

Article

Effect of Vibration on Open-Cathode Direct Methanol Fuel Cell Stack Performance

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Abstract

This study investigates the impact of vibration frequency on the performance of a 10-cell open-cathode direct methanol fuel cell (OC-DMFC) stack. Experiments were conducted using three different vibration frequencies (15, 30, and 60 Hz) and compared against a baseline condition without vibration. Performance was evaluated under varying methanol–water fuel flow rates (1, 5, 25, and 50 mL·min^{−1}) while maintaining constant operating conditions: methanol temperature at 70 °C, methanol concentration at 1 M, and cathode air flow velocity at 4.8 m·s^{−1}. The optimal performance was observed at a fuel flow rate of 5 mL·min^{−1}, where the maximum power density reached 26.05 mW·cm^{−2} under 15 Hz vibration—representing a 14% increase compared to the non-vibrated condition. These findings demonstrate that low-frequency vibration can enhance fuel cell performance by improving mass transport characteristics.

Keywords: direct methanol fuel cell; open cathode; vibration-assisted enhancement; power density; stack performance



Academic Editor: José Solla Gullón

Received: 20 July 2025

Revised: 27 September 2025

Accepted: 4 October 2025

Published: 8 October 2025

Citation: Celik, S.; Atalmis Sari, G.; Yagiz, M.; Özcan, H.; Amini Horri, B. Effect of Vibration on Open-Cathode Direct Methanol Fuel Cell Stack Performance. *Physchem* **2025**, *5*, 44. <https://doi.org/10.3390/physchem5040044>

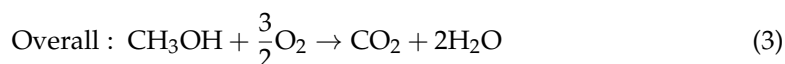
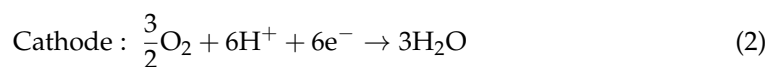
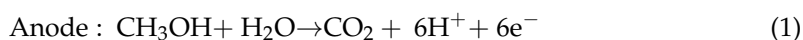
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1. Introduction

Fuel cells play a pivotal role in the transition to clean energy technologies [1–3]. Among them, direct methanol fuel cells (DMFCs) stand out due to their high fuel energy density, ease of liquid fuel storage, low operating temperature, minimal pollutant emissions, and compact system design. These advantages make DMFCs attractive for a wide range of applications, including portable electronics, automotive systems, and stationary power generation [4,5]. DMFCs operate similarly to proton exchange membrane fuel cells (PEMFCs), with the key distinction being the use of methanol as a direct fuel source rather than pure hydrogen. Methanol is electrochemically oxidized at the anode to produce hydrogen ions (protons), electrons, and carbon dioxide.

The protons migrate through a polymer electrolyte membrane (PEM) to the cathode, while the electrons travel through an external circuit, generating electrical power. At the cathode, the protons and electrons react with oxygen from ambient air to form water. This direct conversion of methanol to electricity eliminates the need for a separate hydrogen

production unit, enhancing system simplicity and portability. The overall electrochemical reactions in a DMFC can be summarized as follows [5,6]:



The operating temperature range for DMFC is between 50 and 120 °C. This low temperature range and the ease of storage of methanol make the direct methanol fuel cell advantageous in applications. Since DMFC does not require additional systems such as reformers/converters during its operation, it has a very small size and simple structure. In addition, the methanol it uses as fuel has a high volumetric hydrogen density, and its greatest advantage is that it can be stored. Due to these advantages, DMFC is more suitable for use in vehicle applications and portable electronic devices than other fuel cells [7–10]. Disadvantages include problems caused by carbon dioxide bubbles leaving the liquid fuel from the anode catalyst layer, low performance in terms of cell efficiency and power density, and the need for further development studies [11–14].

In the actual reaction, the complete conversion of carbon in the fuel to carbon dioxide cannot be achieved, resulting in the formation of carbon monoxide. Carbon monoxide is toxic in fuel cells. Currently, Pt is the best-performing catalyst for methanol oxidation. Pt can be poisoned and passivated by CO gas generated at the operating temperatures of fuel cells. In DMFC fuel cells, carbon monoxide generated in the fuel reformer must be converted to carbon dioxide. The CO₂ released here is intended to be removed from the active site by vibration. Furthermore, the catalysts used in methanol fuel cells can also be poisoned by byproducts or contaminants. Minimizing contamination and poisoning is crucial for long-life cells. The quality of materials used, such as membranes, electrodes, and catalysts, is also crucial for the cell's durability and longevity. However, for long-term operations, many structural (MEG, flow plates, etc.) and operational (temperature, methanol concentration, oxygen flow, methanol flow rate) parameters must be considered in DMFC fuel cells [13,14].

Scott and Shukla [15] highlighted key challenges faced by direct methanol fuel cells (DMFCs), emphasizing that the overall performance is highly dependent on the membrane electrode assembly (MEA) fabrication methods, materials, and operating conditions [16]. In recent years, the role of mechanical vibration in fuel cell systems has gained increased attention, particularly for applications in mobile and automotive platforms [17,18]. It has been observed that vibration can significantly influence the operational lifespan and efficiency of fuel cells. For instance, Tseng et al. [19] tested a PEMFC stack under vibration conditions simulating vehicular environments. During frequency sweeps between 30 and 150 Hz, they reported a 20% reduction in torque. However, pre- and post-vibration performance comparisons revealed only minimal changes, suggesting that the impact of vibration on fuel cell output requires deeper investigation.

Vibrational effects can influence liquid water behavior, methanol concentration gradients, and mass transport through the gas diffusion layer in DMFCs, thereby affecting cell performance [20]. This has led to a growing body of research on vibration–fuel cell interactions [21,22]. Emam et al. [22], for example, showed that low-frequency vibrations could enhance performance, but increasing the vibration frequency beyond a certain threshold reduced both peak power density and hydrogen utilization efficiency in PEMFCs. They also demonstrated that structural aspects of the fuel cell stack—such as the number and placement of bolts, layer thickness, and component interfaces—can significantly affect local

vibration modes. Even minor structural changes can alter dynamic responses, necessitating detailed modeling and analysis [23,24]. Direct methanol fuel cells (DMFCs), the most advanced fuel cells, offer significant advantages such as high fuel energy density, easy liquid fuel storage, low operating temperatures, low pollutant emissions, and simple system architecture. However, many unsolved technical challenges remain regarding the design, production, and operation of these fuel cell power systems [25]. Choroen et al. [26] they attempted to find the optimal conditions for direct methanol fuel cells and direct ethanol fuel cells to achieve maximum power density. They considered three independent variables: operating temperature in the range of 30–70 °C, flow rate in the range of 5–50 mL/min, and alcohol concentration in the range of 0.5–3 M. The response results revealed that higher operating temperatures and higher alcohol concentrations led to an increase in maximum power density for both direct methanol fuel cells (DMFH) and direct ethanol fuel cells (DEYH). In the work of Tong [27], bubble behavior was investigated through simulation using the phase field method. A contour plot of the bubble's separation diameter was generated. The forces acting on the bubble during separation were quantitatively analyzed. The flow of CO₂ bubbles in the anode flow channel is a key issue in the commercialization of direct methanol fuel cells (DMFCs). In their study, they observed that increasing the liquid flow rate results in the formation of smaller bubbles that rupture more quickly due to the increased frictional force (FD) and shear force (FSL) to overcome the surface tension on the bubble. The CO₂ inflow rate can promote bubble rupture due to the increase in FSL, but it also leads to a larger rupture diameter. When the ratio of gas momentum to liquid momentum is greater than 1, bubble separation becomes more difficult. In the work of Vasu et al. [28], a 3D model was developed in DMFCs and CO₂ bubble dynamics were investigated. Rapid CO₂ saturation regions and dynamic accumulation were identified in DMFCs. Their study investigated CO₂ bubble dynamics in the anode chamber of DMFCs. Significant bubble accumulation in the flow field channels was observed between 0.06 and 0.09 s. The designed DMFC demonstrated a peak power density of 12.6 mW·cm⁻², demonstrating effective CO₂ gas management and improved fuel utilization. Chi et al. [29], in their study, investigated the optimum operating methanol concentration for the direct methanol fuel cell (DMFC) system, which effectively increased the efficiency of the DMFC system. They found that the fuel consumption of the DMFC system was reduced by 7.9% and 30.9%, respectively, when compared with the optimum methanol concentration of 0.3 mol/L and the fixed methanol concentration of 0.4 mol/L.

In the current study, an open-cathode DMFC (OC-DMFC) 10-cell stack was evaluated under varying methanol–water solution flow rates (1, 5, 25, and 50 mL·min⁻¹) at a constant fuel temperature of 70 °C, ambient temperature of ~21 °C, 1 M methanol concentration, and cathode air flow rate of 4.8 m·s⁻¹ [30]. To identify the optimal operating point, performance tests were conducted at all four flow rates, with 5 mL·min⁻¹ yielding the highest peak power density. This condition was then used for further testing under three vibration frequencies (15, 30, and 60 Hz) to examine their effects on cell performance. The OC-DMFC stack was developed with mobility in mind, making vibration-induced effects highly relevant. It was hypothesized that vibration could enhance reactant diffusion across the membrane surface by disturbing flow patterns within the channels, especially at moderate fuel flow rates. Moderate vibration was found to improve methanol transport and reaction kinetics, whereas excessive vibration induced turbulence, which adversely affected power output. To validate this behavior, the impact of vibration frequency on power density was experimentally investigated. The results confirmed that vibrational effects can significantly alter performance, and under optimal conditions (15 Hz, 5 mL·min⁻¹ fuel rate), an increase in peak power density was observed compared to non-vibrated operation.

2. Materials and Methods

2.1. Design and Assembly of the OC-DMFC Stack

In this study, an open-cathode direct methanol fuel cell (OC-DMFC) stack was developed, comprising key components including a membrane electrode assembly (MEA), graphite bipolar plates (BPs), copper current collectors, aluminum support plates, and silicone gaskets for sealing (Figure 1a). Detailed specifications and dimensions of these components have been presented in a previous study [31]. The stack consists of 10 individual cells, each with an active area of 25 cm², totaling 250 cm². The flow fields were designed using a 3D solid modeling program and machined onto graphite bipolar plates. The methanol–water fuel mixture is distributed through a serpentine flow channel on the anode side, with both inlet and outlet aligned on the same edge of the MEA. For air supply to the cathode, 13 parallel channels were integrated on the same side of each bipolar plate and fed by a fan to ensure active air circulation. Nafion 115 membranes (Alfa Aesar® 45.364, Los Angeles, CA, USA) were used as the electrolyte material. A 0.45 mm thick aluminum sheet surrounding the active area was paired with a silicone gasket, compressed to a torque of 3 Nm to ensure sealing. Copper plates (2 mm thick) were laser-cut for current collection and subsequently gold-coated (Ted Pella Sputter Coater, Redding, CA, USA) to enhance corrosion resistance and conductivity. The entire stack was assembled with bolts and fasteners, as illustrated in Figure 1b.

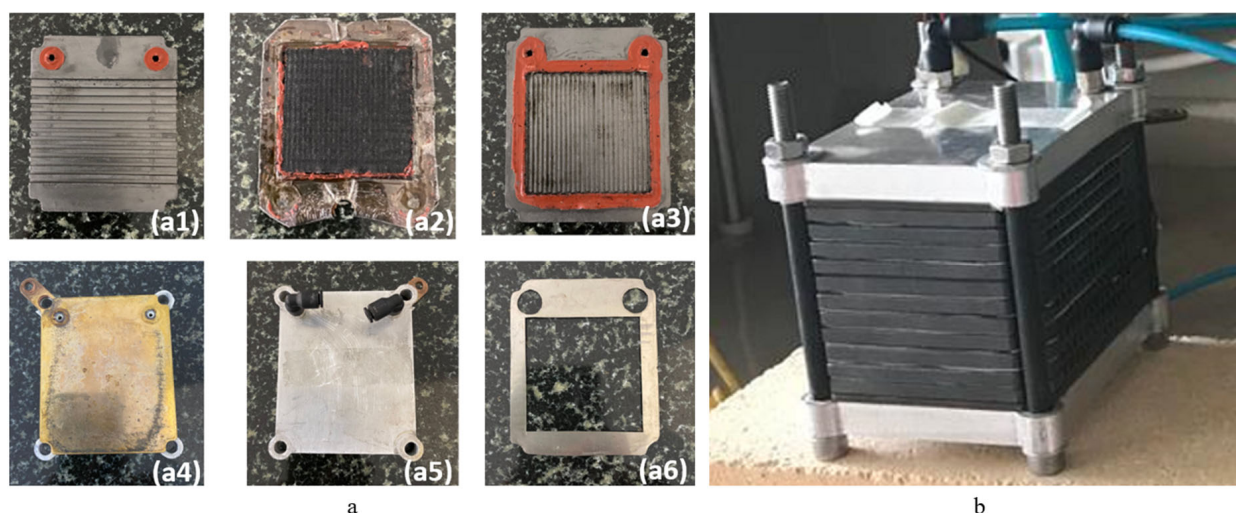


Figure 1. Components and Assembled Configuration of the OC-DMFC Stack: (a) Exploded view of stack components: (a1) Cathode-side bipolar plate with flow field, (a2) Membrane Electrode Assembly (MEA), (a3) Anode-side bipolar plate with flow field, (a4) Copper current collector plate, (a5) Compression plate, (a6) Metallic gasket; (b) Fully assembled OC-DMFC stack.

A semi-empirical model was developed to analyze the performance of the open-cathode direct methanol fuel cell (OC-DMFC) stack under varying vibration conditions. The model incorporates electrochemical kinetics, mass transport, and ohmic losses, with particular emphasis on the impact of vibration frequency on methanol transport and concentration dynamics. Other than the electrochemical reactions provided in Equations (1)–(3), the cell voltage is expressed as follows [5,6,14]:

$$V = E - \eta_{act} - \eta_{ohm} - \eta_{conc} \quad (4)$$

where E is the reversible cell voltage while η_{act} , η_{ohm} , η_{conc} are activation, ohmic and concentration overpotentials. Activation overpotential is modeled using the simplified Butler-Volmer equation as follows:

$$\eta_{act} = \frac{RT}{\alpha nF} \sinh^{-1} \left(\frac{i}{2i_0} \right) \quad (5)$$

Here, i is the current density, i_0 is the exchange current density, α is the charge transfer coefficient and n is the number of electrons transferred. Ohmic losses are also given as follows:

$$\eta_{ohm} = i \left(\frac{t_{mem}}{\sigma_{mem}} + \frac{t_{elec}}{\sigma_{elec}} \right) \quad (6)$$

where t and σ represent thickness and conductivity, while subscripts *mem* and the *elec* subscript correspond to membrane and electrolyte, respectively. Concentration losses are associated with the reference reactant concentration C_R^* and the actual concentration C_R :

$$\eta_{conc} = \frac{RT}{nF} \ln \frac{C_R^*}{C_R} \quad (7)$$

In order to incorporate the vibration effect, the local effective diffusion coefficient is modeled as a frequency-dependent function and the time-dependent methanol concentration at the anode is provided as follows:

$$D_{eff}(f) = D_0(1 + \beta \cdot \sin(2\pi ft)) \quad (8)$$

$$C_{CH_3OH}(x, t) = C_0 \cdot e^{-kx} \cdot (a + \gamma \cdot \sin(2\pi ft)) \quad (9)$$

where D_0 is baseline diffusion coefficient, β is an empirical vibration enhancement factor, f is the applied vibration frequency, γ is the fluctuation amplitude due to periodic vibration-induced convection. Based on these, an empirical model can be retrieved to describe the effect of vibration on performance with the experimental coefficients (α and δ):

$$P(f) = P_0 \cdot \left(1 + af \cdot e^{-\delta f} \right) \quad (10)$$

This equation captures the initial performance enhancement at moderate vibration levels, followed by degradation at higher frequencies due to possible turbulent flow or structural resonance effects.

2.2. Experimental Setup and Test Conditions

A schematic representation of the fixed experimental setup used for performance testing of the OC-DMFC stack is shown in Figure 2a, while the actual test bench and equipment are illustrated in Figure 2b. In this setup, a 1 M methanol–ultrapure water solution was prepared and stored in a 500 mL fuel tank. A peristaltic pump capable of delivering flow rates up to 100 mL·min^{−1} was employed to ensure continuous and controlled fuel delivery to the stack. This allowed for the uninterrupted circulation of methanol solution between the sealed tank and the fuel cell. An electronic flow meter was used to monitor and record real-time fuel flow rates. To maintain a stable fuel temperature, the tank was heated to 70 °C using a Heidolph MR Hei-Standard heater, Schwabach, Germany). Temperatures at the fuel inlet, outlet, and stack surface were recorded using thermocouples connected to a Pico TC-08 data acquisition system (Texas Instruments, Dallas, TX, USA). Cathode air was supplied via a fan, achieving an airflow velocity of 4.8 m·s^{−1}, as measured with a CEM 618 Thermo Anemometer, Dhaka, Bangladesh). The polarization curves and internal resistance measurements were obtained using a fuel cell (FC) test station provided by ElectroChem Inc., Union City, CA, USA, and recorded via computer software interfaced with the test equipment. The vibration effect, a key variable in this study, was controlled using a frequency-adjustable vibration generator (Daihan Scientific

VM-10, Wonju, Republic of Korea), allowing for precise tuning to 15, 30, and 60 Hz. The test stack in our case is around 1020 g and the amplitudes have been kept lower than 1 mm. The power consumption does not exceed 1 mW and for lower amplitudes it is below 0.39 mW. In the test case for the optimal conditions, the power consumption of the vibration device is around 0.16 mW. This has not been considered in the energy balance of the cell, since the optimal frequency condition provides a significant increase in power density.

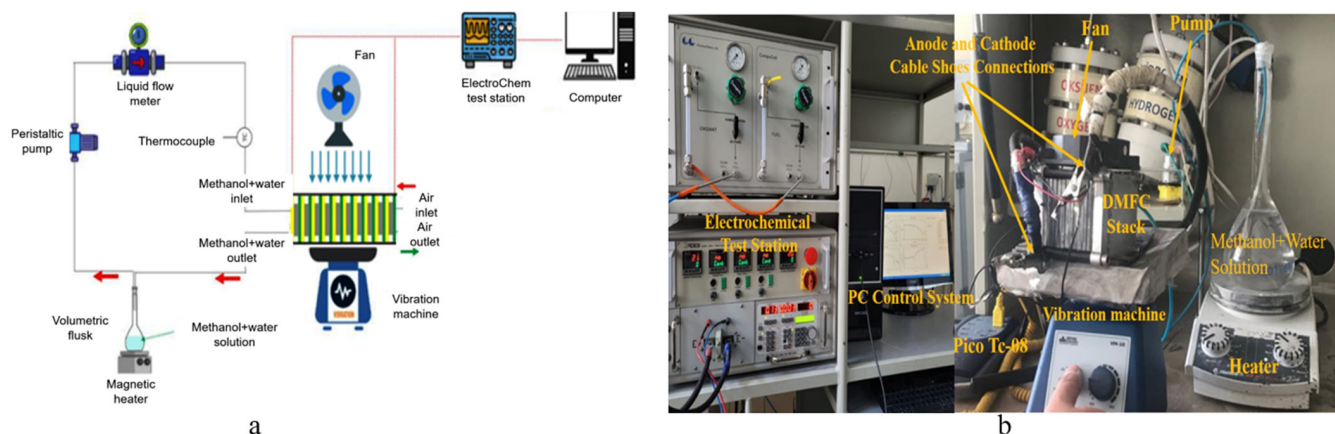


Figure 2. Experimental Setup for OC-DMFC Stack Testing: (a) Schematic diagram of the test system (Red arrows show the direction of the flow, green arrow shows the air exit); (b) Photograph of the assembled experimental setup.

The primary experimental parameters are listed in Table 1. Based on preliminary studies, the optimal operating conditions were established as follows: fuel temperature at 70 °C, ambient temperature ~21 °C, methanol concentration at 1 M, and cathode airflow rate of 4.8 m·s⁻¹. Performance tests were carried out at methanol solution flow rates of 1, 5, 25, and 50 mL·min⁻¹, under both vibrated and non-vibrated conditions. Prior to testing, the stack underwent an MEA activation process to ensure reliable operation. Deionized water at 70 °C was circulated through the system for approximately 15 min to fully hydrate the MEA. This was followed by the introduction of a 1 M methanol solution to the anode and ambient air to the cathode at respective flow rates of 1 mL·min⁻¹ and 4.8 m·s⁻¹, operated at a constant voltage of 3 volt (V) for 1 h. This procedure ensured that the MEA was fully conditioned and ready for consistent performance testing.

Table 1. Experimental Parameters Used in the Performance Testing of the OC-DMFC Stack.

Operational Parameters	Results
Methanol flow rate	1, 5, 25, 50 mL min ⁻¹
Vibration frequency	15, 30, and 60 Hz
Methanol fuel test temperature	70 °C
Methanol concentration	1 M
Air flow rate	2.4, 4.8, and 7.2 m/s
Air temperature	21 °C (Ambient air)
Vibration power	0.160–1 mW

The performance of the OC-DMFC stack was evaluated using the fixed experimental system illustrated in Figure 2b. This study aimed to determine the optimal operating parameters by systematically investigating the effects of methanol flow rate, vibration frequency, fuel temperature, methanol concentration, and airflow rate. Among these, the methanol flow rate and vibration frequency were the primary focus due to their significant influence on performance behavior. Vibration frequencies of 15, 30, and 60 Hz were ap-

plied individually to the stack at methanol solution flow rates of 1, 5, 25, and 50 mL·min⁻¹. These conditions were selected to simulate different fuel delivery regimes and assess the effect of mechanical vibration on mass transport and electrochemical reaction dynamics. Performance was evaluated under constant methanol solution temperature (70 °C), methanol concentration (1 M), and airflow velocity (4.8 m·s⁻¹) provided from ambient laboratory air (~21 °C). These operating parameters were held constant throughout the experiments unless otherwise specified, as summarized in Table 1. Each experimental condition was maintained for approximately 10 min to ensure steady-state operation and allow for consistent performance data collection. The vibration effect was investigated by comparing the stack behavior under vibrated and non-vibrated conditions at each methanol flow rate. In addition, time-resolved power density profiles were recorded under a constant electrical load of 2 V over a period of 600 s to evaluate dynamic performance stability. These measurements provided further insight into the transient behavior of the stack and the influence of vibration under real operating conditions.

3. Results and Discussion

The influence of methanol solution flow rate on the batch performance of the OC-DMFC stack was investigated. Experiments were carried out with a horizontally aligned stack, fed with a 1 M methanol solution maintained at 70 °C, and an air flow rate of 4.8 m/s supplied by an integrated fan. The test conditions were selected based on preliminary parametric optimization studies yielding the highest power density. The variation in peak power density at four distinct flow rates (1, 5, 25, and 50 mL·min⁻¹) is presented in Figure 3a. At a flow rate of 1 mL·min⁻¹, the stack achieved a peak power density of 19.3 mW·cm⁻², which increased to 22.8 mW·cm⁻² when the flow rate was raised to 5 mL·min⁻¹, indicating a performance enhancement with a moderate increase in fuel supply. However, at higher flow rates of 25 mL·min⁻¹ and 50 mL·min⁻¹, the performance declined, with peak power densities dropping to 16.4 mW·cm⁻² and 11.9 mW·cm⁻², respectively. These observations suggest the existence of an optimal flow rate (5 mL·min⁻¹) beyond which further increases negatively impact performance.

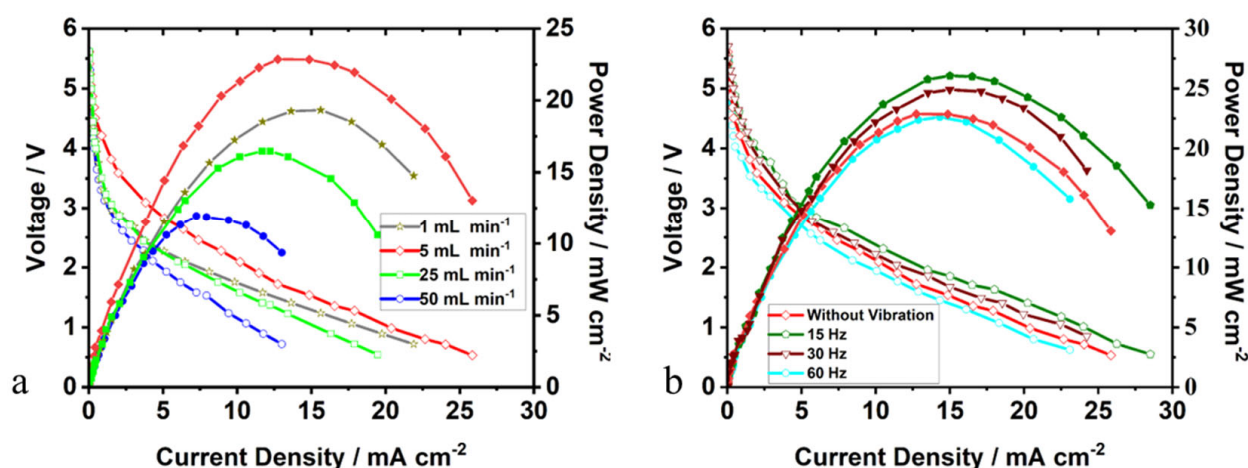


Figure 3. (a) Effect of methanol solution flow rate (1, 5, 25, and 50 mL·min⁻¹) on cell performance at 1 M methanol concentration and 70 °C fuel temperature, (b) Effect of vibration frequency (15, 30, and 60 Hz) on performance at 5 mL·min⁻¹ flow rate under identical operating conditions.

The anode side of the OC-DMFC was designed with a serpentine flow field, ensuring even distribution of methanol from the inlet to the outlet. This configuration aids in removing the CO₂ gas produced during methanol oxidation, especially under moderate flow conditions. At low flow rates (e.g., 1 mL·min⁻¹), the residence time of the methanol

solution in the flow field increases, leading to the formation of elongated CO₂ bubbles. These bubbles hinder mass transfer by reducing the contact area between the methanol and the gas diffusion layer [30–33], resulting in lower performance. Conversely, at excessively high flow rates (25 and 50 mL·min^{−1}), CO₂ is removed more rapidly, which might initially seem beneficial. However, the accompanying increase in convective heat loss from the stack reduces its thermal efficiency. Additionally, higher pressure gradients at the anode may cause methanol crossover to the cathode side through the membrane [34], further reducing the cell's efficiency. In summary, both insufficient and excessive fuel flow rates adversely affect stack performance. The optimal flow rate of 5 mL·min^{−1} represents a balance between fuel utilization, heat management, and gas bubble removal efficiency, leading to maximum power density.

To isolate the effect of vibration, all tests were conducted at a methanol concentration of 1 M, a solution temperature of 70 °C, and an air flow velocity of 6.4 m/s at the cathode. The stack performance at a flow rate of 5 mL·min^{−1}, where optimal behavior was previously observed, was used as a baseline for comparison. These results are presented in Figure 3b. Initially, the stack was stabilized in a fixed (non-vibrating) position for 10 min, after which a baseline performance measurement was recorded. Under these steady conditions, the peak power density was measured as 22.8 mW·cm^{−2}. Following this, the test setup was configured to introduce mechanical vibration at frequencies of 15, 30, and 60 Hz, sequentially. Between each vibration test, the system was allowed to stabilize for 10 min. The results show that stack performance can change positively depending on the vibration effect, as demonstrated by increasing power density values. The peak power densities obtained under vibration were 26.0 mW·cm^{−2} at 15 Hz, 24.8 mW·cm^{−2} at 30 Hz and 22.6 mW·cm^{−2} at 60 Hz.

These findings indicate that low-frequency vibration (15 Hz) enhances both the power density and overall stack efficiency. Specifically, the ~14% improvement at 15 Hz over the non-vibrating case is attributed to enhanced mass transport and more effective water management. At low vibration levels, it is thought to reduce catalyst surface blockage by facilitating the removal of excess water from the cathode surface and allowing CO₂ bubbles trapped on the anode side to be expelled from the region. Through these mechanisms, it can be concluded that vibration increases the accessibility of electrocatalytically active regions and enhances reaction kinetics. However, as vibration frequency increases beyond 30 Hz, performance begins to decline. This is likely due to the destabilization of the two-phase flow structure within the membrane-electrode assembly (MEA) and gas diffusion layers (GDL). At higher frequencies, CO₂ bubbles may rapidly agglomerate in the anode channels, blocking active sites and restricting methanol access. Additionally, excess vibration can promote water droplet accumulation on the cathode GDL surface, leading to channel blockage and the formation of a water film. This obstructs oxygen supply from ambient air, degrading reaction rates and lowering cell efficiency [22,35].

Figure 4a illustrates the effect of vibration frequency on peak power density for different methanol flow rates. The results show that a vibration frequency of 15 Hz consistently yielded the highest power densities across all tested flow rates (1, 5, 25, and 50 mL·min^{−1}), with a peak value observed at 5 mL·min^{−1}, confirming this as the optimal flow condition. At higher frequencies (30 and 60 Hz), a gradual decline in power output was observed, particularly at higher flow rates, indicating that excessive vibration may disrupt reactant and product transport within the cell. These trends support the conclusion that low-frequency vibration improves mass transport and CO₂ bubble removal, while excessive vibration leads to instability and performance loss [36–39]. Figure 4b presents the time-dependent power density behavior at constant voltage (2 V) over a 600-s duration, comparing operation with and without 15 Hz vibration. Although the initial power density under vibration

is significantly higher than the non-vibrating case, it gradually decreases over time, while the no-vibration condition maintains a relatively stable and consistent output. This suggests that while vibration enhances short-term performance, it may also introduce mechanical or electrochemical instabilities that reduce long-term efficiency. Together, these results highlight the need to balance vibration intensity and duration for optimal and sustainable OC-DMFC operation.

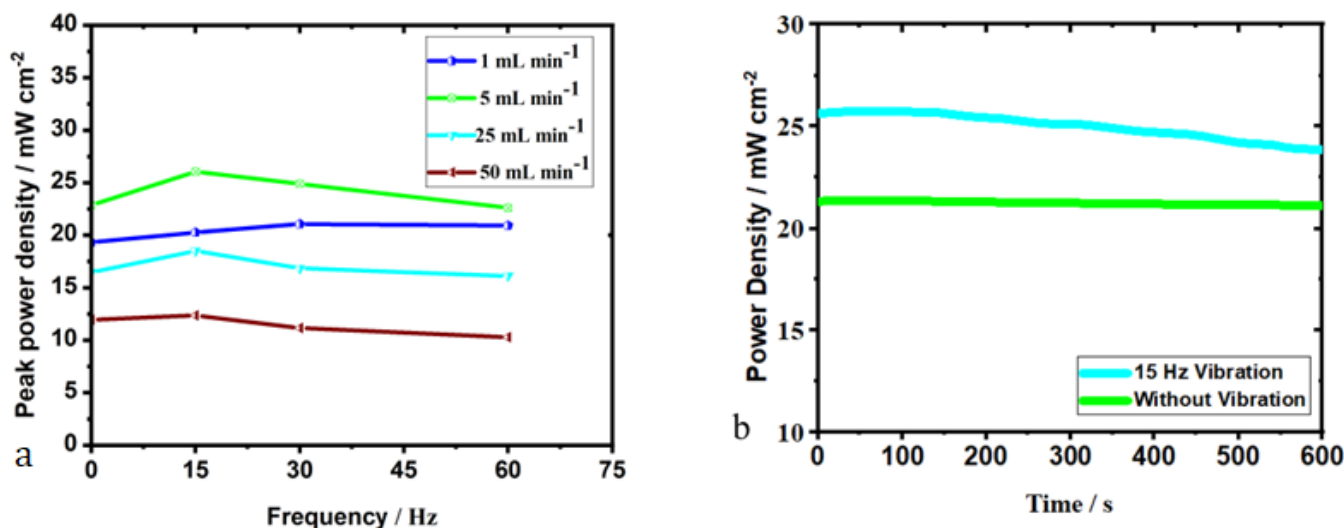


Figure 4. (a) Peak power density variation with vibration frequency at different methanol flow rates (1, 5, 25, and 50 mL·min⁻¹). (b) Time-dependent power density behavior at constant voltage (2 V) under 15 Hz vibration and non-vibrating conditions over 600 s.

The air flow rate supplied to the cathode plays a critical role in determining the performance of open-cathode direct methanol fuel cells (OC-DMFCs), particularly under vibrational operating conditions. At a constant methanol concentration of 1 M and a fuel temperature of 70 °C, increasing the air velocity from 2.4 m/s to 4.8 m/s led to a significant rise in peak power density, primarily due to enhanced oxygen availability and improved water removal from the cathode. While further increasing the air flow to 7.2 m/s resulted in a marginal improvement in performance under low-frequency vibration, it also introduced greater heat loss and energy consumption. Among the vibration frequencies tested, 15 Hz consistently produced the highest power densities across all air flow rates, with a maximum of 27.26 mW·cm⁻² recorded at 7.2 m/s. However, nearly equivalent performance was achieved at 4.8 m/s with 26.05 mW·cm⁻², making this condition more favorable in terms of energy efficiency and thermal stability. In contrast, higher frequency vibrations (30 and 60 Hz) have shown reduced performance advantages, particularly at low air flow rates, probably due to unstable water, gas transport dynamics, and compression-related leaks [40,41]. Overall, the optimal condition for OC-DMFC performance was achieved at 15 Hz vibration and 4.8 m/s air flow, balancing enhanced reactant transport, water management, and energy efficiency [40,41].

Finally, the relationship between vibration frequency and peak power density was modeled and validated, as shown in Figure 5a, using an empirical exponential function. The model exhibited an excellent fit to the experimental data with an R^2 value of 99.6% and identified the optimal frequency for maximum performance to be around 15 Hz, using the coefficients $\alpha = 0.0325$ and $\delta = 0.0815$. This peak corresponds to the point where enhanced mass transfer and effective removal of CO₂ and water coincide, before adverse effects such as instability and water flooding dominate at higher frequencies. Figure 5b presents a contour map of power density as a function of both vibration frequency and methanol

flow rate, offering a broader insight into the coupled effects of these two parameters. The contours reveal that the highest power densities ($\geq 25 \text{ mW}\cdot\text{cm}^{-2}$) are achieved at moderate flow rates (around $5\text{--}10 \text{ mL}\cdot\text{min}^{-1}$) and low vibration frequencies ($10\text{--}20 \text{ Hz}$). Conversely, performance drops substantially at higher flow rates and frequencies, confirming that excessive input of fuel and mechanical energy can reduce cell efficiency due to poor utilization and increased internal losses. These results further reinforce the importance of tuning both flow rate and vibration frequency to achieve optimal and sustainable OC-DMFC performance.

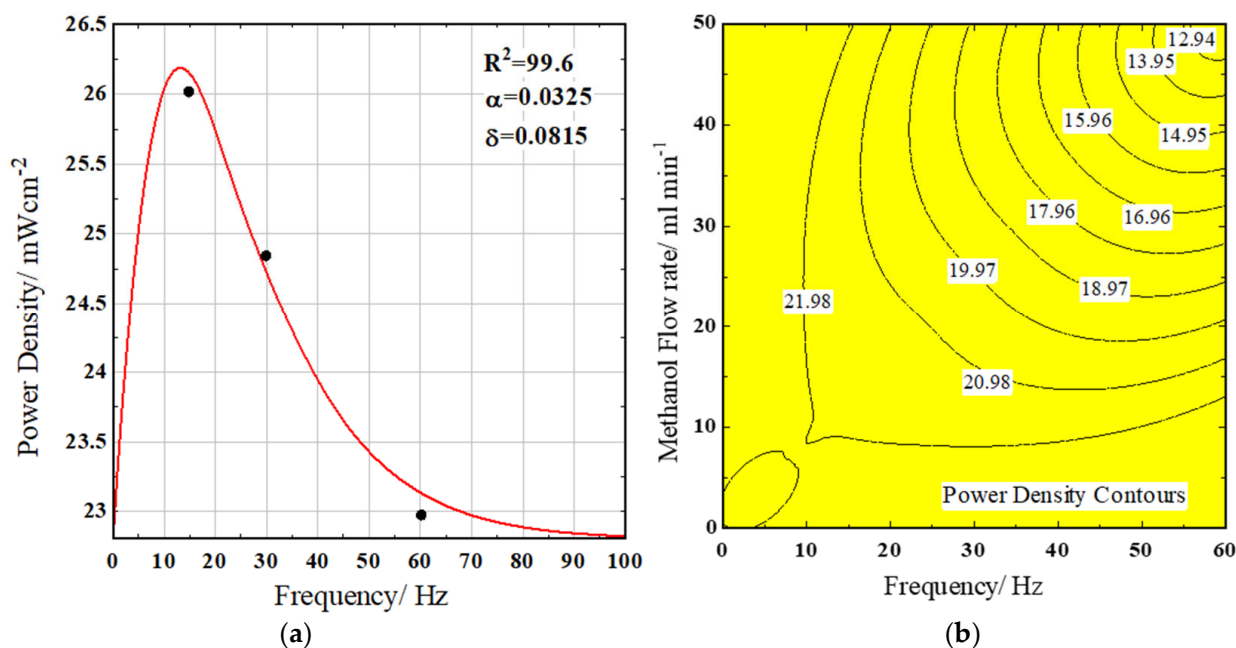


Figure 5. (a) Curve fitting of power density versus vibration frequency using an empirical exponential model at $5 \text{ mL}\cdot\text{min}^{-1}$ flow rate. (b) Contour map showing power density as a function of both vibration frequency and methanol flow rate.

The introduction of low-frequency vibration (15 Hz) significantly enhanced cell performance across all flow rates, with up to 14% improvement observed at the optimal fuel feed rate. This enhancement is attributed to the mitigation of water accumulation at the cathode and the improved removal of CO_2 gas bubbles at the anode. However, increasing the vibration frequency beyond this optimum led to a decline in power density, likely due to flow instability, water flooding, and disturbance of the membrane–electrode interface. Time-dependent measurements further confirmed that while 15 Hz vibration boosts short-term performance, it may slightly degrade long-term stability due to mechanical loosening and local dehydration effects. Air flow rate was also shown to significantly impact stack performance. Increasing the airflow from 2.4 m/s to 4.8 m/s markedly improved power output, with only marginal gains observed at 7.2 m/s . The optimal overall performance was achieved at 15 Hz vibration and 4.8 m/s air flow, balancing power enhancement and energy efficiency. Observed power density change is due to mechanical or electrochemical instabilities is that this performance degradation is more pronounced and rapid at higher frequencies (e.g., $30\text{--}60 \text{ Hz}$). Increasing vibration frequency may be indicative of mechanical degradation, resulting in stresses in the membrane electrode assembly (MEA). High-frequency vibrations may accelerate the physical erosion of the catalyst layer or cause unstable fluctuations in the membrane’s water content, leading to increased proton resistance.

A two-variable model describing the power density as a function of vibration frequency and methanol flow rate was developed and validated, achieving an R^2 of 99.6%. Contour analysis highlighted a clear region of optimal operating conditions, reinforcing the experimental findings. In conclusion, this work demonstrates that careful tuning of flow rate, air supply, and vibration input can significantly improve OC-DMFC performance. These findings provide valuable insights for the design and operation of portable and vibration-prone fuel cell systems, especially in transportation and aerospace applications, where mechanical disturbance and energy efficiency are critical concerns. To clarify the limits of vibration's effects on DMFC operating dynamics, it is recommended that different diagnostic methods, such as advanced imaging techniques or local current density measurements, be applied. However, these comprehensive validation studies exceed the scope of the present work and are proposed as suggestions for future research. In addition to this study, the focus will be on the integration of adaptable control systems for long-term mechanical durability, dynamic response to real-world vibration profiles, and sustainable high-performance operation.

4. Conclusions

OC-DMFC depends on various process parameters for effective operation. These parameters can significantly affect fuel cell performance and efficiency. Process parameters that directly affect methanol fuel cells, such as methanol concentration, methanol and cell temperature, and flow, have been studied in detail. These process parameters directly affect the efficiency and performance of methanol fuel cells. It is believed that determining the optimum values could contribute to the development and implementation of more efficient and long-lasting fuel cells.

In this study, the effects of methanol flow rate, vibration frequency, and air flow on the performance of an open-cathode direct methanol fuel cell (OC-DMFC) stack were systematically investigated. The experiments were conducted at a fixed methanol concentration of 1 M and a solution temperature of 70 °C, with particular focus on the interplay between mechanical vibration and operational parameters. The results revealed that both methanol flow rate and vibration frequency are critical to achieve optimal performance. Among the tested conditions, a flow rate of 5 mL·min^{−1} consistently yielded the highest power density due to improved reactant utilization and balanced water management. Lower flow rates led to incomplete fuel utilization and CO₂ accumulation, while higher flow rates caused methanol crossover and excessive cooling, both of which adversely affected performance.

Author Contributions: Conceptualization, S.C., H.Ö. and B.A.H.; methodology, S.C. and H.Ö.; software, G.A.S., M.Y., S.C., H.Ö. and B.A.H.; formal analysis, G.A.S. and M.Y.; investigation, G.A.S. and M.Y.; resources, S.C., H.Ö. and B.A.H.; data curation, G.A.S. and M.Y.; writing—original draft preparation, G.A.S., M.Y. and S.C.; writing—review and editing, S.C., H.Ö. and B.A.H.; visualization, S.C. and H.Ö.; supervision, S.C., H.Ö. and B.A.H.; project administration, S.C., H.Ö. and B.A.H.; funding acquisition, S.C., H.Ö. and B.A.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: The authors thank Ankara Yıldırım Beyazıt University for its IT support and experimental assistance. They also appreciate the technical support and advice provided by T. Nejat Veziroğlu from the Clean Energy Research Center at Nigde Omer Halisdemir University.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

OC-DMFC	Open cathode-direct methanol fuel cell
M	Molar concentration
Hz	Hertz
DEFC	Direct ethanol fuel cells
DMFC	Direct methanol fuel cells
FD	Frictional force
FSL	Shear force
BPs	Bipolar plates
MEA	Membrane electrode assembly
PEMFC	Proton exchange membrane fuel cells

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