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1 **Modeling and dynamic characteristic simulation of air-cooled proton exchange**
2 **membrane fuel cell stack for unmanned aerial vehicle**

3 Chengyuan Gong^a, Lu Xing^{b,*}, Cong Liang^{c,d}, Zhengkai Tu^{a,*}

4 ^a School of Energy and Power Engineering, Huazhong University of Science and
5 Technology, Wuhan, 430074, China

6 ^b Mechanical and Construction Engineering, Northumbria University, Newcastle upon
7 Tyne, NE1 8ST, United Kingdom

8 ^c China Automotive Technology and Research Center Co., Ltd., No.68 East Xianfeng
9 Road, Tianjin, China

10 ^d CATARC Automotive Test Center (Wuhan) Co., Ltd., No.55 Zhuanyang Avenue,
11 Wuhan, China

12
13 *Corresponding author:

14 Lu Xing, lu.xing@northumbria.ac.uk;

15 Zhengkai Tu, tzklq@hust.edu.cn.

16 Fax: +86 27 87540724

17 Tel.: +86 (0) 2787542618
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22 **Abstract**

23 Air-cooled low-temperature proton exchange membrane fuel cell stack applied with
24 metallic bipolar plate is considered as a promising power source for an unmanned aerial
25 vehicle. This paper presents a coupled electrochemical thermal model for simulating its
26 dynamic characteristic. The impact of the applied metallic bipolar plate on the stack
27 thermal balance is considered; an environmental model estimating atmospheric
28 temperature and pressure variations with altitude is included. Our theoretical analysis
29 shows that with altitude increased from 0m to 4000m, the output electric power
30 declined rate is 4.7-6.5% at the current density of 400-800 mA·cm⁻². To avoid severe
31 stack degradation due to high stack operating temperature, minimum air stoichiometric
32 ratio is required for maintaining stack thermal balance. When the altitude increases
33 from 0 to 4000m, the minimum required air stoichiometric ratio decreases from 110 to
34 22 at the current density of 800 mA·cm⁻².

35 **Keywords:** Proton exchange membrane fuel cell; Air-cooled; Performance; Thermal
36 management; Unmanned aerial vehicle

37

38 **1. Introduction**

39 Proton exchange membrane fuel cell (PEMFC) has been widely applied all over the
40 industrial and commercial fields, due to its low operation temperature, high power/mass
41 ratio, fast response, no emission and low noise [1, 2]. It can be used for combined heat
42 and power generation [3, 4], for automobiles industry [5-8] and for unmanned aerial
43 vehicles (UAVs) [9, 10]. The low-temperature PEMFC stack for UAV is preferred to be
44 applied with metallic bipolar plate and to be air cooled because of severe restrictions
45 for weight and space available [11].

46 Fuel cell stack made of metallic bipolar plates weighed much less than a fuel cell stack
47 made of carbon graphite [12, 13]. Furthermore, stainless steel bipolar plates have better
48 electrical and thermal conductivity, higher shock resistance and higher gas barrier
49 properties compared with graphite bipolar plates [14, 15]. Considerable efforts focusing
50 on the surface coating [16-18] or on flow channel optimization [19-21] have been made
51 to optimize the design of bipolar plates. These researches focus on liquid-cooled stack,
52 while there are few researches on air-cooled stack applied to UAV. Other materials like
53 polymers also have been used in bipolar plates which are suitable for compression
54 molding, transfer molding, or injection molding [22]. However, studies mentioned
55 above have been mainly conducted in stationary and laboratory settings, where
56 vibration intensity and lightweight are not critical. The metallic bipolar plates have the
57 advantage of vibration-resistant, firm structure, light weight [23] which can withstand
58 harsh and uncertain environments effectively. Therefore, the metallic bipolar plate is

59 more suitable for UAV.

60 The dynamic performance and thermal management of the air-cooled PEMFC stack are
61 crucial for the UAV since both of them concern efficiency optimization and fuel cell
62 life span, especially for mission success. For PEMFC powered UAV, the atmospheric
63 temperature, atmospheric pressure, and oxygen partial pressure will change with the
64 variation of altitude during the operation of UAV. Altitude variations can lead to the
65 stack performance degradation and bring challenges for thermal management.
66 Therefore, theoretical analysis of altitude variations influence on stack operational
67 performance and thermal management is critical and necessary to be performed.

68 Electrochemical models for steady state and dynamic characteristic simulations of the
69 PEMFC have been developed over the years. Mann et al. [24] established a generalized
70 steady-state electrochemical model for a PEMFC. Thermodynamic potential, the
71 activation overvoltage and the ohmic overvoltage were included in this expression.
72 Musio et al. [25] constructed a validated and modular model of a PEMFC stack which
73 includes the concentration overvoltage in the fuel cell voltage formula, a good match
74 with experimental data was observed in their results. Seleem et al. [26] proposed a novel
75 and simplified precise model for the PEMFCs. The unknown model parameters were
76 reduced to four and could be obtained using the metal-heuristic algorithm (or called
77 equilibrium optimizer). Khan and Iqbal [27] discussed dynamic modeling and
78 simulation methods for a PEMFC system, it reflected various features arising due to
79 transients in cell electrochemistry, energy balance and reactant flow. Zhang et al. [29]

80 developed a control-oriented thermal model for the air-cooled PEMFC and proposed a
81 model predictive control-based temperature regulation strategy. The temperature
82 characteristics of the open-cathode PEMFC can be effectively described by the
83 developed models and the better performance could be obtained comparing to the
84 traditional PI controller.

85 Some researches focused on the fuel cell hybrid propulsions systems in UAV, fuel cells
86 with other power sources such as batteries [30, 31], super capacitors [13], and solar
87 cells [32]. Depcik et al. [33] compared the UAV powered by lithium-ion batteries,
88 hydrogen fueled combustion engines and the fuel cell. The results showed that a Li-air
89 battery pack would have the longest flight time and simplest configuration. Gonzalez-
90 Espasandin [34] investigated the direct methanol fuel cell (DMFC) and PEMFC
91 performance under flight conditions for the UAV. Renau et al. [35] presented the design
92 of high-temperature PEMFC and its cooling system to power a UAV for a high-altitude
93 mission. The design, manufacture and operational tests of a lightweight HT-PEMFC
94 were optimized. Horde et al. [36] studied the sensitivity to altitude using experimental
95 data and a developed electrochemical model, at three different altitudes 200, 1200 and
96 2200m. Results indicated that the fuel cell power decreased as the altitude increased.

97 So far, the coupled electrochemical and thermal model for the PEMFC stack of a UAV
98 applied with metallic bipolar plate has not been developed. The dynamic characteristic
99 simulation considering influences of altitude variations has not been performed. In this
100 paper, we propose an electrochemical model and a thermal model for the air-cooled

101 PEMFC stack of a UAV. The impact of the applied metallic bipolar plate on the stack
102 thermal balance and an environmental model estimating atmospheric temperature and
103 pressure variations with altitude are included. Theoretical analysis for the influence of
104 altitude variations on stack operational performance and thermal management has been
105 carried out. Fan supplies cathode intake air, meanwhile, the air flow removes waste heat
106 to maintain stack thermal balance. We also investigate influence of air stoichiometric
107 ratio on the thermal performance of the PEMFC stack.

108 **2. Methodology**

109 A coupled electrochemical and thermal model is proposed for the simulation of air-
110 cooled PEMFC stack of an UAV. An environmental model which considers the
111 atmospheric temperature and pressures changes due to the altitude variations is
112 integrated with the coupled electrochemical and thermal model. The electrochemical
113 model has been validated against experimental data. The cell temperature is affected by
114 the environment (pressure, ambient temperature) and load, the output power of the cell
115 will be in turn affected by the cell temperature. Therefore, this is a complex coupling
116 process for the performance of a single cell. The heat transfer and heat generation
117 process between numerous single cells forms the temperature distribution in an PEMFC
118 stack.

119 **2.1. Electrochemical model**

120 The PEMFC stack uses hydrogen as a fuel and oxygen (in the ambient air) as an oxidant,

121 continuously outputs electrical energy through an electrochemical reaction. The
 122 electrochemical model is developed based on method proposed by Jia et al. [37],
 123 detailed information of empirical parameters for the model equations are also presented
 124 by Khan and Iqbal [27]. The output voltage of fuel cell can be obtained considering
 125 ohmic loss, concentration loss and activation loss in the fuel cell stack, as shown in
 126 Equation (1):

$$127 \quad V_{\text{cell}} = E_{\text{nernst}} - V_{\text{ohmic}} - v_d \quad (1)$$

128 Where, V_{cell} is the single fuel cell voltage (V). V_{ohm} is the ohmic loss (V) due to the
 129 impedance of transmission. v_d is the overall voltage drop because of concentration
 130 loss and activation loss, it will be calculated using the equivalent circuit model and
 131 explained in detail in section 2.1.1. E_{nernst} is the Nernst open circuit voltage (V) can
 132 be expressed as a function of fuel cell operating temperature, partial pressures of
 133 hydrogen and oxygen in the fuel cell as shown in Equation (2):

$$134 \quad E_{\text{nernst}} = \frac{1}{2F} (\Delta G - \Delta S(T - T_{\text{ref}})) + \frac{RT}{2F} \ln (P_{\text{H}_2} (P_{\text{O}_2})^{0.5}) \quad (2)$$

135 The ohmic overvoltage V_{ohmic} can be calculated with Ohm's law as shown in Equation
 136 (3):

$$137 \quad V_{\text{ohmic}} = I_{\text{cell}}(R_M + R_c) \quad (3)$$

138 Where, I_{cell} is the cell current (A). R_c is the contact resistances both between the
 139 membrane and electrodes as well as the electrodes and the bipolar plates (Ω). R_M is
 140 the equivalent membrane impedance (Ω) as shown in Equation (4) [37]:

$$R_M = \frac{r_M l_{\text{mem}}}{A}$$

$$r_M = \frac{181.6[1+0.03(\frac{l}{A})+0.062(\frac{T}{303})^2(\frac{l}{A})^{2.5}]}{[\lambda-0.634-3(\frac{l}{A})]\exp(4.18\frac{(T-303)}{T})}$$
(4)

2.1.1. Equivalent circuit model

There is a ‘double layer capacitance’ phenomenon in PEMFC [38] as shown in Fig. 1. An electrical capacitor can be considered as the layer of charge on or near the electrode–electrolyte interface [37]. They act as charge and energy storage devices, which are equivalent to a capacitor. This phenomenon will impact the activation and concentration losses. The ohmic overvoltage will not be affected. The activation losses can be computed according to the empirical equation as shown in Equation (5) [37]:

$$V_{\text{act}} = \xi_1 + \xi_2 T + \xi_3 T [\ln(C_{\text{O}_2})] + \xi_4 T [\ln(I)]$$

$$\xi_1 = -0.948$$

$$\xi_2 = 0.00286 + 0.0002 \ln(A) + 4.3 \times 10^{-5} \ln(C_{\text{H}_2})$$

$$\xi_3 = 7.6 \times 10^{-5}$$

$$\xi_4 = -1.93 \times 10^{-4}$$
(5)

Where C_{H_2} is the hydrogen concentration at the anode/membrane interface. The reactant concentrations at the electrode/membrane interfaces could be determined by Henry’s law [24]:

$$C_{\text{O}_2} = P_{\text{O}_2} \times 1.97 \times 10^{-7} \exp \frac{498}{T}$$

$$C_{\text{H}_2} = P_{\text{H}_2} \times 9.174 \times 10^{-7} \exp \frac{-77}{T}$$
(6)

The concentration loss is needed to be included because of high concentration loss at high current density regime. The concentration loss can be expressed as [35]:

$$V_{\text{con}} = \frac{RT}{2F} \ln \left(1 - \frac{i}{i_{\text{max}}} \right)$$
(7)

As shown in Fig. 1 (a), at the surface of the fuel cell cathode, a simple equivalent circuit

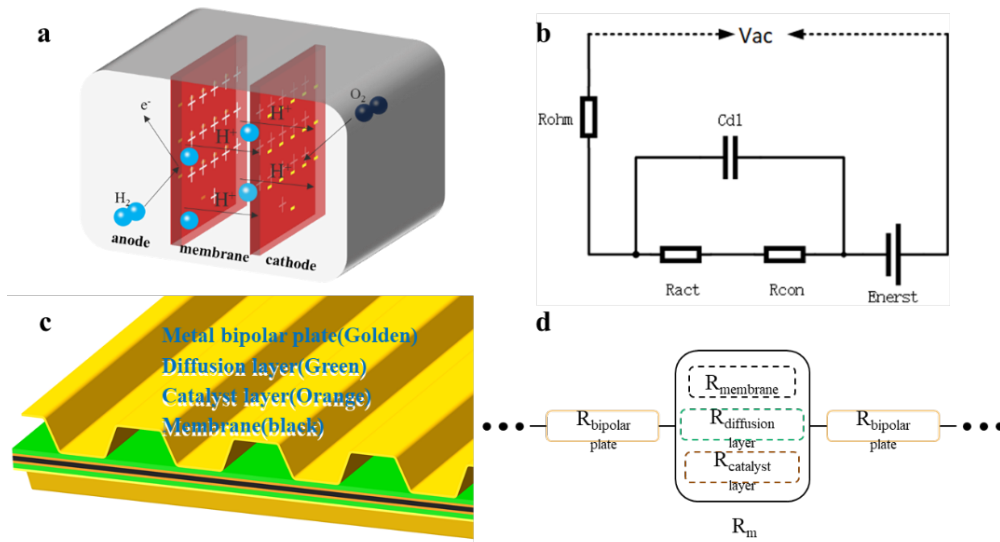
158 model of the PEMFC in which an electrical capacitor can be considered as the layer of
 159 charge on or near the electrode-electrolyte interface as shown in Fig. 1 (b) [37-39]. The
 160 voltage at both ends of the equivalent capacitor varies dynamically with the current
 161 until the voltage reaches the next steady value. The process can be expressed as
 162 Equation (8):

$$163 \quad \frac{dv_d}{dt} = \frac{I_{cell}}{C} - \frac{v_d}{\tau} \quad (8)$$

164 Where, t is time (s). C is the equivalent capacitance of the capacitor (F). τ is time
 165 constant (s) which can be expressed by functions of the activation overvoltage and the
 166 concentration overvoltage as shown in Equation (9) [37]:

$$167 \quad \tau = C(R_{act} + R_{con}) = \frac{C(V_{act} + V_{con})}{I} \quad (9)$$

168 Where, R_{con} is the concentration equivalent resistance and R_{act} is the activation
 169 equivalent resistance as shown in Fig. 1 (b).



171 Fig. 1. (a) and (b) Charge double layer and equivalent circuit model of PEMFC; (c)

172 Cross-sectional picture of single cell; (d) Heat transfer equivalent circuit.

173 **2.1.2. Reactant flow model**

174 Reactant flow model is developed for determining the effective partial pressure of
 175 hydrogen and oxygen at the anode and cathode [27, 28]. The reactant flow model is
 176 established on the ideal gas law and the principle of molar conservation. Reactant flow
 177 at any instant is equal to the gas inlet flow rate minus gas outlet flow rate and gas
 178 consumption. The anode gas pressure can be calculated using Equation (10):

$$179 \quad \frac{V_a}{RT} \frac{dP_{H_2}}{dt} = \dot{m}_{H_2,in} - \dot{m}_{H_2,out} - \dot{m}_{H_2,used} \quad (10)$$

$$\dot{m}_{H_2,out} = k_a(P_{H_2} - P_{tank})$$

180 Where V_a is anode volume (m^3), $\dot{m}_{H_2,in}$ and $\dot{m}_{H_2,out}$ are hydrogen inlet and outlet
 181 flow rate ($mol \cdot s^{-1}$), respectively. $\dot{m}_{H_2,out}$ is related to hydrogen pressure at the inlet
 182 and anode flow constant k_a ($mol \cdot s^{-1} bar^{-1}$). $\dot{m}_{H_2,used}$ is the total hydrogen usage
 183 ($mol \cdot s^{-1}$) which is related to the cell numbers and stack current. Parameters of the
 184 electrochemical model are presented in Table 1. The air-cooled PEMFC stack is
 185 assembled by metallic bipolar plates that made of 316L stainless steel.

186 Table 1: Parameters of the electrochemical model

Parameter	Value	Units
Number of cells N	50	N/A
Hydrogen pressure	1.5	bar
Cell area A	100	cm^2
Anode volume V_a	0.0025	m^3
Cathode volume V_c	0.0025	m^3

Anode flow constant	0.065	$\text{mol}\cdot\text{s}^{-1}\text{bar}^{-1}$
Cathode flow constant	0.065	$\text{mol}\cdot\text{s}^{-1}\text{bar}^{-1}$

187 **2.2. Thermal model**

188 Fig. 2 presents the thermal balance within the air-cooled PEMFC stack, there are mainly
189 two parts: membrane electrode assembly (MEA) and metallic bipolar plate (made of
190 316L stainless steel). The MEA is considered as heat source, the thermal energy is
191 transferred to bipolar plates by heat conduction and air by convection. In this study, the
192 excess hydrogen is re-circulated to the anode, hydrogen flow is much less than air flow,
193 Therefore the heat exchange with hydrogen can be ignored. The thermal model is
194 lumped model and the temperature gradients between the inlet and the outlet of each
195 cell is neglected. As shown in Fig. 1, only in the gas channels, the MEA (GDL) and the
196 metallic bipolar plate contact with ambient air. Therefore, heat loss to the air will occur
197 in these surfaces. The thermal balance within the MEA of the stack can be calculated
198 using Equation (11):

199
$$C_M \frac{dT}{dt} = P_{\text{tot}} - P_{\text{elec}} - q_{M,\text{mbp}} - q_{M,\text{a,loss}} \quad (11)$$

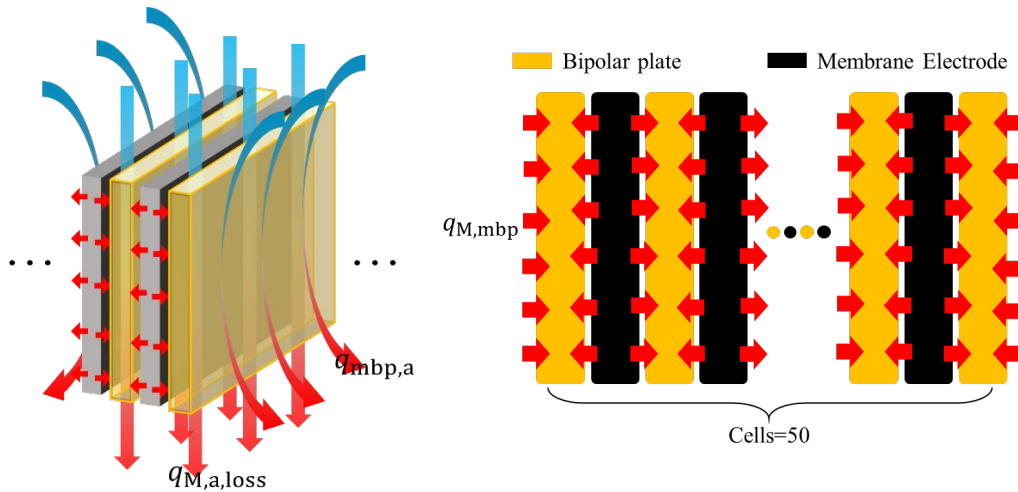
200 Where, T is the stack temperature (K). C_M is the thermal capacitance ($\text{J}\cdot\text{K}^{-1}$). P_{elec}
201 is the cell electrical power output (W) which equals to $V_{\text{Cell}}I_{\text{cell}}$. $q_{M,\text{mbp}}$ is the heat
202 flow through the MEA surface to the metallic bipolar plate (W). $q_{M,\text{a}}$ is the heat flow
203 from the MEA to the air flowing in the gas channel (W). P_{tot} is the total power input
204 (W) which can be calculated using Equation (12):

205
$$P_{\text{tot}} = \frac{N I_{\text{cell}}}{2F} \Delta H \quad (12)$$

206 Where, ΔH is the enthalpy of oxidation for the hydrogen ($285.5 \text{ KJ}\cdot\text{mol}^{-1}$). F is the
 207 Faraday constant ($96,485 \text{ C}\cdot\text{mol}^{-1}$). The thermal balance of the metallic bipolar plate
 208 can be calculated using Equation (13):

209
$$C_{\text{mbp}} \frac{dT_{\text{mbp}}}{dt} = q_{M,\text{mbp}} - q_{\text{mbp},a} \quad (13)$$

210 Where T_{mbp} is the metallic bipolar plate temperature (K). C_{mbp} is thermal
 211 capacitance ($\text{J}\cdot\text{K}^{-1}$). $q_{\text{mbp},a,\text{loss}}$ is the heat loss to the air from the metallic bipolar plate
 212 (W).



214 Fig. 2. Thermal balance of PEMFC stack applied with metallic bipolar plate.

215 In Equation (11) and (13), the heat transfer $q_{M,\text{mbp}}$ can be calculated as $\frac{T-T_{\text{mbp}}}{R_M}$;

216 $q_{M,a,\text{loss}}$ can be calculated as $\frac{T-T_{\text{amb}}}{R_{M,a}}$ and $q_{\text{mbp},a}$ can be calculated as $\frac{T_{\text{mbp}}-T_{\text{amb}}}{R_{\text{mbp},a}}$.

217 T_{amb} is the ambient temperature (K). Thermal resistance of the MEA R_M ($\text{K}\cdot\text{W}^{-1}$),

218 thermal resistance between the MEA and the surrounding air $R_{M,a}$ ($\text{K}\cdot\text{W}^{-1}$) and

219 thermal resistance between the metallic bipolar plate and the surrounding air $R_{\text{mbp},a}$

220 ($\text{K}\cdot\text{W}^{-1}$) can be expressed as shown in Equation (14) – (15). The thermal resistance of

221 the MEA is the summation of thermal resistance of the membrane, the catalyst layers
 222 and the gas diffusion layers:

$$223 \quad R_{M,mbp} = \frac{\delta_m}{\kappa_m \times A_m} + \frac{\delta_{cl}}{\kappa_{cl} \times A_{cl}} + \frac{\delta_{gdl}}{\kappa_{gdl} \times A_{gdl}} + \frac{\delta_{mbp}}{\kappa_{mbp} \times A_{mbp}} \quad (14)$$

$$224 \quad R_{M,a} = \frac{1}{h_{M,a} \times A_M} \quad (15)$$

$$225 \quad R_{mbp,a} = \frac{1}{h_{mbp,a} \times A_{mbp}} \quad (16)$$

226 Where, k_m is the thermal conductivity of the membrane ($W \cdot m^{-1}K^{-1}$). A_m is the area
 227 of the membrane (m^2). δ_m is the membrane thickness (m). k_{cl} is the thermal
 228 conductivity of the catalyst layer ($W \cdot m^{-1}K^{-1}$). A_{cl} is the area of the catalyst layer (m^2).
 229 δ_{cl} is the catalyst layer thickness (m). k_{gdl} is the thermal conductivity of the gas
 230 diffusion layer ($W \cdot m^{-1}K^{-1}$). A_{gdl} is the area of the gas diffusion layer (m^2). δ_{gdl} is the
 231 gas diffusion layer thickness (m). δ_{mbp} is the metallic bipolar plate thickness (m),
 232 k_{mbp} is the thermal conductivity of the metallic bipolar plate ($W \cdot m^{-1}K^{-1}$). A_M is the
 233 area of the MEA (m^2). A_{mbp} is the area of the metallic bipolar plate (m^2). $h_{M,a}$ is the
 234 convective heat transfer coefficient of the MEA to the surrounding air ($W \cdot m^{-2}K^{-1}$).
 235 $h_{mbp,a}$ is the convective heat transfer coefficient of the metallic bipolar plate to the
 236 surrounding air ($W \cdot m^{-2}K^{-1}$). For the air-cooled PEMFC stack, fan supplies cathode
 237 intake air, meanwhile, the air flow removes waste heat to maintain thermal balance for
 238 the PEMFC stack. Both $h_{M,a}$ and $h_{mbp,a}$ are function of air stoichiometric (or air
 239 flow rate). In other words, the air stoichiometric is expected to impact on the cooling
 240 capacity and thermal imbalance of the PEMFC stack. This will be investigated and
 241 discussed later in more details.

242 **2.3. Environmental model**

243 The ambient temperature and oxygen partial pressure varies with altitude which greatly
 244 affect the performance of the stack. According to the International Standard
 245 Atmosphere (ISA) model [40, 41], the variation of atmospheric temperature T_{atmo} (K)
 246 and atmospheric pressure P_{atmo} (bar) with altitude is given as follow Equations (17)
 247 and (18):

248
$$T_{\text{atmo}} = T_0 - 6.5 \times h_L \quad (17)$$

249 Where, h_L is the altitude (km). T_0 is the air temperature at sea level (K).

250
$$P_{\text{atmo}} = P_0 \left[1 - \left(6.5 \times \frac{h_L}{T_0} \right) \right]^{5.2561} \quad (18)$$

251 Where, P_0 is the air pressure at sea level (K). Parameters of the MEA consists of
 252 membrane, catalyst layers and gas diffusion layers and the metallic bipolar plates are
 253 shown in Table 2.

254 Table 2: Parameters of the thermal model

Parameter	Value	Units
Membrane thickness δ_m	0.02	mm
Catalysts layers thickness δ_{cl}	0.01	mm
Gas diffusion layers thickness δ_{gdl}	0.02	mm
Metallic bipolar plate thickness δ_{mbp}	1.00	mm
Thermal conductivity of membrane k_M	0.67	$\text{W} \cdot \text{m}^{-1} \text{K}^{-1}$
Thermal conductivity of catalyst layer k_{cl}	8	$\text{W} \cdot \text{m}^{-1} \text{K}^{-1}$

Thermal conductivity of gas diffusion layer k_{gdl}	1.6	$\text{W}\cdot\text{m}^{-1}\text{K}^{-1}$
Thermal conductivity of metallic bipolar plate k_{mbp}	16.2	$\text{W}\cdot\text{m}^{-1}\text{K}^{-1}$

255 **3. Results and discussions**

256 **3.1. Model validation**

257 The predicted polarization curve is compared to the experimental data from Ref. [25].

258 As shown in Fig. 3, the generally good fit to the experimental data confirms the model

259 is reliable (the average error is below 0.5%). It should be noted that this current density

260 range is representative of common steady-state operating conditions [25]. The number

261 of cells, the cell area is 50 and 100 cm^2 respectively and the operation conditions are

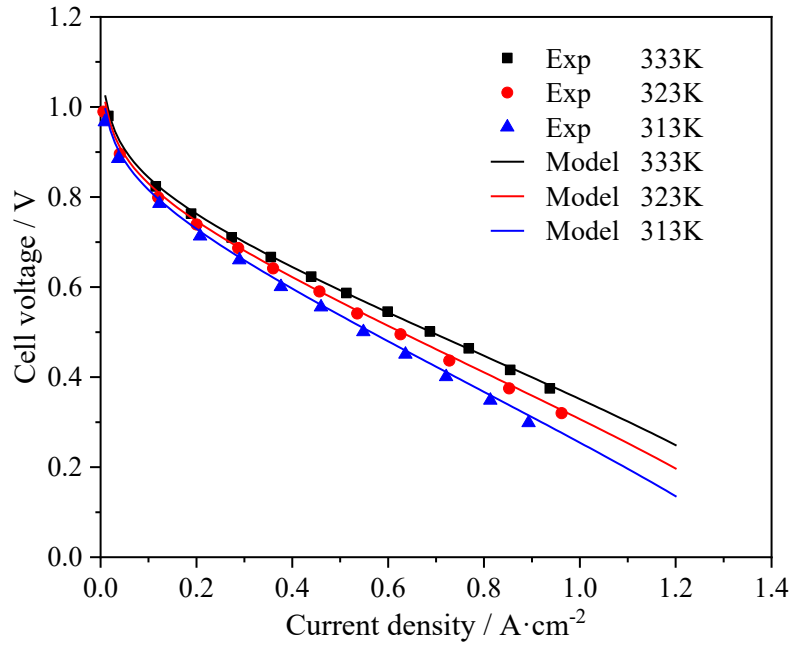
262 shown in Fig. 3. Since the influence on losses of porous media microstructure, of cell

263 water uptake and of lack of precise reactant gases distribution at the cathode side at

264 high current density (over $0.8 \text{ A}\cdot\text{cm}^{-2}$), the error between model and experimental data

265 is less satisfactory. These microstructure features are not properly accounted for in the

266 present modeling.

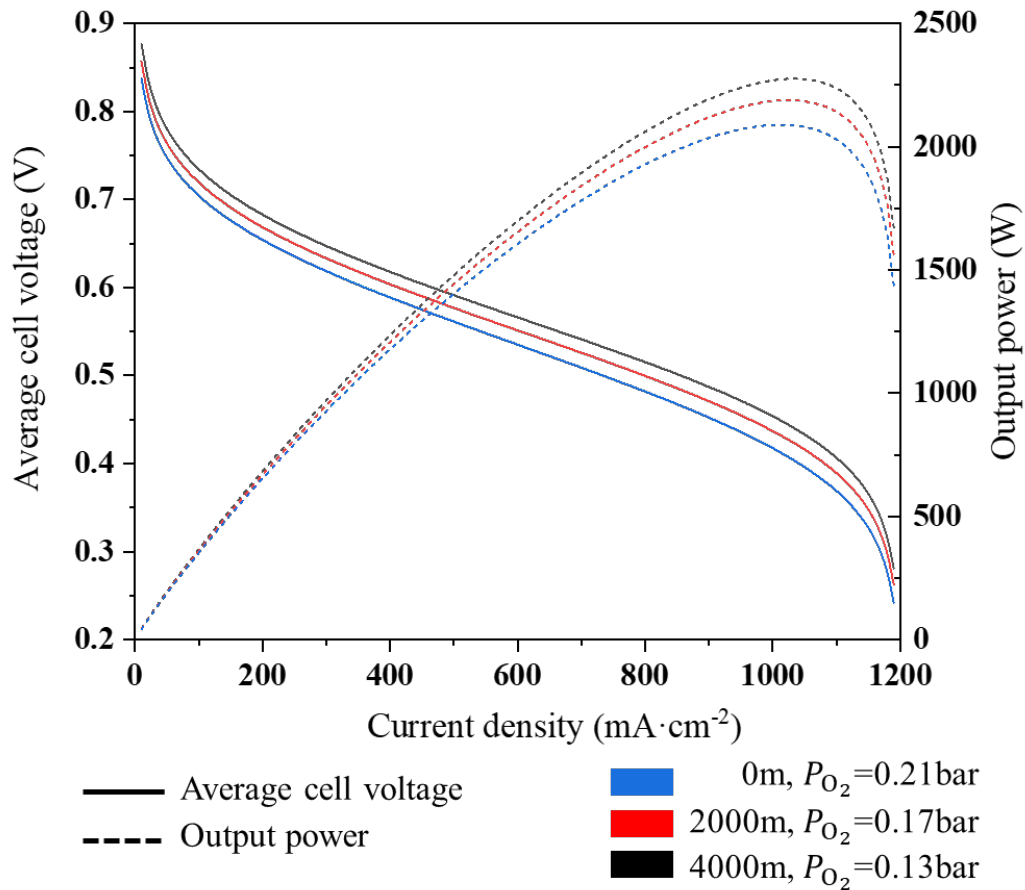


268 Fig. 3. Polarization curve – comparison of PEMFC electrochemical model results and
 269 experimental data

270 **3.2. Impact of altitude variations**

271 **3.2.1. Stack voltage and current density**

272 During the flight missions, altitude variations lead to changes in the atmospheric
 273 temperature and pressure, have significant impact on the stack performance and bring
 274 great challenges for the thermal management as well. It will also affect the individual
 275 cell voltages and temperatures within the stack. The calculation results of dynamic
 276 characteristics will be described in the following sections.



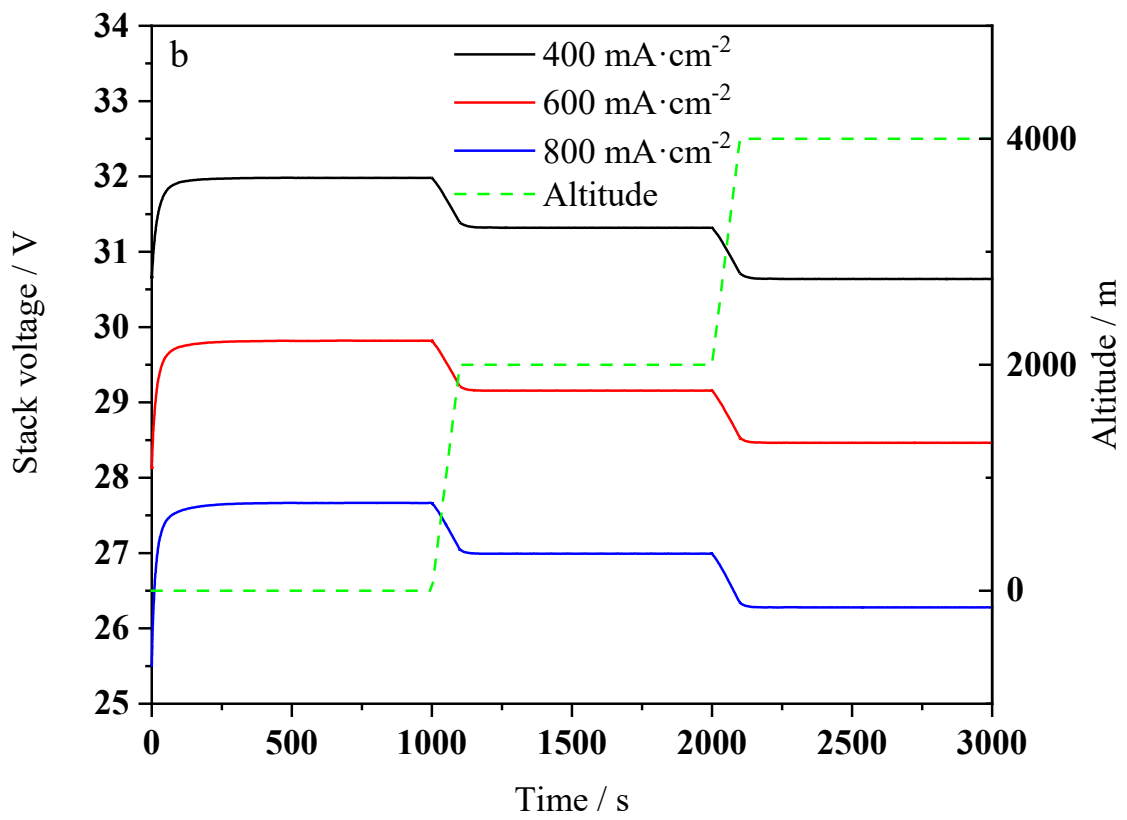
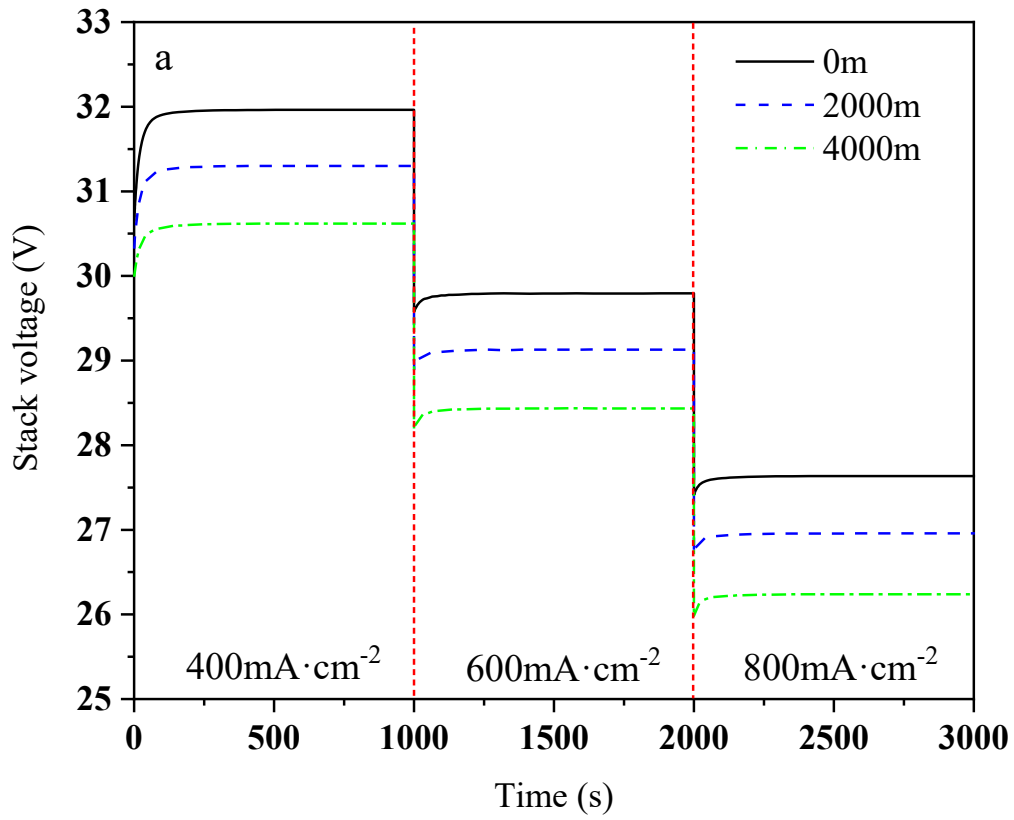
278 Fig. 4. Air-cooled PEMFC cell voltage and power output varies with current density
 279 at different altitudes (simulation results).

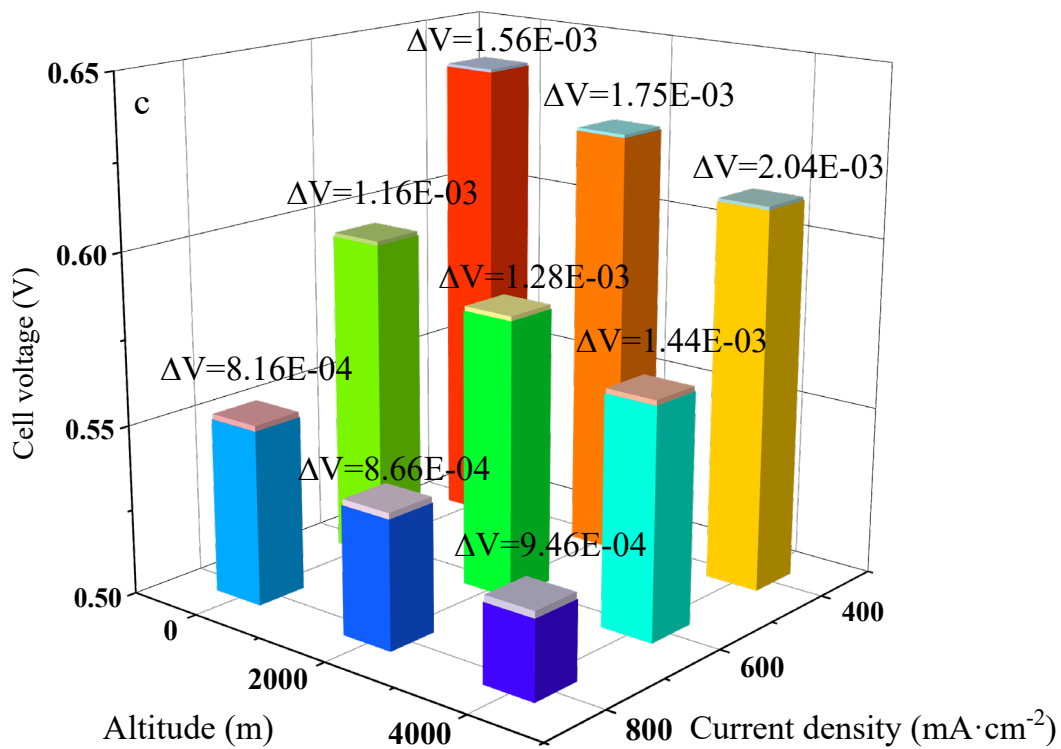
280 Fig. 4 presents the cell voltage and stack power output variations with the current
 281 density at different altitudes of 0m, 2000m and 4000m. At the current density of 400
 282 mA·cm⁻², the output electric power decreases from 1,236W to 1,178W with altitude
 283 increases from 0m to 4000m, the decline rate is 4.7%. This value is 6.5% at the current
 284 density of 800 mA·cm⁻², from 2269W to 1972W. As presented in Equation (17), altitude
 285 increment leads to decrease in the atmospheric pressure, so as the oxygen partial
 286 pressure, this results in the stack power loss and stack performance decrease. The
 287 performance degradation of the PEMFC stack responding to the altitude variations is

288 relatively more serious at the high current density.

289 As shown in Fig. 5 (a), at the sea level (altitude = 0m), the stack voltage drops from
290 32.0 V and gradually rises to 29.8 V when the current density increases from 400
291 $\text{mA}\cdot\text{cm}^{-2}$ to $600\text{ mA}\cdot\text{cm}^{-2}$. The voltage reaches stability around 200s due to the thermal
292 balance between the stack and the air flow in the gas channels. In addition, it takes
293 longer before the voltage reaches stability at low altitude (about 20-50s). This because
294 the ambient temperature is higher at low altitude, the stack will stabilize at a higher
295 temperature.

296 Fig. 5 (b) presents the dynamic response of the stack voltage to the change in altitude
297 (from 0 m to 2000 m during the time of 1000-1100s and from 2000 m to 4000 m during
298 the time of 2000-2100) at the same operating current. The voltage does not change
299 suddenly with the change of altitude, but has a certain delay, and the change is more
300 smooth. Since the stack temperature decreases with the increase of altitude as
301 mentioned before, the voltage decreases slowly with the altitude and reaches stability
302 within 100s after the altitude stabilizes. When the current density is $400\text{ mA}\cdot\text{cm}^{-2}$, the
303 stack voltage is 32.0 V at the altitude of 0 m, it drops to about 31.5 V at the altitude of
304 2000 m, the decline is 0.16%. When the altitude varies from 2000 m to 4000 m, the
305 decline will be less than 0.16%. Overall, stack voltage drop as altitude increases is quite
306 small about $0.25\text{ V}\cdot\text{km}^{-1}$ ($5\text{E-}3\text{V}\cdot\text{km}^{-1}$ for cell voltage). The impact of the current
307 density on the stack voltage is 1.2 V per $100\text{ mA}\cdot\text{cm}^{-2}$ variation.





311 Fig. 5: (a) Dynamic response of stack voltage to the current density step change at
 312 different altitudes (0 m, 2000 m and 4000 m); (b) Dynamic response of stack voltage
 313 to the altitude change at different current density (400 mA·cm⁻², 600 mA·cm⁻², 800
 314 mA·cm⁻²); (c) Cell voltage and voltage differences under different current densities
 315 (400, 600 and 800 mA·cm⁻²) and different altitudes (0 m, 2000 m and 4000 m).

316 In the PEMFC stack, each cell will output different voltage, the voltage distribution is
 317 parabolic and symmetrical, the cell voltage is higher at the center and lower at the side.

318 Fig. 5 (c) presents the cell voltage and the largest cell voltage difference under different
 319 current densities (400, 600 and 800 mA·cm⁻²) and different altitudes (0 m, 2000 m and
 320 4000 m). Cell voltage decreases as altitude increases or as current density increases. At
 321 the altitude of 0 m, the difference between the highest and lowest voltages are 8.16E-

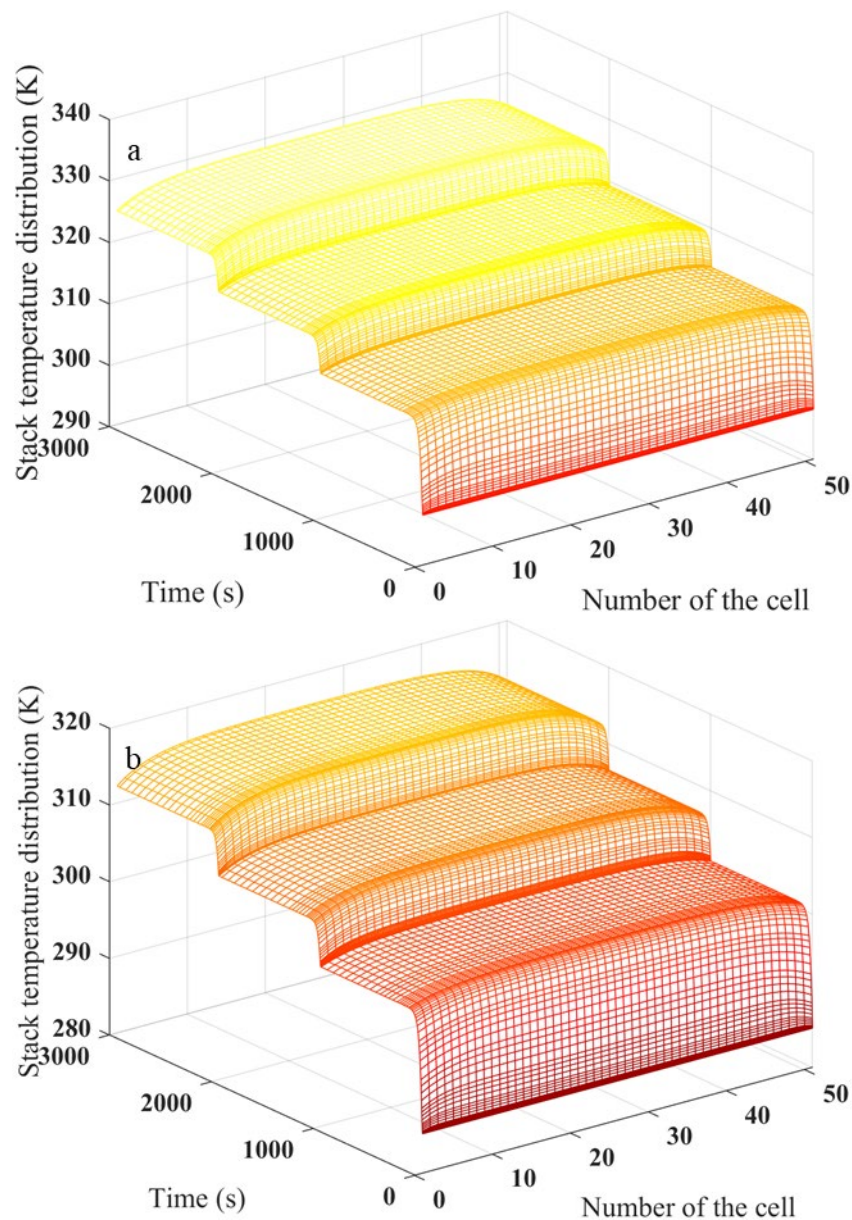
322 04, 1.16E-03 and 1.56E-03V at the current density of 400, 600 and 800 mA·cm⁻²
323 respectively. When the altitude reached 4000m, the largest voltages are 9.49E-04,
324 1.44E-03 and 2.04E-03V respectively. The cell voltage distribution is slightly less
325 homogeneous as altitude increases or as current density decreases.

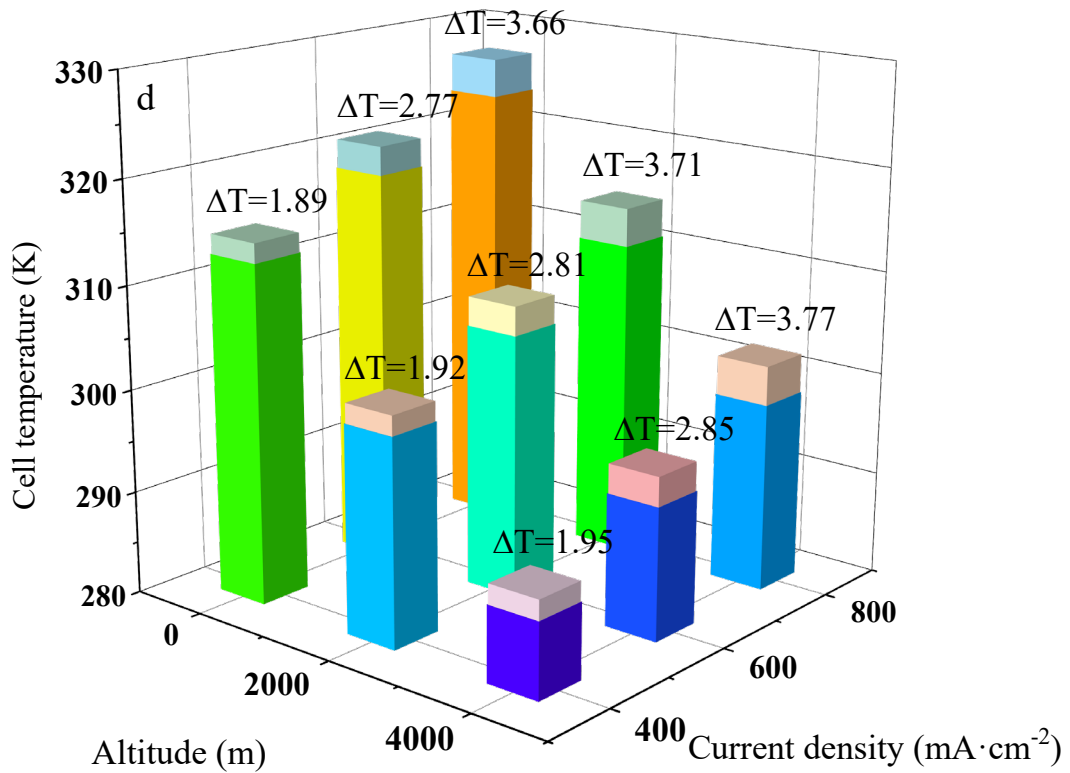
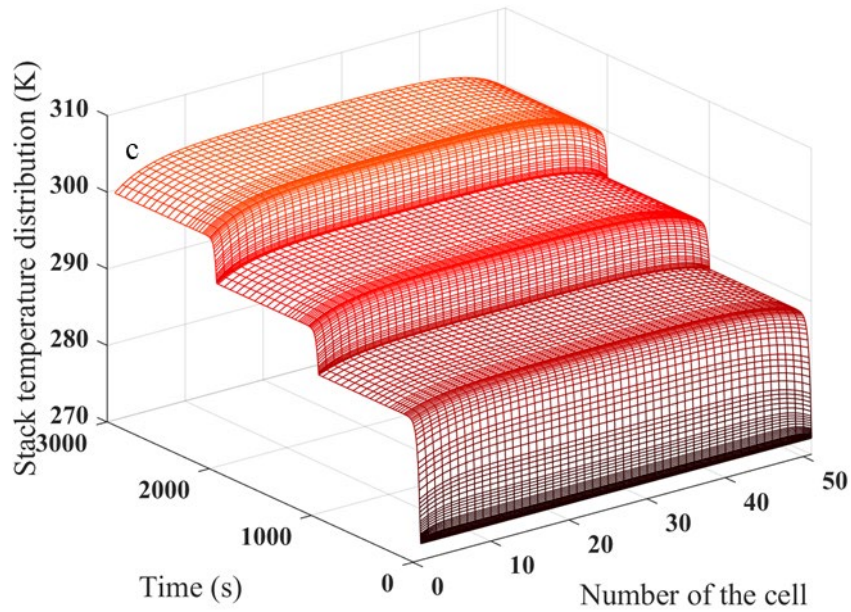
326 **3.2.2. Cell temperature distribution**

327 The PEMFC operating temperature and temperature difference are critical. Too high
328 operating temperature leads to dehydration and even rupture of the membrane. Fig. 6
329 (a), (b) and (c) present the cell temperature distribution when current densities step
330 change at altitudes 0, 2000 and 4000 m. The stack could be considered as an assemble
331 of many plates containing internal heat sources, the fuel cell temperature distribution is
332 'symmetric parabola' as shown in Fig. 6. More details of the cell temperature
333 distribution and temperature differences have been summarized and presented in Fig. 6
334 (d). As shown in Fig. 6 (d), the cell temperature increases with increasing current
335 density or with decreasing altitude. At the altitude of 0m, the operating temperature is
336 325K when the current density is at 800 mA·cm⁻². At the altitude 4000 m, the operating
337 temperature drop to 300K at the same current density. At the lower altitude, the
338 atmospheric temperature is relatively higher, the difference of stack or cell temperature
339 with surrounding air decreases, this makes it extremely challenging for thermal
340 management.

341 As shown in Fig. 6 (d), the air-cooled PEMFC stack applied with metallic bipolar plate
342 demonstrates a largest cell temperature difference of about 1.9 K (or °C) at the current

343 density of $400 \text{ mA}\cdot\text{cm}^{-2}$ and the altitude of 0 m. The largest temperature difference
344 within the stack increases from 1.9 to 2.8 and 3.7 K when the current density increases
345 from 400, to 600 and $800 \text{ mA}\cdot\text{cm}^{-2}$. The temperature difference increases significantly
346 with the increasing current density. The largest cell temperature difference barely
347 changes when the altitude varies from 0 m to 2000 m or 4000 m.





352 Fig. 6. Temperature distribution when current densities step changed at altitudes (a) 0m;

353 (b) 2000m; (c) 4000m; (d) cell temperature difference.

354 **3.3. Impact of air stoichiometric ratio**

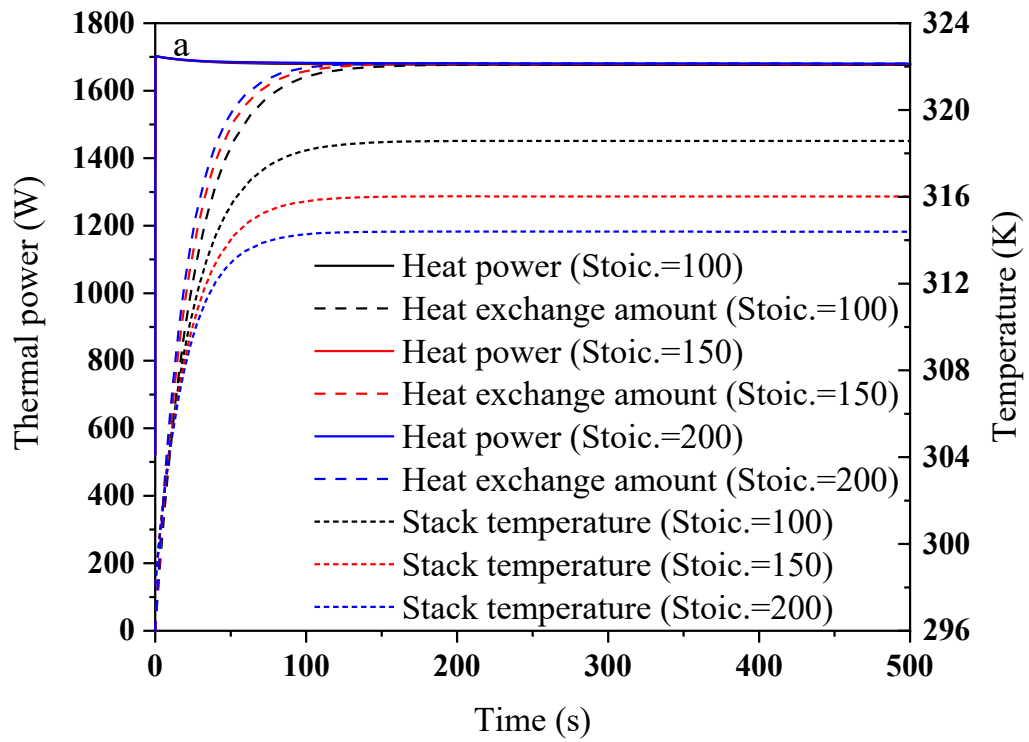
355 The altitude variations during the flight mission impact on the stack performance and
356 thermal management. For the air-cooled PEMFC stack, fan supplies cathode intake air,
357 meanwhile, the air flow removes waste heat to maintain thermal balance. The air flow
358 is used to ensure the sufficient reactant oxygen and for cooling purpose. The stack
359 power output and thermal power are both functions of the air stoichiometric ratio. It is
360 possible to regulate the air stoichiometric ratio for controlling stack power output and
361 operating temperature to compensate certain impact of the altitude variations.

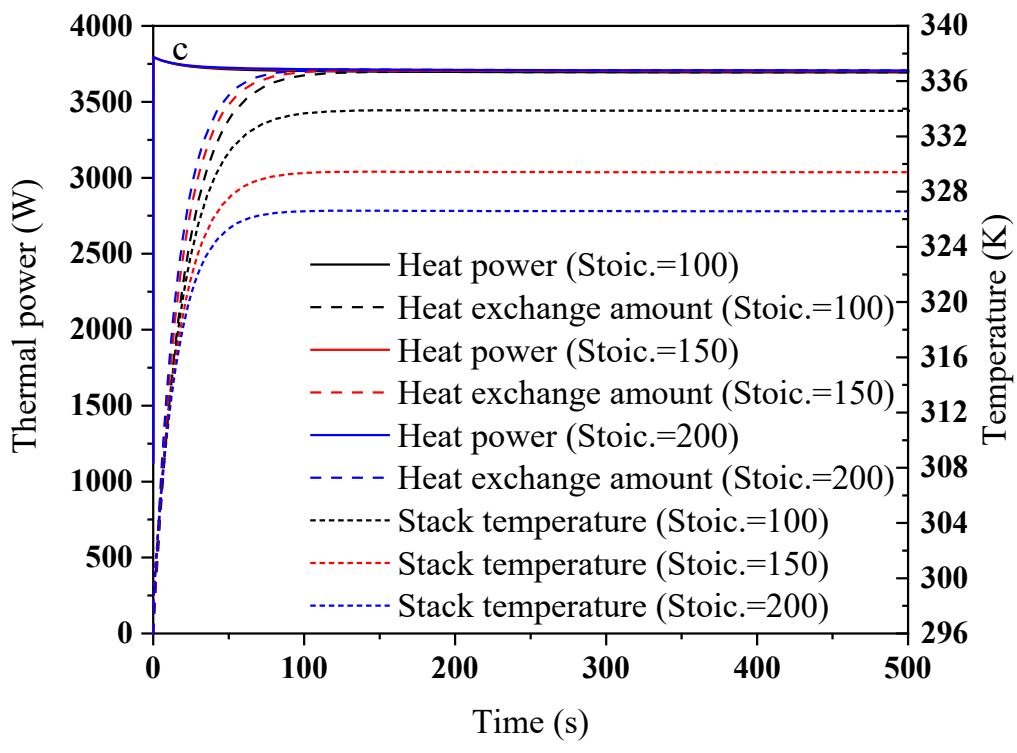
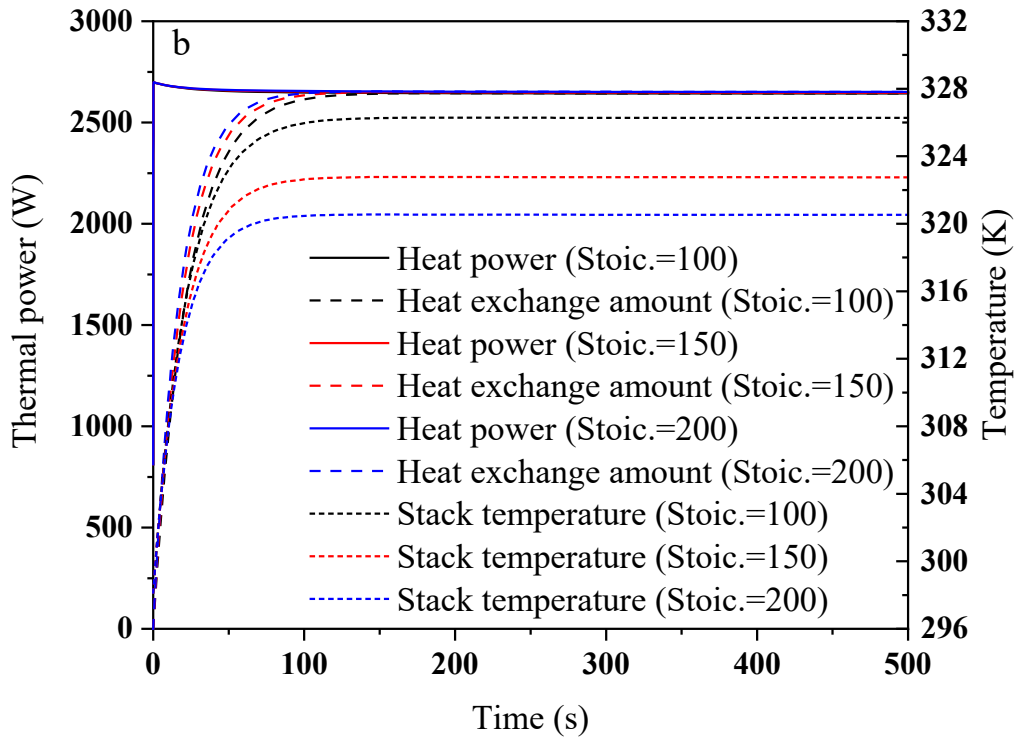
362 **3.3.1. Stack thermal power and temperature**

363 Fig. 7 (a), (b) and (c) present the impact of the air stoichiometric ratio variations (stoic.
364 = 100, 150 and 200) on heat power, heat exchange rate and stack temperature at three
365 different current density ($400 \text{ mA}\cdot\text{cm}^{-2}$, $600 \text{ mA}\cdot\text{cm}^{-2}$ and $800 \text{ mA}\cdot\text{cm}^{-2}$) and the
366 altitude of 0m. As shown in Fig. 7 (a), the current density is $400 \text{ mA}\cdot\text{cm}^{-2}$, thermal
367 power and heat exchange rate stay almost the same after 150s and the results stabilizes
368 to around 1670 W independent of the air stoichiometric ratio. The stack operating
369 temperature decreases from 318.6 K to 316.0 K and to 314.4 K when the air
370 stoichiometric ratio increases from 100 to 150 and to 200.

371 As shown in Fig. 7 (c), the stack temperature reached 333.9 K at the current density of
372 $800 \text{ mA}\cdot\text{cm}^{-2}$ and a stoichiometric ratio of 100. Comparing Fig. 7 (a), (b) and (c), at the
373 air stoichiometric ratio of 100, the thermal power increases from 1670 W to 2650 W
374 and to 3700 W, the stack temperature increases from 318.6 K to 326.3 K and to 333.9
375 K when the current density increases. Increasing the air stoichiometric ratio barely

376 affects the stack thermal power, but help decreasing the stack temperature.



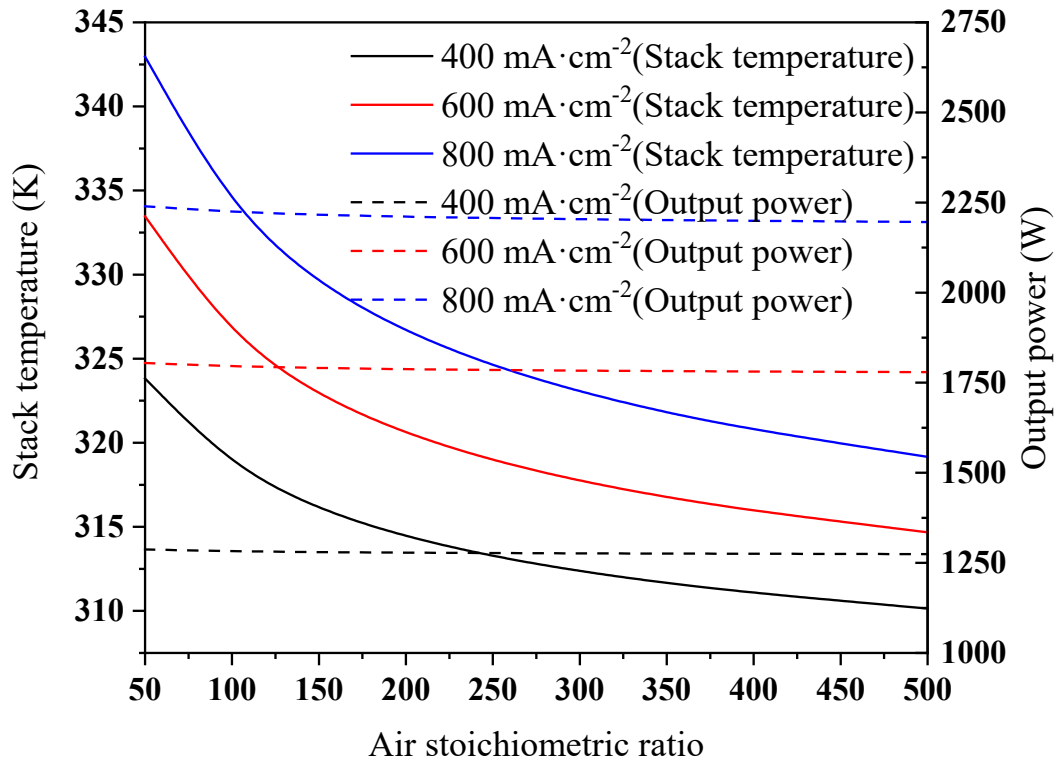


380 Fig. 7. Thermal power and stack temperature at altitude of 0 m and at various current

381 density (a) $400 \text{ mA}\cdot\text{cm}^{-2}$ (b) $600 \text{ mA}\cdot\text{cm}^{-2}$ (c) $800 \text{ mA}\cdot\text{cm}^{-2}$

382 **3.3.2. Stack power output and temperature**

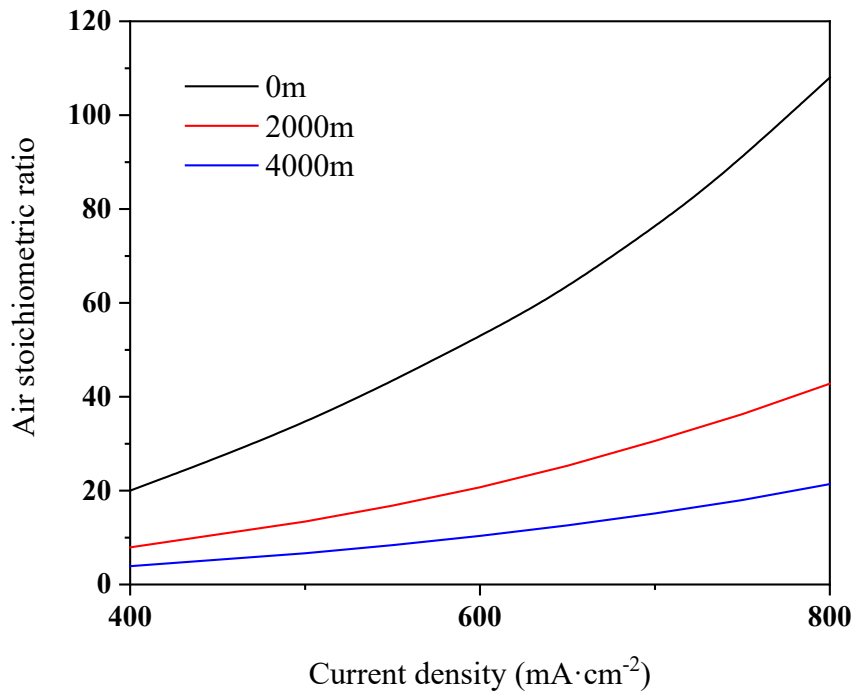
383 When the air stoichiometric ratio increases, Reynolds number, Nusselt number and
384 convective heat transfer coefficient increase which enhance the cooling heat transfer,
385 thus the stack temperature decreases. Fig. 8 presents the stack temperature and power
386 output at different current density when air stoichiometric ratio increases at the altitude
387 of 0m (298K). At current density $400 \text{ mA}\cdot\text{cm}^{-2}$, the effect of air stoichiometric ratio on
388 temperature reduction decreases as the ratio increases. The air stoichiometric ratio
389 variations mainly impact on stack temperature, barely impact on stack power output.
390 When the current density varies from $400 \text{ mA}\cdot\text{cm}^{-2}$ to $600 \text{ mA}\cdot\text{cm}^{-2}$ and to $800 \text{ mA}\cdot\text{cm}^{-2}$,
391 the stack power output increases from 1260 W to 1760 W and to 2180 W and the
392 stack temperature increases from 323.0 K to 342.2 K.



394 Fig. 8. Stack temperature and power output at different current density (400, 600 and
 395 $800 \text{ mA}\cdot\text{cm}^{-2}$)

396 3.3.3. Minimum air stoichiometric ratio

397 To avoid severe stack degradation, the maximum stack operating temperature is set as
 398 333 K. According to temperature limitation, the minimum required air stoichiometric
 399 ratio at the current density range of 400 to $800 \text{ mA}\cdot\text{cm}^{-2}$ and at different altitude has
 400 been shown in Fig. 9. If the air stoichiometric ratio stays constant, the maximum current
 401 density for operation at different altitudes can be found as well according to Fig. 9.



403 Fig. 9. Minimum required air stoichiometric ratio at different altitudes (0 m, 2000 m
 404 and 4000 m)

405 The minimum required air stoichiometric ratio at the current density of 400 mA·cm⁻² is
 406 20. When the current density is 800 mA·cm⁻², the air stoichiometric ratio should be at
 407 least 108. According to the Eq. (17), the ambient temperature decreases with the
 408 increasing altitude (Fig. 6(d)). More energy is converted into thermal energy at lower
 409 temperature under the same current density (Fig. 5(c)). In this turn, larger air
 410 stoichiometric ratio is needed to satisfy the stack cooling demand. However, the
 411 increase of heat exchange temperature difference caused by the lower ambient
 412 temperature makes a significant improvement of heat exchange capacity. Therefore, the
 413 minimal air stoichiometric ratio is lower at the higher altitude. At the same altitude of

414 0 m, when current density increases, more energy is converted into thermal energy at
415 high current density, a higher air stoichiometric ratio is needed to enhance the cooling
416 capacity. Therefore, minimum required air stoichiometric ratio is larger at high current
417 density.

418 When the altitude increases to 2000m, atmospheric temperature reduces by 12 K (°C)
419 for the studied case, which leads to the increase of temperature difference between the
420 PEMFC stack and the surrounding air, so a smaller air stoichiometric ratio will be
421 required. Fig. 9 shows that at the current density of $400 \text{ mA} \cdot \text{cm}^{-2}$, the minimum required
422 air stoichiometric ratio is 20 at the altitude of 0 m, this requirement decreases to 8 when
423 the altitude increases to 2000 m, it reduces to 4 when the altitude increases to 4000m.
424 At the current density of $800 \text{ mA} \cdot \text{cm}^{-2}$, the minimum required ratio decreases from 110
425 to 22 when the altitude increases to 4000m.

426 **4. Conclusions**

427 In this paper, a dynamic coupled electrochemical and thermal model for the air-cooled
428 PEMFC used in UAV is proposed. The impact of the metallic bipolar plate on the stack
429 thermal balance is considered; an environmental model estimating atmospheric
430 temperature and pressure variations with altitude is included. Influences of altitude
431 variations and air stoichiometric ratio on stack operational performance and thermal
432 management are studied. The main conclusions for this study are as follows:

433 a. With altitude increases from 0 to 4000 m, the output electric power decline is 4.7-
434 6.5% at the current density of 400-800 $\text{mA} \cdot \text{cm}^{-2}$. The power loss of the stack due to the

435 altitude increment is larger at the high current density regime. The stack voltage drop
436 is $0.25 \text{ V} \cdot \text{km}^{-1}$ ($5\text{E-}3\text{V} \cdot \text{km}^{-1}$ for cell voltage) when altitude increases.

437 b. At sea level, the stack operating temperature increases to 325K at the current density
438 of $800 \text{ mA} \cdot \text{cm}^{-2}$; it is more challenging for the stack thermal management. The
439 temperature difference of cells in the stack barely change when altitude varies from 0
440 to 4000 m, it stays 3.8K at current density of $800 \text{ mA} \cdot \text{cm}^{-2}$.

441 c. To avoid severe stack degradation due to high stack temperature, a minimum air
442 stoichiometric ratio is required for maintaining stack thermal balance. When the altitude
443 increases from 0 to 4000m, the minimum required air stoichiometric ratio decreases
444 from 110 to 22 at the current density of $800 \text{ mA} \cdot \text{cm}^{-2}$.

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575 **Nomenclature**

A	Area, cm ²
C	Thermal capacitance, J·K ⁻¹
E_{Nernst}	Nernst open circuit voltage, V
I	Current, A
k	Flow constant, mol·S ⁻¹ atm ⁻¹

m	Flow rate, mol·s ⁻¹
N	Number
P	Pressure, Pa
R	Circuit impedance, Ω
t	Time, s
T	Temperature, K
V	Volume, m ³
V _{cell}	Single cell voltage, V

Greek symbols

δ	Thickness, m
k	Thermal conductivity, W·m ⁻¹ K ⁻¹
v	Overall voltage drop, V
τ	Time constant

Subscripts

a	Anode
act	Activation
atmo	Atmospheric
c	Contact resistances

ca	Cathode
cl	Catalyst layer
con	Concentration
d	Voltage drop
gdl	Gas diffusion layer
$H_{2, in}$	Hydrogen inlet
$H_{2, out}$	Hydrogen outlet
$H_{2, used}$	Total hydrogen usage
M	Membrane
mbp	Metallic bipolar plate
ohmic	Ohmic impedance

576

577