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Original Article

Reliability and Sensitivity Analysis of Membrane Biofilm Fuel Cell

Syed Mohd Rizwan[1], Kajal Sachdeva[2], Noura Al Balushi[3], Shabib Al Rashdi[4], S. Z. Taj[5]

[1,3,4,5] *College of Engineering, National University of Science and Technology, Oman.*
[2]*Department of Mathematics, MD University, Rohtak, India.*

[1]*Corresponding Author : syedrizwan@nu.edu.om*

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Abstract - *Oilfield wastewater is recognized as a critical resource for reusing water and saving energy. Membrane Biofilm Fuel Cells (MBfFC) is an advanced technology with the extraordinary ability to use living organisms' metabolic reactions to produce organic energy into electrical energy. However, their reliability needs to be investigated and increased to integrate them into transportation systems. The same can be addressed through a robust case-specific mathematical model for analyzing the system performance. The present article analyses a single membrane biofilm fuel cell mainly composed of a proton exchange membrane, anode and cathode electrodes. Different system reliability indices and profit equations are investigated using Markov and the regeneration process. Sensitivity analysis of the availability and the profit function have also been carried out to understand the effects of changing parameters.*

Keywords - *Catalyst layers, Gas diffusion layers, Membrane biofilm fuel cells, Profit function, Reliability, Sensitivity analysis.*

1. Introduction

The Oilfield-generated water is the organic solvent component that is simultaneously produced with oil from a producing well during routine production processes. Industrial effluents, oilfield gases, saltiness, suspended particles, and pollutants are typically present in high concentrations in oilfield-generated water, which is primarily very salty water that occurs under high pressure and temperatures. Oman's oilfields generate more than 1 million cubic meters of oil daily. Due to the effluent's poor quality, most water is being released into wetlands. The catalytic processes of microorganisms turn the chemical energy in organic substances into electrical power. This mechanism has generated a great deal of interest among different researchers [1- 4].

The membrane biofilm fuel cell (MBfFC) is an efficient method for treating oilfield wastewater while simultaneously producing energy. It has been identified as a promising and demanding energy conservation and wastewater treatment technology, resolving environmental issues [5, 6]. The MBfFC include two glass cylinders and dead-end hollow fiber electrodes coated with noble Pt and graphene oxide. A glass bridge featuring a proton exchange membrane will connect the cylinders. Figure 1 shows the specific parts and design of the membrane biofilm fuel cell (MBfFC). Voltage, current, and resistance measurements can all be made using the multimeter. Both electrodes are wired with copper to a multimeter and an external direct current source. It mainly comprises a membrane, catalyst layers (anode and cathode electrodes) and gas diffusion layers (anode and cathode electrodes)[7, 8]. These layers are the most critical elements of the cell. The bacteria on the anode break down organic material and release electrons and H+ ions. These substrates allow the bacteria to produce electrons, which are afterwards moved from the anode to the cathode by a substance containing a resistor, generating electric energy to power a device [9]. The semi-permeable membrane allows the H+ ions to pass through to the cathode. This process is driven by the electrical potential close to the anode. Pure water is created when oxygen is combined with electrons from the cathode. [10, 11]. Fowler et al. [12] examined the modes of failure and improvements in fuel cell stack reliability. Fuel cells are susceptible to several different problems.

Due to its structure and functions, the membrane is the essential component. Its failure mechanisms fall into three categories: mechanical (inhibit the production and crack growth), thermal (clean out and skin patch), and chemical degradation [8]. Balushi et al. [41] developed a noble fouling-resistant membrane. The second most crucial element is the catalyst layers. They are made up of cathode and anode electrodes. A catalyst layer-covered carbon support is visible on the cathode side, where the oxygen reduction is visible. Carbon monoxide (CO) poisoning primarily causes anode-side degradation. On the catalyst particle surfaces, CO accumulates fast. As a result, sites for hydrogen adsorption and subsequent oxidation are no longer accessible. Gas

Diffusion Layers connect bipolar plates and catalyst layers. They are often constructed from fabric or carbon paper. The corrosion of the carbon paper directly impacts the cell's lifespan since it supports the catalyst. To address such challenges and understand the impacts of degradations on the important components of the membrane biofilm fuel cell, the reliability analysis of MBfFC is of great importance. Thus, reliability is one of the critical issues that must be tackled before membrane biofilm fuel cells (MBfFC) can be successfully industrialized. Reduced reliability entails higher maintenance costs and a greater reliance on overpriced electrical energy backup resources. It is related to operational and safety concerns as well. Adopting new technology, such as fuel cells, could become unappealing due to these reasons. Therefore, fuel cell reliability needs to be established and proven. Sensitivity analysis [42] will further be a value addition for determining whether a parameter significantly impacts the derived measures.

Researchers have focused on the reliability aspects of industrial systems in the past where the continuous casting plant [15-19], the desalination plant [20, 21, 25, 28], the PLC system along with other industrial systems [22, 23, 24], the wastewater treatment plant [26, 27], desalinated water pumping station system [29], the rodding anode plant of an aluminuim industry [30-34] and the cable manufacturing plant [35-40] have been analysed under different operating and the failure conditions. Therefore, the reliability analysis of technological systems is an essential requirement to assess the overall system performance to align effective maintenance practices and avoid frequent failures.

However, the reliability analysis of MBfFC is yet to be investigated. Thus, the current research focuses on estimating the performance degradation of MBfFC components. This article examines the reliability of a single membrane biofilm fuel cell (MBfFC), and detailed sensitivity analysis has been carried out. The article is structured as follows:

Section 2 outlines the assumptions and description of the system. Section 3 includes the system states, probabilities, and mean stay times. In Sections 5-7, various system effectiveness metrics, such as MTSF, system availability, busy period, and the number of replacements, have been assessed to determine the system's profitability. Measures are evaluated in Section 8 by assuming specific values of parameters. Section 9 performs the sensitivity analysis of the profit function and availability. Finally, Section 10 provides some insightful findings.

2. Assumptions and System Description

The assumptions and descriptions employed in the analysis of the system under consideration are as follows:

1. A single-unit Membrane Biofilm Fuel Cell (MBfFC) is considered. It mainly comprises a proton exchange membrane, anode and cathode electrodes.
2. The repairman examines the cell to determine which component of the MBfFC has degraded. As a result, failure is identified.
3. The MBfFC may deteriorate due to the degradation of the membrane, catalyst, or gas diffusion layer.
4. The membrane may deteriorate due to mechanical, thermal, or chemical failure.
5. The degradation of the catalyst or gas diffusion layers may occur on the cathode or anode side.
6. If the MBfFC fails, the only option is to replace it.
7. All the transition time distributions have been taken in general.

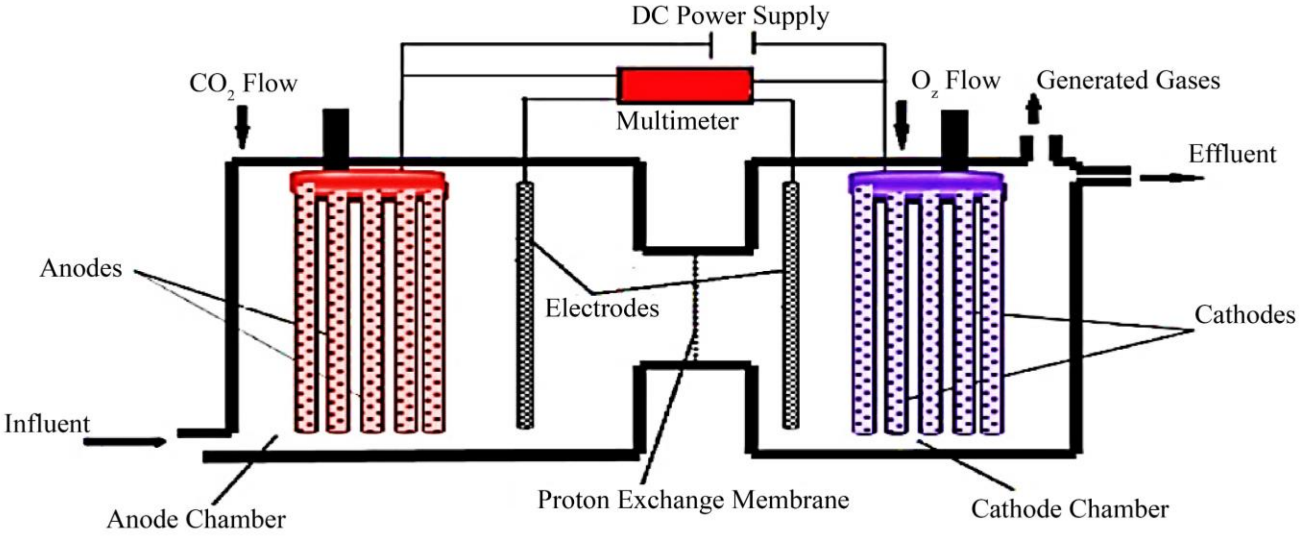

Fig. 1 Membrane Biofilm Fuel Cell (MBfFC)

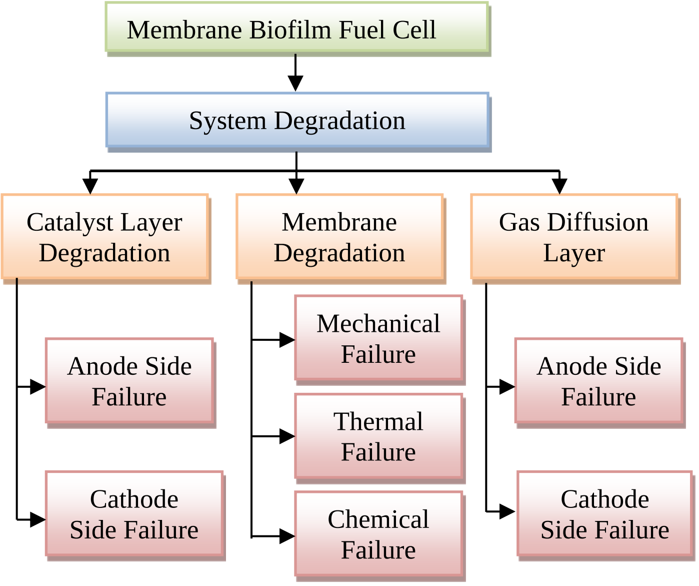

Fig. 2 System Failure Description

3. Nomenclature

The following are the notations used in the modelling

MBfFC: Membrane Biofilm Fuel Cell

$d_c(t)$: probability density function of MBfFC degradation

$i_c(t)$: probability density function of inspection time to detect the cause of MBfFC degradation

$g_k(t)$: probability density function of MBfFC degradation time due to some fault in layer 'k=cl/m/gl'.

$h_k(t)$: probability density function of MBfFC replacement time due to layer 'k'.

p_k: the probability of MBfFC degradation due to some fault in layer 'k'.

$p_{cla}(p_{gla})/p_{clc}(p_{glc})$: probability of MBfFC failure due to failure detection in the anode/cathode side of the catalyst layer (gas diffusion layer).

$p_{mm}/p_{mt}/p_{mc}$: the probability of MBfFC failure due to membrane mechanical/thermal/chemical failure.

$A_i^c(t)$: the probability of MBfFC in upstate at time t, given that it is in state i at $t = 0$.

$B_i^c(t)$: the probability that the repairman is busy for inspection at time t, given that it is in state i at $t = 0$.

$B_i^k(t)$: the probability that the repairman is busy for failure detection in layer 'k' of MBfFC at time t, given that it is in state i at $t = 0$.

$R_i^k(t)$: expected number of replacements of MBfFC due to failure in layer 'k' up to time t, given that it is in state i at $t = 0$.

Here, k = catalyst layer (cl), membrane (m), gas diffusion layer (gl).

4. System Modelling

The description of the states of the system are:

State 0 (OFC) : Operative Fuel Cell (MBfFC)
State 1 (D_i) : Degraded cell under inspection
State 2 (CL_d) : Catalyst layer degradation
State 3 (M_d) : Membrane degradation
State 4 (GL_d) : Gas diffusion layer degradation
State 5 (F_{cla}) : Anode side failure in the catalyst layer
State 6 (F_{clc}) : Cathode side failure in the catalyst layer
State 7 (F_{mm}) : Mechanical failure of membrane
State 8 (F_{mt}) : Thermal failure of membrane
State 9 (F_{mc}) : Chemical failure of membrane
State 10 (F_{gla}) : Anode side failure in the gas diffusion layer
State 11 (F_{glc}) : Cathode side failure in the gas diffusion layer

The transition between various system states is shown in Figure 3. The operative state spaces are O= {0}, the degraded state spaces are D= {1, 2, 3, 4}, and the failed state spaces are F= {5, 6, 7, 8, 9, 10, 11}. The state space comprises regenerative states, S= {0, 1, 2, ..., 11}.

4.1. Transition Densities

The transition densities $q_{ij}(t)$ are:

$$q_{01}(t) = d_c(t)$$
$$q_{12}(t) = p_{cl} i_c(t)$$
$$q_{13}(t) = p_m i_c(t)$$
$$q_{14}(t) = p_{gl} i_c(t)$$
$$q_{25}(t) = p_{cla} g_{cl}(t)$$
$$q_{26}(t) = p_{clc} g_{cl}(t)$$
$$q_{37}(t) = p_{mm} g_m(t)$$
$$q_{38}(t) = p_{mt} g_m(t)$$
$$q_{39}(t) = p_{mc} g_m(t)$$
$$q_{4,10}(t) = p_{gla} g_{gl}(t)$$
$$q_{4,11}(t) = p_{glc} g_{gl}(t)$$
$$q_{50}(t) = h_{cl}(t)$$
$$q_{60}(t) = h_{cl}(t)$$
$$q_{70}(t) = h_m(t)$$
$$q_{80}(t) = h_m(t)$$
$$q_{90}(t) = h_m(t)$$
$$q_{10,0}(t) = h_{gl}(t)$$
$$q_{11,0}(t) = h_{gl}(t) \quad (1\text{-}18)$$

The probability

$p_{ij} = \lim_{s\to 0} q_{ij^*}(s)$ can be evaluated.

4.2. Mean Sojourn Time

Using the definition of mean sojourn time (μ_i), i.e., stay time in state i, we get:

$$\mu_0 = \int_0^\infty t\, d_c(t)dt, \qquad \mu_1 = \int_0^\infty t\, i_c(t)dt,$$
$$\mu_2 = \int_0^\infty t\, g_{cl}(t)dt, \qquad \mu_3 = \int_0^\infty t\, g_m(t)dt,$$

$$\mu_4 = \int_0^\infty t\, g_{gl}(t)dt, \qquad \mu_5 = \int_0^\infty t\, h_{cl}(t)dt,$$
$$\mu_6 = \int_0^\infty t\, h_{cl}(t)dt, \qquad \mu_7 = \int_0^\infty t\, h_m(t)dt,$$
$$\mu_8 = \int_0^\infty t\, h_m(t)dt, \qquad \mu_9 = \int_0^\infty t\, h_m(t)dt,$$
$$\mu_{10} = \int_0^\infty t\, h_{gl}(t)dt, \qquad \mu_{11} = \int_0^\infty t\, h_{gl}(t)dt$$

Defining $m_{ij}=\int_0^\infty t\, q_{ij}(t)dt$, impact to mean sojourn time, given as:

$$m_{01} = \mu_0, \qquad m_{12} + m_{13} + m_{14} = \mu_1,$$
$$m_{25} + m_{26} = \mu_2, \qquad m_{37} + m_{38} + m_{39} = \mu_3,$$
$$m_{4,10} + m_{4,11} = \mu_4, \qquad m_{50} = \mu_5, m_{60} = \mu_6$$
$$m_{70} = \mu_7, \qquad m_{80} = \mu_8, m_{90} = \mu_9,$$
$$m_{10,0} = \mu_{10}, \qquad m_{11,0} = \mu_{11}.$$

Several system profitability metrics are established in the following sections.

4.2.1. Availability of MBfFC

We have the following recurrence relations based on the definition of Aci(t) (given in Section 3) and the transitions that occur throughout the period.

$$A_0^c(t) = M_0(t) + q_{01}(t)\copyright A_1^c(t)$$
$$A_1^c(t) = q_{12}(t)\copyright A_2^c(t) + q_{13}(t)\copyright A_3^c(t) + q_{14}(t)\copyright A_4^c(t)$$
$$A_2^c(t) = q_{25}(t)\copyright A_5^c(t) + q_{26}(t)\copyright A_6^c(t)$$
$$A_3^c(t) = q_{37}(t)\copyright A_7^c(t) + q_{38}(t)\copyright A_8^c(t) + q_{39}(t)\copyright A_9^c(t)$$
$$A_4^c(t) = q_{4,10}(t)\copyright A_{10}^c(t) + q_{4,11}(t)\copyright A_{11}^c(t)$$
$$A_5^c(t) = q_{50}(t)\copyright A_0^c(t)$$
$$A_6^c(t) = q_{60}(t)\copyright A_0^c(t)$$
$$A_7^c(t) = q_{70}(t)\copyright A_0^c(t)$$
$$A_8^c(t) = q_{80}(t)\copyright A_0^c(t)$$
$$A_9^c(t) = q_{90}(t)\copyright A_0^c(t)$$
$$A_{10}^c(t) = q_{10,0}(t)\copyright A_0^c(t)$$
$$A_{11}^c(t) = q_{11,0}(t)\copyright A_0^c(t)$$

(19-30)

Applying Laplace Transformation on the above equations and solving for $A_0^{c*}(s)$, we get

$$A_0^{c*}(s) = \frac{N_1^*(s)}{D_1^*(s)} \qquad (31)$$

The system's steady state availability is:

$$A_0^c = \lim_{s\to 0} s\, A_0^{c*}(s) = \frac{N_1^*(0)}{D_1^{*\prime}(0)} = \frac{N_1^c}{D_1^c}$$

where,

$N_1^c = \mu_0$;

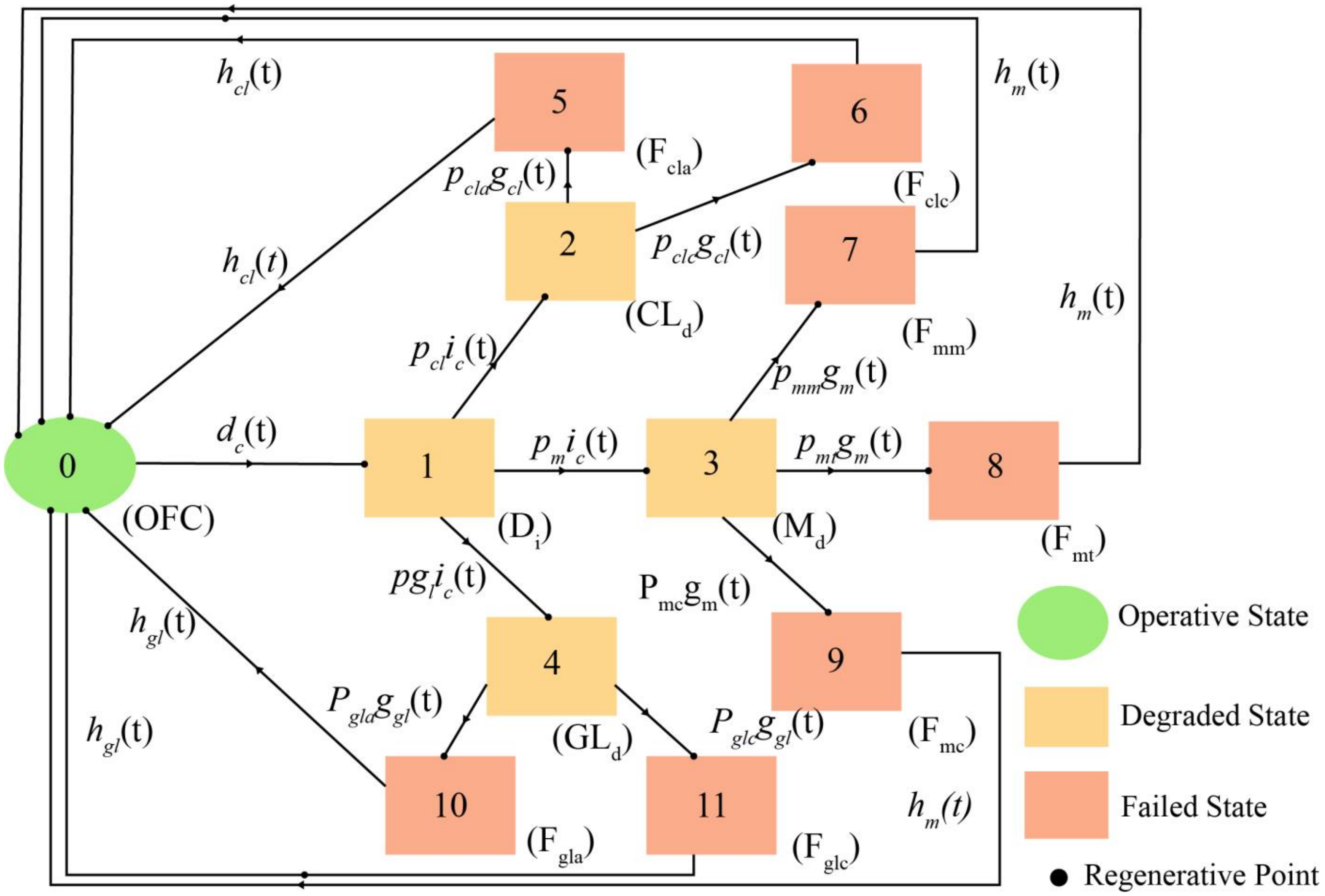

Fig. 3 State Transition Diagram

$$D_1^c = \mu_0 + \mu_1 + p_{cl}\mu_2 + p_m\mu_3 + p_{gl}\mu_4 + p_{cl}p_{cla}\mu_5 + p_{cl}p_{clc}\mu_6 + p_m p_{mm}\mu_7 + p_m p_{mt}\mu_8 + p_m p_{mc}\mu_9 + p_{gl}p_{gla}\mu_{10} + p_{gl}p_{glc}\mu_{11} \quad (32)$$

4.2.2. Expected Fraction of Busy Period and Number of Replacements of MBfFC

Using the definitions of B_0^c, B_0^{cl}, B_0^m and B_0^{gl} (specified in section 3) and the similar steps mentioned in the preceding section, the estimated time a repairman spends examining or identifying a fault in MBfFC is as follows:

$$B_0^c = \frac{N_2^c}{D_1^c}$$

$$B_0^{cl} = \frac{N_3^c}{D_1^c}$$

$$B_0^m = \frac{N_4^c}{D_1^c}$$

$$B_0^{gl} = \frac{N_5^c}{D_1^c} (33\text{-}35)$$

where,

$$N_2^c = \mu_1$$

$$N_3^c = p_{cl}\mu_2$$

$$N_4^c = p_m\mu_3$$

$$N_5^c = p_{gl}\mu_4 (36\text{-}39)$$

Furthermore, based on the definitions of R_0^{cl}, R_0^m and R_0^{gl} (described in section 3), the expected number of replacements of MBfFC in steady-state are:

$$R_0^{cl} = \frac{N_6^c}{D_1^c}$$

$$R_0^m = \frac{N_7^c}{D_1^c}$$

$$R_0^{gl} = \frac{N_8^c}{D_1^c} (40\text{-}42)$$

where,

$$N_6^c = p_{cl}$$

$$N_7^c = p_m$$

$$N_8^c = p_{gl} (43\text{-}45)$$

D_1^c is the same as mentioned earlier in Section 5.

4.2.3. Profit Analysis

A profit function is a mathematical relationship between a system's entire output and the total expenditure. In steady-state, profit functions are as follows:

$$P^c = R_c A_0^c - C_1 B_0^c - C_2 B_0^{cl} - C_3 B_0^m - C_4 B_0^{gl} - C_5 R_0^{cl} - C_6 R_0^m - C_7 R_0^{gl} (46)$$

where,

R_c = Revenue generated by the system

C_1= Cost per unit up time for which the repairman is busy for inspection.

$C_2/C_3/C_4$= Cost per unit up time for which repairman is busy for failure detection in catalyst layer/ membrane/ gas diffusion layer.

$C_5/C_6/C_7$= Cost per replacement of MBfFC due to failure in catalyst layer/ membrane/ gas diffusion layer.

5. Results and Discussion

This section provides numerical illustrations of the system characteristics determined in sections 5-7. Assume all distributions have exponential distributions and the following probability density functions:

$$d_c(t) = \lambda_0 e^{-\lambda_0 t},\ i_c(t) = \gamma_0 e^{-\gamma_0 t},\ g_{cl}(t) = \alpha_{cl} e^{-\alpha_{cl} t}$$
$$g_m(t) = \alpha_m e^{-\alpha_m t},\ g_{gl}(t) = \alpha_{gl} e^{-\alpha_{gl} t},\ h_{cl}(t) = \beta_{cl} e^{-\beta_{cl} t},$$
$$h_m(t) = \beta_m e^{-\beta_m t},\ h_{gl}(t) = \beta_{gl} e^{-\beta_{gl} t} \quad (47)$$

Let us assume particular values of parameters as:

$$\begin{array}{lll}
\lambda_0 = 0.000015, & \gamma_0 = 1.5, & \alpha_{cl} = 0.001, \\
\alpha_m = 0.04, & \alpha_{gl} = 0.025, & \beta_{cl} = 0.0024, \\
\beta_m = 0.002, & \beta_{gl} = 0.0025, & p_{cl} = 0.3, \\
p_m = 0.5, & p_{gl} = 0.2, & p_{cl} = 0.3,\ p_m = 0.5 \\
p_{gl} = 0.2, & p_{cla} = 0.4, & p_{clc} = 0.6,\ p_{mm} = 0.3, \\
p_{mt} = 0.4, & p_{mc} = 0.3, & p_{gla} = 0.4,\ p_{glc} = 0.6, \\
R_c = 1000, & C_1 = 200, & C_2 = 150,\ C_3 = 175, \\
C_4 = 130, & C_5 = 40000, & C_6 = 40000, \\
C_7 = 40000 & & (48)
\end{array}$$

Using these fixed values of parameters, we get the values of system effectiveness measures as

A_0^c = 0.9885,
B_0^c = 9.8849× 10-6,
B_0^{cl} = 0.0044,
B_0^m = 1.8534×10-4,
B_0^{gl} = 1.1862×10-4,
R_0^{cl} = 4.4482× 10-6,
R_0^m = 7.4137× 10-6,
R_0^{gl} = 2.9655× 10-6. (49-56)

Figure 4 depicts the impact of failure rate on fuel cell availability. It has been observed that availability declines as fuel cell failure rates increase.

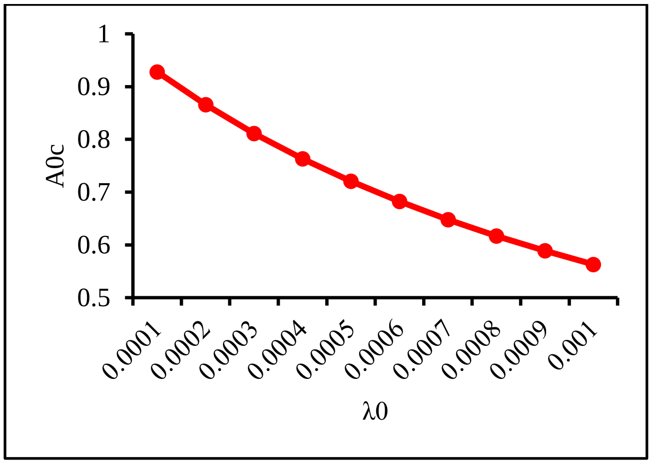

Fig. 4 Change in availability (A_0^c) w.r.t. failure rate (λ_0)

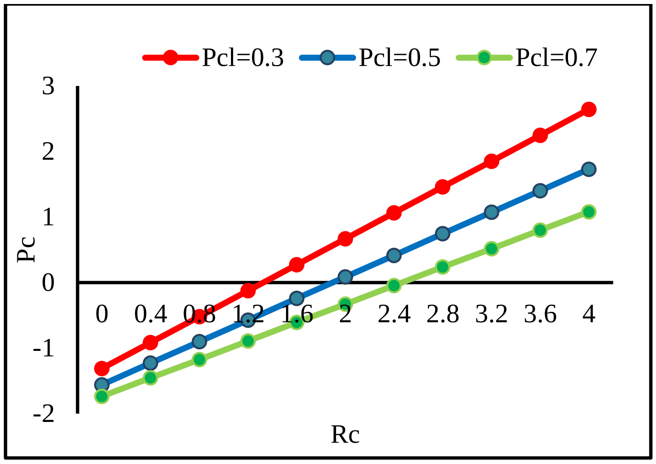

Fig. 5 Change in profit (Pc) w.r.t.revenue (Rc) for different values of p_{cl}

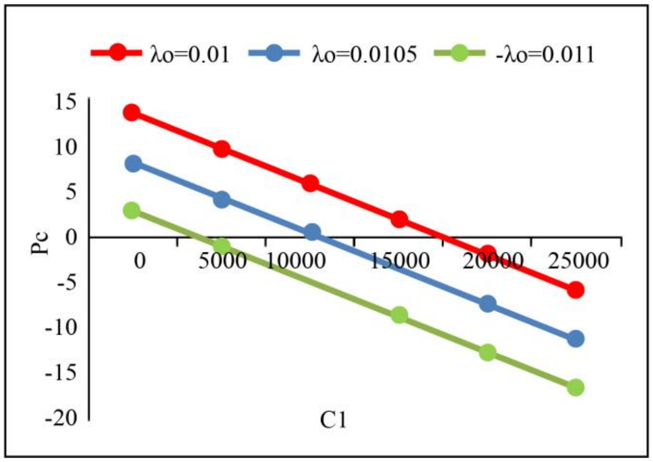

Fig. 6 Change in profit (P^c) w.r.t. C_1 for different value of failure rate (λ_0)

Figure 5 shows the impact of revenue generated and the probability of MBfFC degradation due to some fault in the catalyst layer on profit function. As the p_{cl} decreases, profit increases with an increase in revenue. Also, the revenue cutoff points with a fixed value of p_{cl} for system profitability are interpreted from Figure 3.

- If Rc> 1.367 and $p_{cl} = 0.3$, Pc > 0.
- If Rc> 1.842 and $p_{cl} = 0.5$, Pc > 0.
- If Rc>2.493 and $p_{cl} = 0.7$, Pc > 0.

Figure 6 shows the impact of failure rate and cost C_1 on profit function. As the C_1 and $\lambda_0$decreases, profit increases. As figure 3 reveals the cutoff points for system profitability, here from Figure 4, we get the cutoff point of C_1 as

- If C_1<1.759and $\lambda_0 = 0.01$, Pc > 0.
- If C_1< 1.195 and $\lambda_0 = 0.0105$, Pc > 0.
- If C_1<0.384 and $\lambda_0 = 0.011$, Pc > 0.

Other rates and cost effects on profit function can be analyzed similarly.

5.1. Sensitivity Analysis

Sensitivity analysis is a method for determining whether a parameter significantly impacts the derived measurements. Relative sensitivity analysis is carried out to differentiate the impacts of varied parameters due to the extensive range of numerical values for various parameters. A normalized variant of a sensitivity function is a relative sensitivity function.

The relative sensitivity analysis of availability and profit function for different parameters is shown in Table 1 and Table 2, respectively.

Table 1. Sensitivity Analysis of Availability w.r.t. Different Rates

Parameter k	**Sensitivity Analysis** $\delta_k^c = \frac{\partial(A_0^c)}{\partial k}$	**Relative Sensitivity Analysis** $\Delta_k^c = \delta_k^c \frac{k}{A_0^c}$
λ_0	-758.4044	-0.0115
α_{cl}	4.3970	0.0044
α_m	0.0046	1.8614×10^{-4}
α_{gl}	0.0047	1.1887×10^{-4}
β_{cl}	0.7634	0.0019
β_m	1.8321	0.0037
β_{gl}	0.4690	0.0012

It is observed that the availability and profit are most affected by failure rate and revenue compared to any other parameter, respectively.

Furthermore, the order in which input variables affect availabilities (A_0^c) and profit functions (P^c) are

Table 2. Sensitivity Analysis of Profit Function w.r.t. Different Rates/Costs

Parameter k	**Sensitivity Analysis** $d_k^c = \frac{\partial(P^c)}{\partial k}$	**Relative Sensitivity Analysis** $D_k^c = d_k^c \frac{k}{Pc}$
λ_0	-8.4474×10^5	-0.0128
α_{cl}	5.0584×10^3	0.0051
α_m	5.3850	2.1820×10^{-4}
α_{gl}	5.3008	1.3424×10^{-4}
β_{cl}	762.3596	0.0019
β_m	1.8297×10^3	0.0037
β_{gl}	468.3938	0.0012
R_c	0.9885	1.0013
C_1	-9.8849×10^{-6}	-2.0027×10^{-6}
C_2	-0.0044	-6.6857×10^{-4}
C_3	-1.8534×10^{-4}	-3.2856×10^{-5}
C_4	-1.1862×10^{-4}	-1.5621×10^{-5}
C_5	-4.4482×10^{-6}	-1.8024×10^{-4}
C_6	-7.4137×10^{-6}	-3.0040×10^{-4}
C_7	-2.9655×10^{-6}	-1.2016×10^{-4}

Availability (A_0^c):

$$\lambda_0, \alpha_{cl}, \beta_m, \beta_{cl}, \beta_{gl}, \alpha_m, \alpha_{gl}$$

Profit Function (P^c):

$$R_c, \lambda_0, \alpha_{cl}, \beta_m, \beta_{cl}, \beta_{gl}, C_2, C_6, \alpha_m, C_5, \alpha_{gl}, C_7, C_3, C_4, C_1$$

6. Conclusion

A single membrane biofilm fuel cell that consists of a proton exchange membrane, anode and cathode electrodes has been studied in this paper. Various system performance measures and profit functions are examined. It has been observed that as fuel cell failure rates rise, availability and profit both decline. Sensitivity analysis shows that the profit and the system availability are more sensitive to revenue generated and the failure rate, respectively, compared to other parameters. Future research will validate the proposed model using real-time data once the membrane biofilm fuel cells are operationally industrialized.

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