is updated to an adiabatic condition to simulate a real operation of an SOFC.

Results and discussion

The numerical results in this work are compared with the numerical results from our previous work using Fick's model (FM) for the gas species transport in the electrodes [16]. The details of the experiment can be found elsewhere [129,130]. Fig. 3 shows the comparison of the current-voltage characteristics at temperatures of 973, 1023, and 1073 K by blue, green- and red-coloured squares, dashed and dotted lines, respectively. The squares indicate the experimental results, the dashed lines represent the numerical results from Tan et al. [16], and the prediction of the present SOFC numerical model is shown by the dotted lines. The numerical results from this study have a closer agreement with the experimental results as compared to the numerical results from Tan et al. [16].

Area-specific resistance (ASR) analysis is conducted for the average current density of 3500 A/m² (973 K), 5000 A/m² (1023 K) and 6500 A/m² (1073 K). The obtained ASR values are compared to the same average current density with FM for the gas transportation model within electrodes as shown in Fig. 4. The stacked bar chart shows the ASR values for each voltage



Fig. 3 – Comparison of current-voltage characteristics. For a commercial SOFC with an anode thickness of 240 μ m.

loss within a cell. From the bottom of the stacked bar chart is anode activation loss, anode ohmic loss, anode concentration loss, electrolyte ohmic loss, cathode activation loss, cathode ohmic loss and cathode concentration loss. The ASRs for the FM as gas transportation model as considered in the work of Tan et al. [16] are given on the left-hand side. In contrast, the ASRs for current work are shown on the right-hand side. It is found that the implementation of the DGM for the gas species transport within the electrodes and the consideration of local concentration loss as given by Eqs. (30) and (31) in this study results in a slightly low concentration loss, especially at a high operation temperature for an SOFC. This decrement in concentration loss enables the electrochemical reaction to take place close to the electrode-electrolyte interface regime, which results in a decrement of the ohmic resistance within an electrode. As more electrochemical reaction occurs close to



Fig. 4 – Comparison of ASR values at 973, 1023 and 1073 K for a commercial SOFC with an anode thickness of 240 μ m at the average current density of 3500, 5000 and 6500 A/m², respectively.

the electrode-electrolyte interface regime, the cell experiences an increment of the activation loss.

Miyawaki et al. [26] defined the active thickness of an electrode as the thickness of the electrode from the electrodeelectrolyte interface in which 90% of the electrochemical reaction takes place and it is expressed as $\frac{1}{2}$ ln 10. Fig. 5 shows the comparison of the active thickness in the anode between the FM in the work of Tan et al. [16] and the DGM in the current work at the average current density of 6500 A/m² at 1073 K. The solid and dash lines show the anode active thickness under 90% and 99% of the electrochemical reaction takes place, respectively. Regardless of 90% or 99% of the reaction, the cell has a relatively thin anode active thickness at the inlet region as shown in Fig. 5. This is due to the concentration of fuel mixture being high and the concentration of the product of the electrochemical reaction (steam) is low near the inlet. Such condition allows the electrochemical reaction takes place near the anode-electrolyte interface to reduce the ohmic loss. It is found that the anode active thickness in the current



Fig. 5 – Comparison of 90% and 99% of the anode active thickness in an anode of a commercial SOFC at Z = 0.03 m with the operation of 6500 A/m² at 1073 K.

work is thicker than the previous work under the same operating condition. As the active thickness of the anode is slightly extended in the current work, high ohmic resistance in the cell is observed as shown in Fig. 4. Also, under 99% of the reaction, the required thickness is nearly double the thickness for the case of 90% of the reaction.

The same calculation and boundary conditions are used to study the effect of the anode thickness of an SOFC at the operation temperature of 973 K. Fig. 6 shows the current and power densities for various anode thicknesses of an SOFC. The black and red coloured lines indicate the current density and power density of the considered cells, respectively. It is found that the thinnest anode thickness of 5 μ m (black solid line) shows the highest performance as its current density curve is positioned at the top among all curves for all anode thicknesses. It is also found that this 5 μ m anode thickness cell has the highest power density of 2741.59 W/m². It is worth highlighting that the cell with 10 μ m anode thickness shows a slightly lower performance as compared to the highestperformance cell with the highest power density of 2734.49 W/m².

Further analysis is conducted at the average current density of 6000 A/m^2 for the cells with anode thicknesses of 5, 10, 50 and 100 μ m as shown in Fig. 7. It clearly shows that the thinnest anode thickness cell has the lowest total ASR. It is due to the lowest anode concentration resistance within the cell. As the thickness of the anode is increased, the cell is suffered from high anodic concentration resistance as the gas species are required to travel longer paths between electrochemical reaction sites and the fuel channel. Again, the total ASR for the 10 µm anode thickness cell is found similar to the total ASR for the 5 µm anode thickness cell. As a result, the same performance of both cells is observed in Fig. 6. In Fig. 7, the cells with the anode thickness of 500 and 1000 μ m are excluded as the cells experience a rapid decrement at the average current density before 6000 A/m². High resistance of the transport of gas species is expected within a porous anode due to a high electrochemical reaction rate. It is worsened by



Fig. 6 – Comparison of current density-voltage and current density-power density curves under different anode thicknesses of 5, 10, 50, 100, 500 and 1000 μ m at the temperature of 1073 K.



Fig. 7 – Comparison of ASR values at 6000 A/m² with the anode thickness of 5, 10, 50 and 100 μ m, respectively at the temperature of 1073 K.

an SOFC with a thick electrode as shown in Fig. 7 where the anode concentration is significantly increased. Both SOFCs with an anode thickness of 500 μ m and 1000 μ m experience an insufficient supply of hydrogen from the fuel channel to the reaction sites within the anode active thickness to support the high electrochemical reaction rate.

Based on the observation in Fig. 5, the cell with an anode thickness of 50, 100, 500 and 1000 μ m has no issue with the anode active thickness as the cell has a sufficient thick anode. Therefore, the analysis of the anode active thickness is conducted towards the cell with 5 and 10 μ m thickness of the anode as shown in Fig. 8. The red and blue coloured lines indicate the average current density of 500 and 6000 A/m², respectively. It is found that the active thickness is beyond the

actual thickness of 5 μ m as shown in Fig. 8(a) except for the 90% of the reaction curve at a high average current density of 6000 A/m². Again, the active thickness is also found beyond the actual thickness of 10 μ m as shown in Fig. 8(b) under low average current density operation. It is also found that the cell with high current density (or low terminal voltage) has a thin active thickness as agreed by the results by Zheng et al. [9]. In a summary, the developed quasi-3D model in this study is capable of analysing SOFC as shown in the validation. However, this model is found not suitable for the cell with an extremely thin electrode. This is due to the charge-transfer current for a cell with a relatively thin electrode doesn't follow the decay model as proposed by Miyawaki et al. [26]. In the study of Miyawaki et al. [26], 4 and 8 μ m thickness anodes



Fig. 8 – The active thickness of anode at Z = 0.03 m at the operation of 500 and 6000 A/m² at 973 K for (a) 5 μ m anode and (b) 10 μ m anode.



Fig. 9 – The active thickness of anode at Z = 0.03 m at 973 K for various anode thicknesses at the average current density of (a) 500 A/m² and (b) 6000 A/m².

showed a high charge-transfer current density at the surface of the anode during operation. Therefore, a new chargetransfer current model is mandatory in this quasi-3D SOFC model for a cell with an insufficiently thick electrode.

Fig. 9 shows the anode active thickness under the consideration of a 99% reaction rate for various anode thicknesses from 5 µm to 1000 µm at a low average current density of 500 A/m^2 and a high average current density of 6000 A/m^2 with the operating temperature of 973 K. It is found that an SOFC with a thick anode leads to a thin anode active thickness regardless of its average current density. An SOFC with thick anode results in a high anodic concentration resistance as shown in Fig. 7. Such increment of anodic concentration resistance promotes a reduction of anode active thickness to minimize the total voltage loss within a cell. At a high average current density operation, a cell requires a high supply rate of hydrogen from the fuel channel. At the same time, the cell needs to remove the produced steam at a rapid rate. These phenomena also promote a high anodic concentration resistance. As a result, the anode active thickness for all considered cells decreases at a high average current density. Such observation is found in good agreement with the numerical analysis from Miyawaki et al. [26] and Cai et al. [131].

Conclusions

The dusty-gas model (DGM) was introduced in the quasithree-dimensional (quasi-3D) solid oxide fuel cell (SOFC) model to consider the influence of the active thickness of electrodes. The concentration loss within an electrode was expressed correspond to the active thickness of the electrode in terms of the attenuation factor for the charge-transfer current density, current density, concentrations and coefficients of reactants and products (Eqs. (14)-(18)) within the gas mixture, the thickness of the electrode, as well as the operating conditions such as temperature and pressure of the gas mixture. Note that the coefficient of reactants and products within a gas mixture is a function of properties of gas species such as concentration, Knudsen and binary gas diffusion coefficients, properties of a gas mixture such as pressure and viscosity, and microstructure of the porous medium such as permeability, porosity and tortuosity factor of the pore phase. On the other hand, the attenuation factor of the charge-transfer current density was determined based on the minimum total voltage losses using the Newton-Raphson method by considering all voltage losses including concentration loss. The numerical results from the quasi-three-

dimensional SOFC model closely agree with the experimental results. This indicates that the concentration loss resulting from the mass and species transport within an electrode influences the attenuation factor within the charge-transfer current density model that reflects in both the activation and ohmic losses of an SOFC. The influence of the anode's thickness towards anode active thickness was studied with the thickness of 5, 10, 50, 100, 500 and 1000 μ m. It is found that the quasi-three-dimensional SOFC model is capable of analysing the performance of an SOFC with a sufficiently thick electrode. Also, a thick electrode and a high average current density result in a thin active thickness.

Credit authorship contribution statement

W. C. Tan: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. E. A. Lim: Software, Formal analysis, Investigation, Writing – review & editing. H. A. Rahman: Formal analysis, Writing – review & editing, Proofreading. A. S. Abdullah: Formal analysis, Writing – original draft, Visualization. C. S. Oon: Investigation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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