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COST–EFFICIENCY ANALYSIS OF COOLING FAN OPERATION IN A 100 W PEM FUEL CELL SYSTEM

ANÁLISE DE CUSTO-EFICIÊNCIA DA OPERAÇÃO DE UM VENTILADOR DE REFRIGERAÇÃO EM UM SISTEMA DE CÉLULA DE COMBUSTÍVEL PEM DE 100 W

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ABSTRACT

Proton Exchange Membrane Fuel Cells (PEMFCs) are regarded as a clean energy source with high efficiency, low operating temperature, and low emissions, making them increasingly applied in various fields. However, the system's performance is significantly affected by cooling conditions, particularly the operating mode of the cooling fan. In this study, a 100W PEMFC system connected to a 1Ω resistive load was experimentally tested under different fan supply voltages of 0V, 5V, 10V, 15V, 20V, and 24V. Operating parameters such as temperature, pressure, hydrogen flow rate, and output power were recorded to analyze the impact of fan speed on the electrical efficiency of the system. The experimental results demonstrate that optimized cooling fan operation significantly improves the

RESUMO

As células a combustível de membrana de troca de prótons (PEMFCs) são consideradas uma fonte de energia limpa com alta eficiência, baixa temperatura de operação e baixas emissões, o que as torna cada vez mais aplicadas em diversos campos. No entanto, o desempenho do sistema é significativamente afetado pelas condições de resfriamento, particularmente pelo modo de operação do ventilador. Neste estudo, um sistema PEMFC de 100 W conectado a uma carga resistiva de 1 Ω foi testado experimentalmente sob diferentes tensões de alimentação do ventilador: 0 V, 5 V, 10 V, 15 V, 20 V e 24 V. Parâmetros operacionais como temperatura, pressão, vazão de hidrogênio e potência de saída foram registrados para analisar o impacto da velocidade do ventilador cost efficiency of the 100 W PEM fuel cell system. By reducing auxiliary power consumption while maintaining stable operating temperatures, the net electrical efficiency is enhanced and operating costs are minimized. This study confirms that cooling fan management plays a crucial role in improving both technical performance and economic feasibility of PEM fuel cell systems.

Keywords: PEM Fuel Cell, Hydrogen Flow Rate, Sýstem Efficiency, Energy Conversion, Performance Evaluation.

na eficiência elétrica do sistema. Os resultados experimentais demonstram que a operação otimizada do ventilador melhora significativamente a relação custo-benefício do sistema de célula a combustível PEM de 100 W. Ao reduzir o consumo de energia auxiliar, mantendo temperaturas de operação estáveis, a eficiência elétrica líquida é aprimorada e os custos operacionais são minimizados. Este estudo confirma que o gerenciamento do ventilador desempenha um papel crucial na melhoria do desempenho técnico e da viabilidade econômica dos sistemas de células a combustível PEM.

Palavras-chave: *Célula a combustível PEM. Vazão de hidrogênio. Eficiência do sistema. Conversão de energia. Avaliação de desempenho.*

1 INTRODUCTION

Clean and sustainable energy has become one of the greatest challenges of the 21st century. In the context of climate change, environmental pollution, and the increasing demand for electricity, the search for alternative energy sources that are both efficient and environmentally friendly is an inevitable trend. Among the solutions studied, Proton Exchange Membrane Fuel Cells (PEMFCs) stand out due to their high efficiency, high power density, and low emissions. Consequently, they have been widely applied in various fields ranging from transportation, aerospace, distributed generation, to backup power supply. Particularly, PEMFCs are highly valued for their flexible operation and rapid response to load changes, making them suitable for integration into future smart energy systems.

However, the efficiency and reliability of PEMFCs are strongly dependent on operating conditions. Among these, thermal management and water management are decisive factors for both performance and lifetime. If heat transfer is not properly maintained, temperature gradients in the stack will increase, leading to rapid material degradation, reduced power output, and shortened system lifespan. Conversely, improper water management may cause cathode flooding or membrane dehydration, both of which reduce proton conductivity and directly affect current density. Therefore, research on PEMFC management and control strategies has attracted great interest over the past decades. Early on, M. S. Wilson and S. Gottesfeld [1] pointed out that the design and performance of fuel cells are significantly influenced by stack architecture, including gas distribution, water management, and thermal balance. This has been considered a crucial foundation for subsequent research on the correlation between system design and operating performance. D. Santa Rosa, D. Krapf, and E. Falcão [2] further demonstrated the effective operation of an open-cathode PEMFC stack under ambient conditions, showing that simplifying cooling and air supply systems can bring certain benefits, but also poses challenges in maintaining uniform temperature. Meanwhile, S. Shimpalee, U. Beuscher, and J. Van Zee [3] combined experiments and simulations to analyze the characteristics of portable PEMFCs, highlighting the critical role of current and heat distribution in overall performance, particularly under continuously varying loads. In parallel, many studies have focused on thermal management. M. A. Al-Baghdadi [4] investigated thermal management strategies of PEMFCs under different operating conditions, emphasizing the necessity of maintaining uniform temperature to reduce thermal gradients – the main cause of material degradation. By combining simulations and experimental measurements, A. Iranzo, P. Boillat, and J. Rosa [5] clarified the uneven temperature distribution in the stack and proposed solutions to improve heat transfer, such as modifying cooling channel structures. B. Sundén and A. Mahmoudi [6] also conducted numerical studies on cooling strategies, demonstrating that selecting appropriate cooling configurations not only reduces temperature differences but also extends system lifespan. Another research direction focuses on the interaction between thermal and water management. C. Lim and Y. Yoo [7] experimentally examined a self-regulating PEMFC system, showing the close interdependence between the two factors in maintaining stable performance. C. Lim and Y. Yoo [8] studied the dead-ended anode (DEA) operating mode, showing that periodic purging effectively removes water accumulation, thereby improving performance and extending operation time. More recently, W. Yang, Z. Mao, and X. Chen [9] developed a method for simultaneous measurement of local current density and temperature distribution in DEA mode, enabling direct monitoring of the correlation between electrochemical processes and thermal distribution, which provides essential data for developing intelligent control strategies. Beyond intrinsic characteristics, many works have expanded to system integration and control. Q. He, J. Chen, and L. Xu [10] tested a hybrid energy system integrating fuel cells, electrolyzers, and batteries, demonstrating its capability to meet dynamic power demands in renewable applications. J. Li, X. Zhang, and K. Ma [11] proposed an adaptive coordinated control method for PEMFC cathode air supply, stabilizing operation under nonlinear and variable load conditions. With a more advanced approach, M. Roslan, H. Shaker, and N. Saad [12] applied artificial intelligence algorithms to model and control temperature in water-cooled PEMFC systems. In addition, related research directions have also been pursued in internal combustion engines (ICEs) and hybrid applications. V. D. Ly and T. T. Do [13] used simulations to analyze laser ignition technology for improving ICE performance, while V. D. Ly, T. Q. Le, and T. T. Do [16] studied the effects of swirl and tumble ratios on motorbike engine performance. In another domain, H. Pourrahmani, C. M. I. Bernier, and J. V. Herle [14] focused on integrating fuel cells and batteries in unmanned aerial vehicles (UAVs), highlighting the great potential of PEMFC technology in small-scale aviation. More recently, B. Deng, W. Huang, and Q. Jian [15] proposed an optimization strategy for open-cathode PEMFC efficiency based on exergy analysis and data-driven modeling, demonstrating the capability of combining modern computational methods for performance improvement. Beyond direct PEMFC studies, other works have clarified the related technological context. C. Berggren and T. Magnusson [17] analyzed the potential for reducing automotive emissions through ICE technologies combined with environmental policies, while F. Schäfer and R. Van Basshuysen [18] emphasized the importance of emission reduction and fuel consumption in engine design. Control technologies such as W. C. Wang [19] PWM-based DC motor speed regulation system have also contributed to the foundation of efficient energy management. S. Hanapi, A. S. Tijani, A. H. A. Rahim, and W. A. N. W. Mohamed [21] studied the exergy efficiency of a 1 kW open-cathode PEMFC under varying pressure and temperature, providing valuable data for thermal–water management strategies. M. Kandidayeni, A. Macias, L. Boulon, and S. Kelouwani [22] continued this direction by proposing a systemic management approach to enhance PEMFC efficiency. Meanwhile, M. Islam and S. Jin [20] provided an overview of wireless communication networks, laying the groundwork for IoT-based monitoring and intelligent control of energy systems. Water-cooled PEMFC research further highlights the potential of integrating artificial intelligence into operational management, opening up new prospects for embedding PEMFCs into smart energy systems.

In summary, despite significant progress in optimizing PEMFC thermal management, water management, and system control, several challenges remain. One of the most critical issues is maintaining stable thermal conditions during long-term operation, especially under varying loads or dead-ended anode modes. Studies have shown that uneven thermal distribution reduces efficiency, accelerates material degradation, and shortens stack lifespan. Furthermore, although many proposed cooling strategies are technically effective, they are often complex to implement or involve high operational costs. Thus, there is an urgent need to develop simple, effective, and practical thermal management solutions. From this perspective, the present study focuses on adjusting cooling fan speed to maintain stable operating temperatures in PEMFC systems. Cooling fans are widely used devices with advantages such as low cost, ease of implementation, and fast response. By appropriately controlling fan speed, the system can sustain thermal equilibrium in the stack, limit thermal gradients, and minimize thermal fluctuations during long-term operation. This approach not only enhances PEMFC performance and reliability but also extends system lifetime, laying the foundation for broader applications in fields requiring sustainable, stable, and environmentally friendly energy sources.

2 EXPERIMENTAL MODEL

2.1 Experimental setup for hydrogen leakage monitoring

The experimental research diagram is shown in Figure 1a. All experiments were conducted using a 100W PEM fuel cell (H100, Horizon Fuel Cell Technologies, Singapore) with an active area of 22.5cm². Hydrogen gas was supplied from an H_2 cylinder through a pressure regulator (Regulator Hydrogen Gas, TANAKA Brand, Origin Japan), and the regulator allows adjusting the inlet pressure in the range of 0–1bar to investigate the effect on energy conversion efficiency (Pressurized compressed air, Airtac Brand, Origin of Taiwan), along with a hydrogen flow meter (M-20SLPM-D/5M, Alicat Scientific Inc, USA). In the system, the original controller of the fuel cell was replaced by a laboratory microcontroller unit (MCU) (Arduino Mega2560, Italy) to control the 100W fan speed and perform the anode purging process. The operating parameters were monitored by a temperature sensor (RS20K-C, SULINKIOT, China), a pressure sensor (ES-P300, Electesla, China), and a voltage and current sensor (INA219, Texas Instruments, USA). The output power was delivered through a purely resistive load of 1

Ω to maintain a load current of about 8A. All measurement signals, including pressure, flow rate, voltage, current, and temperature, were collected through the MCU control system and transmitted to the computer for visualization using MATLAB Simulink.

Figure 1a

Schematic diagram and experimental setup of a 100W PEM fuel cell system with different cooling fan and resistive load.

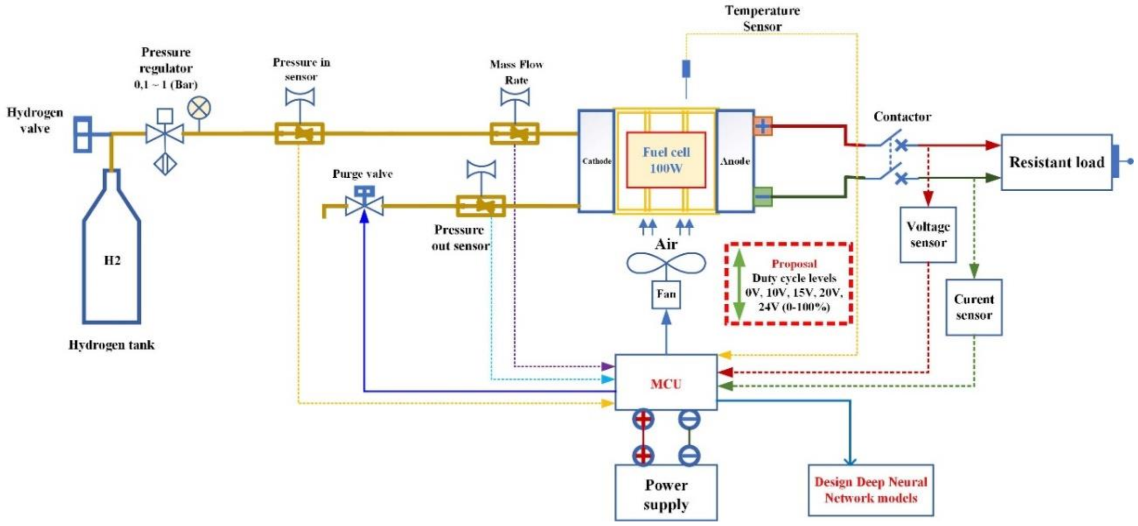
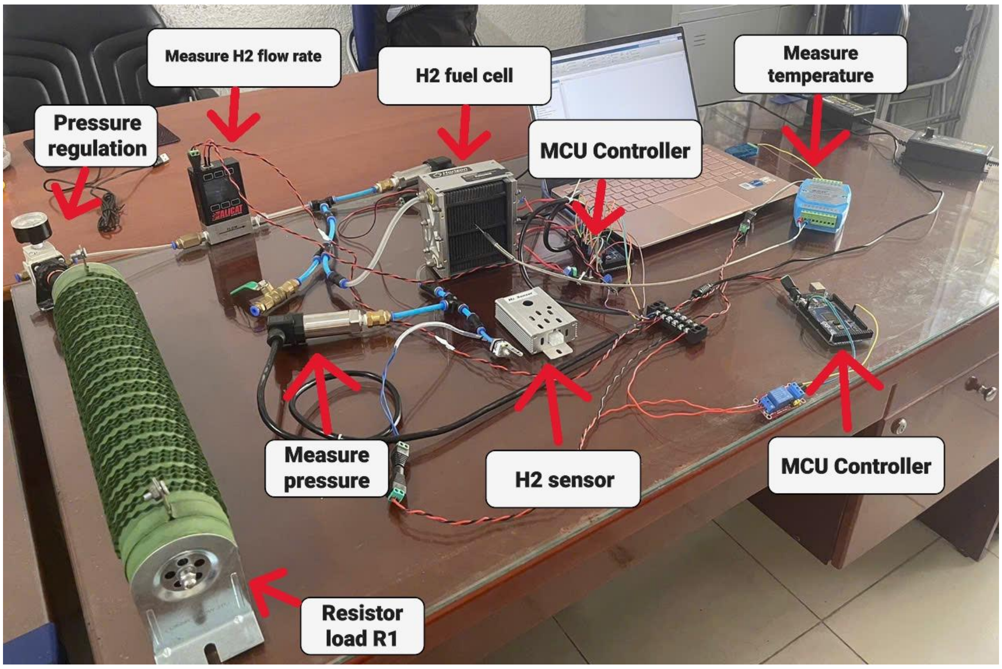


Figure 1b

Experimental model simulating a 100W PEM fuel cell system with cooling fan and resistive load.



3 EXPERIMENTAL PROCEDURE

After opening the hydrogen cylinder and adjusting the pressure regulator to a safe level of 0.5bar, the fuel cell initiated electrochemical reactions to generate voltage. During the experiments, a 1Ω resistive load was connected, and the system was operated continuously for 20 minutes. Results showed that the fuel cell reached a steady state around the 17th minute, with a voltage of approximately 8V and a current of about 7.3A. The supply voltages for the cooling fan were sequentially set to 0V, 5V, 10V, 15V, 20V, and 24V. Key operating parameters, including current, voltage, pressure, and hydrogen flow rate, were measured and monitored through the MCU controller and the data acquisition (DAQ) system. Additionally, the system was tested with supplementary on/off cycles of 10 seconds to simulate practical operating conditions and evaluate their effect on fuel cell stability. The collected results allowed for a comprehensive analysis of the influence of fan voltage on system performance, leading to recommendations for optimal fan control strategies to improve the stability and efficiency of the fuel cell system.

The efficiency of the PEM fuel cell system was calculated using Equation (1):

$$\eta(t)=\frac{P_{out}(t)}{m_{H_2}(t).LHV_{H_2}} \qquad (1)$$

where:

η(t): Efficiency;
$P_{out}(t)$: Electrical output power at time t(W);
$\dot{m}_{H_2}(t)$: Hydrogen mass flow rate at time;
LHV_{H_2}: Lower heating value (LHV) of hydrogen.

4 RESEARCH RESULTS

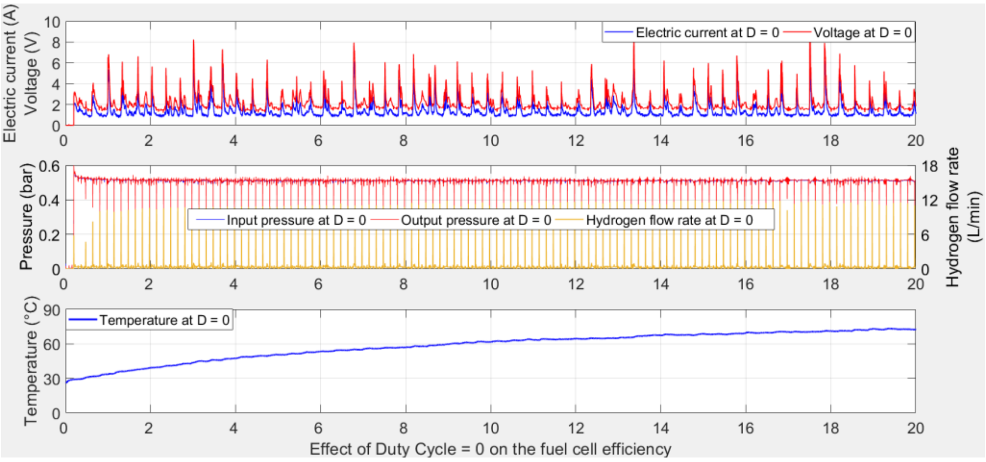
The experimental results of the PEM fuel cell system under the influence of various fan supply voltages (0V, 5V, 10V, 15V, 20V, and 24V) showed that system performance was significantly affected. Efficiency was evaluated through measured parameters, including pressure, temperature, hydrogen consumption flow rate, and output power, thereby reflecting performance variations with increasing fan voltage.

4.1 Effect of 0V fan voltage on PEM fuel cell system

Figure 2 illustrates the experimental results of the 100W PEM fuel cell system under a 1Ω resistive load when the cooling fan was not operating (D = 0). The results showed that hydrogen inlet and outlet pressures remained around 0.45–0.55bar, with minor fluctuations but generally stable. However, the hydrogen flow rate fluctuated strongly between 0–18L/min, reflecting the characteristics of an open-pressure gas supply, leading to uneven fuel delivery. As a result, the output voltage and current fluctuated considerably, with voltage maintained at a low level (2–4V) and current reaching only about 2–5A. Meanwhile, the cell temperature continuously increased from about 30°C to nearly 70°C due to the absence of cooling, causing heat accumulation and reducing proton conductivity of the membrane, which negatively affected the stability of electrochemical reactions. This indicates that the main reason for low efficiency was not fuel shortage but rather the combined effects of unstable hydrogen supply and poor heat transfer. The results confirm that cooling capability and appropriate duty cycle control of the fan play a crucial role in maintaining stability and improving the performance of PEM fuel cell systems under high-load conditions.

Figure 2

Temperature, current, voltage, pressure, and hydrogen consumption characteristics of the PEM fuel cell at 0V fan supply.

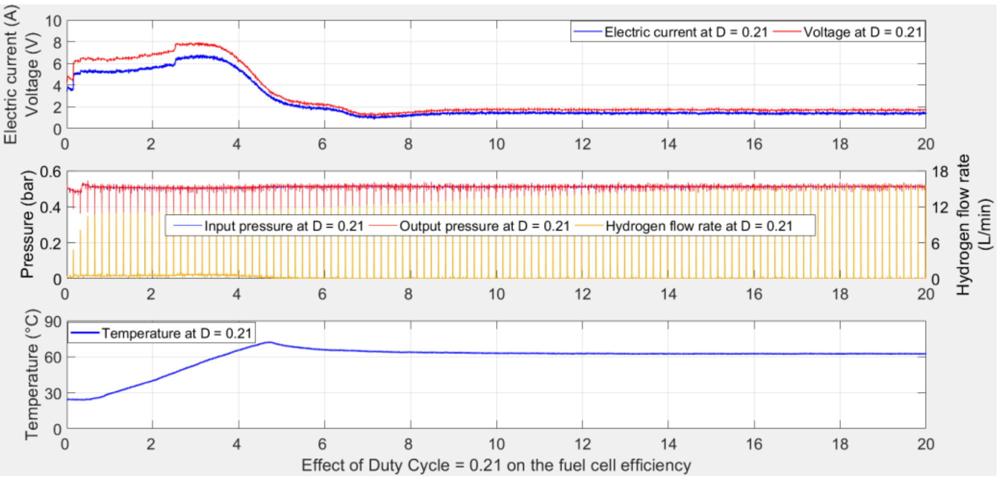


4.2 Effect of 5V fan voltage on PEM fuel cell system

Figure 3 presents the operational characteristics of the 100W PEM fuel cell system under a 1Ω resistive load when the cooling fan operated at Duty Cycle D = 0.21. At the beginning, current and voltage increased rapidly, reaching about 6–7A and 7–8V, indicating that electrochemical reactions were strong when fuel supply was sufficient. However, as temperature exceeded 60°C, current and voltage tended to gradually decrease and stabilize at lower levels (2–3A and 2–3V), indicating that heat accumulation significantly affected efficiency. During the process, hydrogen inlet pressure was stably maintained around 0.45–0.5 bar, while outlet pressure was slightly lower and fluctuated synchronously, reflecting minimal pressure loss. The hydrogen flow rate fluctuated cyclically in the range of 0–18L/min, ensuring continuous fuel supply. This demonstrates that the decline in efficiency was not due to fuel shortage but to limited cooling capability. At elevated temperatures, the proton exchange membrane was affected, leading to increased internal resistance and imbalanced electrochemical reactions. The results indicate that operating the fan at D = 0.21 allowed the system to perform better than in the case without cooling, but it was still insufficient to prevent heat accumulation. Thus, optimizing fan control is necessary to maintain temperature within an optimal range to improve both efficiency and stability of PEM fuel cells.

Figure 3

Temperature, current, voltage, pressure, and hydrogen consumption characteristics of the PEM fuel cell at 5V fan supply.

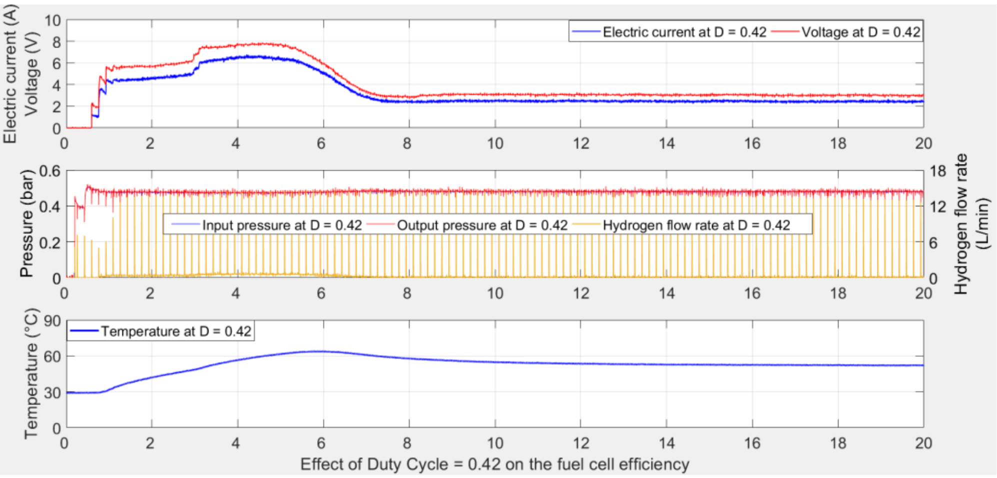


4.3 Effect of 10V fan voltage on PEM fuel cell system

Figure 4 shows the operating characteristics of the 100W PEM fuel cell under a 1Ω resistive load when the cooling fan operated at Duty Cycle D = 0.42. The results indicated that current and voltage initially rose quickly, reaching about 7.5–8A and 8–8.5V, and then remained stable for an extended period before slightly decreasing as temperature exceeded the optimal threshold. The fuel cell temperature gradually increased from 30°C to nearly 65°C, but was subsequently reduced and stabilized around 60°C due to the fan's cooling effect. This demonstrates a significant improvement in cooling efficiency compared to lower duty cycle cases. Throughout the process, hydrogen inlet pressure was maintained steadily at about 0.5bar, while outlet pressure was slightly lower at approximately 0.45bar and fluctuated synchronously, indicating minimal and stable pressure losses. Meanwhile, hydrogen flow rate fluctuated cyclically in the range of 0–20L/min, ensuring continuous fuel supply. These results confirm that maintaining fan operation at Duty Cycle D = 0.42 effectively limited heat accumulation, kept current and voltage more stable, and improved both efficiency and reliability of the PEM fuel cell system.

Figure 4

Temperature, current, voltage, pressure, and hydrogen consumption characteristics of the PEM fuel cell at 10V fan supply.

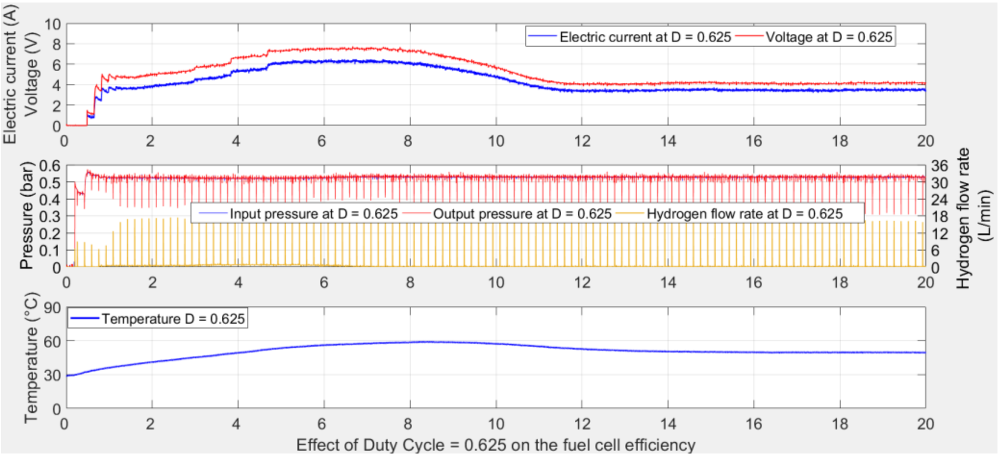


4.4 Effect of 15V fan voltage on PEM fuel cell system

Figure 5 describes the operational characteristics of the 100 W PEM fuel cell under a 1Ω resistive load when the cooling fan operated at Duty Cycle D = 0.625. The results showed that current and voltage initially increased rapidly, reaching about 7–7.5A and 8V, but then gradually decreased as the temperature exceeded the optimal threshold (approximately 65°C), and later stabilized at lower values. This reflects the influence of heat accumulation on efficiency. The cell temperature rose from 30°C to nearly 65°C and then stabilized thanks to the fan's cooling effect. However, the cooling capability at this duty cycle was not as effective as in the case of D = 0.83. Regarding gas characteristics, hydrogen inlet pressure remained around 0.35–0.4bar, while outlet pressure was slightly lower but fluctuated synchronously, confirming a stable fuel supply system. Hydrogen flow rate fluctuated within 0–20L/min, ensuring sufficient fuel for electrochemical reactions. In general, with Duty Cycle D = 0.625, the system achieved a balance between cooling and electrochemical efficiency, allowing more stable operation than at lower duty cycles, although performance degradation was still observed as temperature approached the optimal limit.

Figure 5

Temperature, current, voltage, pressure, and hydrogen consumption characteristics of the PEM fuel cell at 15V fan supply.

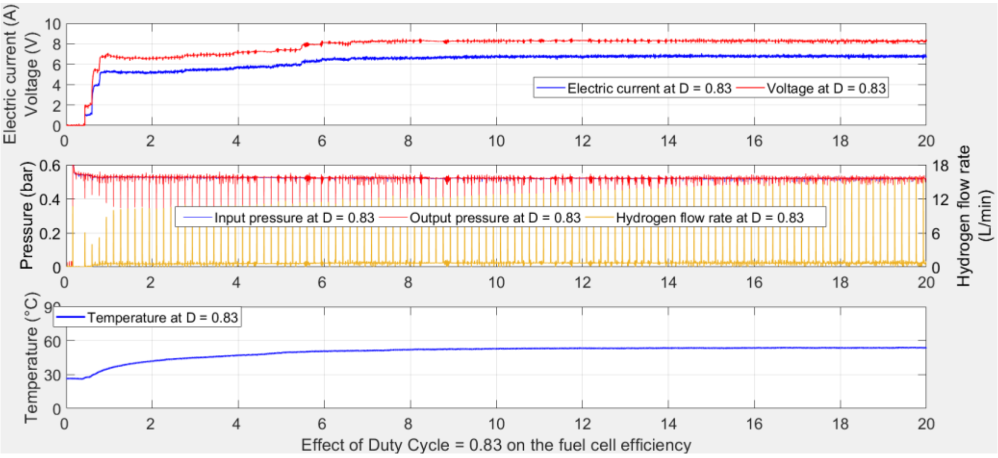


4.5 Effect of 20V fan voltage on PEM fuel cell system

Figure 6 illustrates the operating characteristics of the 100 W PEM fuel cell under a 1Ω resistive load when the cooling fan was supplied at Duty Cycle D = 0.83. The results showed that current and voltage initially rose rapidly, reaching about 7–7.5A and 8V, and then remained stable throughout the process. This indicates that the system achieved good thermal balance due to enhanced cooling efficiency. The cell temperature fluctuated only between 50–55°C, lower than in lower duty cycle cases, demonstrating the superior cooling capacity of the fan. At the same time, hydrogen inlet pressure was maintained around 0.55–0.6bar, while outlet pressure was slightly lower but fluctuated synchronously, confirming stable gas supply. Hydrogen flow rate varied between 0–18L/min, ensuring sufficient fuel for electrochemical reactions. Overall, at Duty Cycle D = 0.83, the PEM fuel cell system maintained stable current and voltage output while preventing excessive heat accumulation, thereby improving efficiency and reliability during operation.

Figure 6

Temperature, current, voltage, pressure, and hydrogen consumption characteristics of the PEM fuel cell at 20 V fan supply.

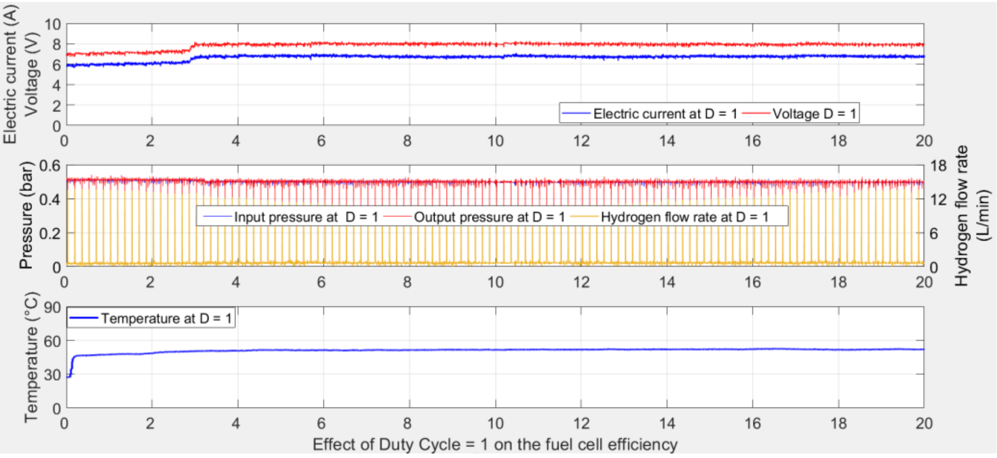


4.6 Effect of 24V fan voltage on PEM fuel cell system

Figure 7 presents the operational characteristics of the 100 W PEM fuel cell under a 1Ω resistive load when the cooling fan operated at full duty cycle (D = 1). The results showed that hydrogen flow rate fluctuated cyclically between 0–20L/min, reflecting a pulsed fuel supply mechanism that maintained balance between pressure and electrochemical demand. Meanwhile, inlet pressure was stable around 0.5–0.55bar, and outlet pressure was slightly lower but fluctuated synchronously, demonstrating a stable gas supply without abnormal pressure drops. Regarding electrical performance, current was steadily maintained in the range of 7–7.5A, while voltage remained high at approximately 8V with almost no fluctuations. This indicates that the system achieved good thermal–electrical balance when the fan operated at maximum speed, significantly reducing heat accumulation compared to lower duty cycles. The fuel cell temperature increased from about 30°C initially but was quickly stabilized around 55°C throughout the process, confirming the optimal cooling efficiency of the fan at D = 1. With temperature well-controlled at a moderate level, electrochemical reactions proceeded smoothly, internal resistance decreased, and both current and voltage remained high and stable. This enhanced energy conversion efficiency and reduced power fluctuations compared to incomplete cooling cases. These results confirm that controlling the fan at Duty Cycle D = 1 provides superior effectiveness in maintaining temperature, stabilizing electrochemical and gas parameters, and improving both reliability and efficiency of the PEM fuel cell system under heavy load.

Figure 7

Temperature, current, voltage, pressure, and hydrogen consumption characteristics of the PEM fuel cell at 24V fan supply.

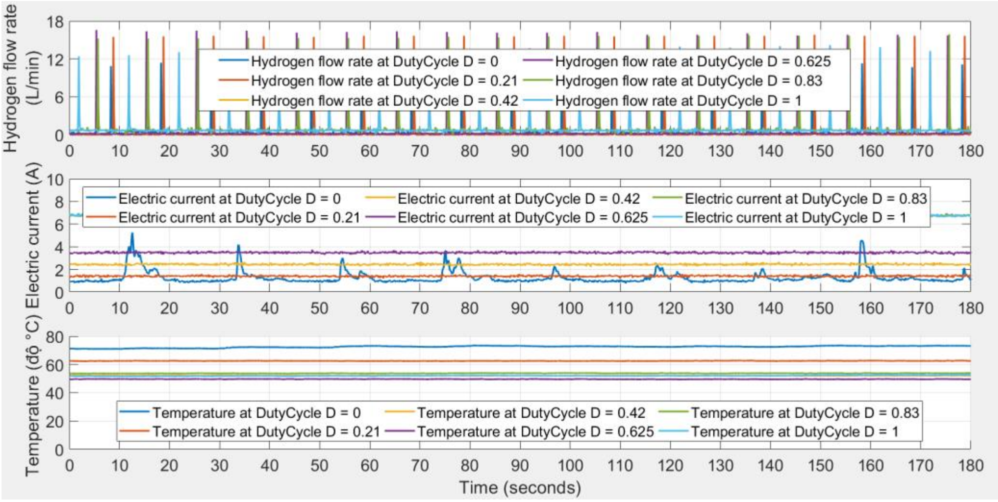


4.7 Effect of temperature and current on hydrogen consumption

When the 100W PEM fuel cell system was tested under a 1Ω resistive load, the results showed that variations in fan duty cycle significantly influenced operational characteristics. When the fan was inactive (D = 0), current and voltage remained at low levels with large fluctuations due to rapid temperature increase, even though pressure and hydrogen flow were relatively stable. As the duty cycle gradually increased (D = 0.21 → 0.42 → 0.625 → 0.83), temperature control improved, voltage and current fluctuations decreased, and power generation efficiency increased. Particularly at higher duty cycles (D = 0.83 and D = 1), the system reached optimal conditions with temperature stabilized around 55°C, high and stable current and voltage, while hydrogen flow fluctuated cyclically but did not significantly affect performance. These results confirm the critical role of the cooling fan in temperature regulation, output stabilization, and improved reliability of PEM fuel cell operation under heavy loads.

Figure 8

Temperature, current, and hydrogen consumption characteristics of the PEM fuel cell at various duty cycles (D = 0, 0.21, 0.42, 0.625, 0.83, and 1) under a 1Ω resistive load at 100W.

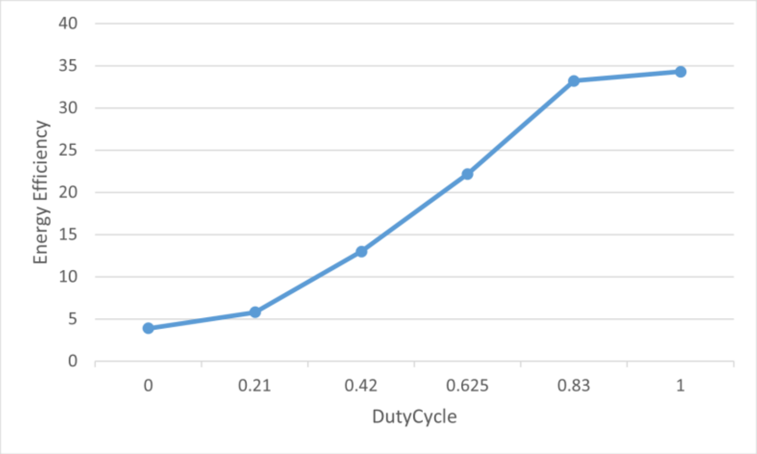


4.8 Experimental results: system efficiency under varying duty cycles

Figure 9 shows that the efficiency of the 100 W PEM fuel cell system under a 1Ω resistive load varied significantly with fan duty cycle. Efficiency increased from about 4% at duty cycle D = 0, gradually rising through 0.21, 0.42, 0.625, and 0.83, and reaching a peak of nearly 35% at duty cycle D = 1. This increase demonstrates that as duty cycle rises, both cooling rate and gas supply improve, helping to maintain stable operating temperature and hydrogen–oxygen flow, thereby enhancing electrochemical reaction efficiency and improving output voltage and current. At the same time, the results highlight the critical role of the cooling system in fuel cell operation: at very low duty cycles, the system is prone to overheating and fuel starvation, causing sharp efficiency drops. By contrast, high duty cycles significantly improve efficiency, but beyond D = 0.83, further improvements become marginal while fan power consumption increases. Therefore, selecting an appropriate duty cycle is essential to balance electrochemical performance and auxiliary power consumption, ultimately optimizing overall system operation.

Figure 9

Efficiency of the PEM fuel cell system at various duty cycles (D = 0, 0.21, 0.42, 0.625, 0.83, and 1) under a 1Ω resistive load at 100W.



5 CONCLUSION

A comparative analysis of operating results at different cooling fan duty cycles (D = 0–1) indicates a strong correlation between enhanced cooling control, system stability, and cost-efficient operation. At low duty cycles (D = 0 and D = 0.21), insufficient cooling led to rapid temperature increases, pronounced fluctuations in current and voltage, and unstable inlet–outlet pressure. From an economic perspective, such unstable operating conditions not only reduce energy conversion efficiency but also increase indirect operating costs due to performance losses, accelerated component degradation, and inefficient hydrogen utilization.

As the duty cycle increased (D = 0.42 → 0.625 → 0.83), thermal conditions improved significantly, resulting in reduced voltage and pressure fluctuations and more stable current output. These improvements reflect a more balanced thermal–electrical operation, which enhances net system efficiency while limiting unnecessary auxiliary power consumption. Consequently, the system operates closer to its optimal cost–performance trade-off, where improved electrical output outweighs the additional energy consumed by the cooling fan.

At the maximum duty cycle (D = 1), the system achieved its most stable and efficient operating state. The stack temperature was maintained at approximately 55 °C, electrical parameters remained consistently high with minimal fluctuations, and hydrogen flow was regulated evenly and cyclically. This operating mode resulted in the highest energy conversion efficiency and improved reliability, suggesting a reduction in long-term operating and maintenance costs. Overall, the results confirm that appropriate increases in cooling fan duty cycle contribute not only to enhanced technical performance but also to improved cost efficiency, system reliability, and economic feasibility of PEM fuel cell operation.

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CONFLICT OF INTEREST

The authors declare no conflict of interest in this article.

Authors' Contribution

All authors contributed equally to the development of this article.

Data availability

All datasets relevant to this study's findings are fully available within the article.

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