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A brief overview on finite element analysis for mechanics of proton exchange membrane fuel cell

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ABSTRACT

Hydrogen energy is an ideal alternative for energy-intensive industrial processes, long-distance transportation, and enabling the integration of decentralized renewable energy sources like solar and wind power. Many countries have implemented strategies for the development of hydrogen energy. Proton exchange membrane fuel cells (PEMFC) are a highly efficient hydrogen conversion technology that can be utilised in a variety of applications, including backup power systems, portable electronics, and transportation, due to its high-power density and simple architecture. Finite element analysis (FEA) is a prominent numerical tool to simulate and to predict the mechanical behaviour of PEMFC under operating conditions. The main goal of this paper is to conduct a review on the utilisation of FEA in improving the performance of PEMFC. The FEA utilisation to evaluate the geometrical design of PEMFC end plate is first discussed, followed by fatigue life of PEMFC stack. Finally, the design optimisation of PEMFC performed in various investigations is also reported. Well validated FEA is found to be a powerful tool to evaluate the mechanics of PEMFC. It can be integrated with modern optimisation methods to improve the performance of PEMFC.

1. INTRODUCTION

Hydrogen energy is the best option for long-distance transportation, energy-intensive industrial operations, and facilitating the integration of decentralized renewable energy sources like solar and wind power (Ren et al., 2020). Strategies for the development of hydrogen energy have been adopted by numerous nations. Because of their high-power density and straightforward design, proton exchange membrane (PEM) fuel cells, a highly efficient hydrogen conversion device can be used in a wide range of applications, such as backup power systems, portable electronics, and transportation. A single fuel cell typically comprises of a

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sandwich-shaped membrane electrode assembly (MEA), bipolar plate (BPP), and sealant. Fuel cells typically have an open circuit voltage of less than 1.0 V because of hydrogen crossover, mixed potential, and the effects of pollution under typical working conditions (Qiu et al., 2021). Electrical devices demand high power and voltage, which are often achieved by stacking numerous unit cells in series and clamping them together with endplates under tens of thousands of newtons (Qiu et al., 2021).

Chemical and mechanical factors, such as dry/wet cycling, localized hot spots, catalyst stripping, and dissolution, can affect the PEM in the workplace (Lim et al., 2014). The membrane will be attacked by hydrogen peroxide free radicals, which will make it thinner and more brittle (Shimizu et al., 2017). The free radicals can induce degradation at the vulnerable sites, specifically the functional end groups or C-H bonds within the PTFE chain. The radical attack results in the formation of new C-H bondings, the end groups elimination and the breakdown of either the main chain or the side chains of the ionomer, leads to the membrane thinning (Wallnöfer-Ogris et al., 2024). Early fuel cell failure is thought to be mostly caused by mechanical degradation at the frame (Crum & Liu, 2006). Even with the installation of extra frame structures to safeguard the PEM and avoid early failure, there are still certain issues with the current frame structure (Zhang et al., 2023). The joint region of the frame and the active area exposed to the working environment is a weak point for mechanical degradation (Qiu et al., 2018). PEM fuel cells (PEMFC) stacks must withstand a wide range of deformation and loads, depending on the application. The material characteristics of the fuel cell stack's constituent parts largely determine how the stack behaves under these kinds of stresses. Additionally important in this regard is the function of the stack clamping pressure. It keeps the assembly together and guarantees that the stack operates without leaks. Bolting arrangements are used to do this most of the time across the cell area. The improved contact between the electrode and BPP is the result of the force applied in this way (Dey et al., 2019).

Finite element analysis (FEA) is a widely used numerical tool to simulate the mechanics of PEMFC during operating condition. Lee et al. (1999) developed the FEA methods for a PEM single cell. By inserting a pressure film between the BPP and the MEA, an experiment was conducted to compute and confirm the pressure distribution within the single cell. In order to achieve the ideal clamping load for large PEMFC stacks, Lin et al. (2010) have proposed a highly efficient construction technique. This was done by considering this as a mechanical equivalent stiffness model with several elastic elements (springs) in either series or parallel connection. Three-dimensional FEA was used to validate the equivalent stiffness model results for a single PEMFC. After performing a three-dimensional simulation examination of the stack, Bates et al. (2013) found that the seal bears the majority of the clamping force. It was also discovered that the pressure within the MEA's active region was lower than the pressure at the frame. Furthermore, brittle interior parts may burst and leak as a result of an incorrect clamping force. Alizadeh et al. (2016) used modelling and experimental work to achieve at a similar conclusion. The stress concentration at the frame increases with the strength of the seal and the contact pressure under the sealing ring. Hygro-thermal stress is brought on by cycles of heat and humidity, and it is during this stress induced that the membrane's yield limit may be reached. Several researchers investigate the effects of cycles of heat and humidity on the membrane using a two-dimensional single-channel simulation model (Khattra et al., 2012; Kusoglu et al., 2007, 2011).

This paper is aimed to conduct an overview of application of FEA in characterising the mechanics of PEMFC. It starts with the FEA utilisation to evaluate the geometrical design of PEMFC end plate, followed by fatigue analysis of PEMFC. The contribution of end plate design and performance of PEMFC stack during static and dynamic compression are discussed. Finally, design optimisation of PEMFC conducted in previous studies is reviewed.

2. DESIGN AND CONFIGURATION OF PEMFC SINGLE STACK

Stack clamping pressure plays an essential role in PEMFC. Insufficient and uneven contact pressure can significantly impede cell function and ultimately result in stack component failure. Larger stack dimensions have a more noticeable effect and optimisation of the contact pressure applied is required. Improved contact between neighbouring cell components occurs at higher normal stresses (Dey et al., 2019). Nonetheless, owing to the compression of the gas diffusion layer (GDL), higher pressure also results in an increase in the mass transport losses within the cell. The spatial pressure distribution on the active region is further impacted by nonhomogeneous externally applied force on the end plates. Consequently, it has to do with the end plate's geometrical structure, which offers opportunity for additional design enhancement.

Fuel cell assembly requires a sufficient load, as evidenced by the ohmic dominated portion of its performance characteristics. Fig. 1 shows the schematic diagram of PEMFC geometrical assembly. The bulk material conductivity alone is insufficient to explain the observed performance reduction. Contact resistance, which results from current flowing across the interfaces between various cell components, is the cause of the further reduction. It is discovered that contact resistance and the compressive force applied across it are directly correlated. Regardless of the clamping technique, tests for rectangular cell designs reveal almost minimal contact pressure in the active area's centre (Bates et al., 2013). Furthermore, nonuniform contact resistance values are a result of irregular pressure distribution on the GDL. Zhang et al. (2006) employed FEA to determine the relationship between contact resistance and clamping pressure. The contact resistance was determined using the contact resistance–pressure constitutive relation in the first technique, which was a simplified prediction. The contact area and contact pressure between the BPP and the GDL were examined using a straightforward geometrical relation. In the second method, the constitutive relation was used to calculate the contact resistance for each contact element, and the contact area and contact pressure between the BPP and GDL were examined using FEA. Next, by taking into account every contact element in parallel, the total contact resistance was computed. Additionally, the impact of load distribution on contact resistance was examined. The experimental results and both approaches' predictions showed good agreement. Fig. 2 shows the comparison between the contact resistance obtained from FEA and experimental.

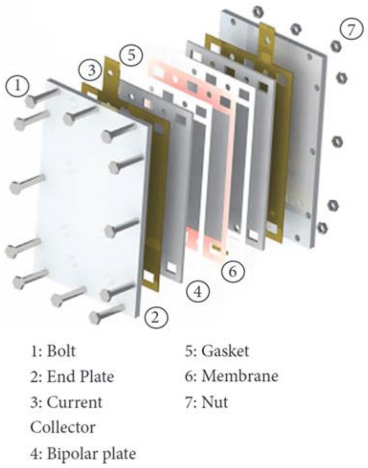

Fig. 1. Schematic diagram of PEMFC geometrical assembly (Dey et al., 2019)

Source: Dey et al. (2019)

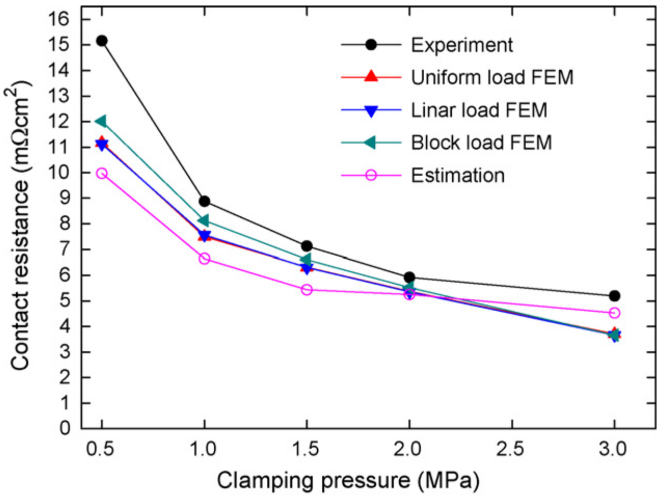

Fig. 2. Contact resistances by experiment and FEM analysis

Source: Zhang et al. (2006)

A numerical model of contact resistance has been constructed in a different study (Zhou et al., 2007) using GDL structure simulation and BPP microscopic surface topology. For any given pair of GDL and BPP in contact, the microscale model so established may accurately predict contact resistance if their structure and material properties are known. In this study, the overview of the porosity distribution, the deformation of GDL, and the contact pressure using the finite element method (FEM) is highlighted. A two-phase flow model to analyse the mass transport be utilised (Zhou et al. 2007). According to the numerical results, a strong clamping force causes the gas phase and liquid phase's transport resistances to increase because it reduces the porosity in the GDL. Conversely, a large clamping force may reduce the electrical resistance loss within the fuel cell by lowering the interfacial contact resistance. The combination of these two factors might provide the fuel cell with the ideal clamping force. Asghari et al.(2010) study on end plate design for 5 kW fuel cells took into account material selection, the development of a finite element model, and the selection of the model to compute deflections and stresses under applied loads and thickness optimisation. While the criteria for material selection and end plate design have been mentioned, more research is needed to fully understand end plate design and contact pressure distribution. In another study, the investigation is aimed to look into how the creation of sheets is impacted by the geometrical parameters of BPP. The impact of every parameter on the filling depth and thinning percentage of the BPP was assessed through the design of several experiments. FEA is used to gather the necessary data through numerical simulation. Finally, a mathematical equation can be used to forecast the filling depth and the thinning percentage given other geometric parameters (Khatir et al., 2021).

3. FATIGUE ANALYSIS OF PEMFC STACK

For fuel cells to last a long time, the proton exchange membrane's mechanical durability needs to be improved. Thus, it is crucial to understand how the fuel cell membrane's fatigue cracks throughout humidity cycles. Indeed, several research has been carried out to increase the membrane's durability. On the one hand, Wang et al. (2024) studied the longevity of the membrane is greatly impacted by material failure such as interface delamination and pore deformation. It used the cohesive finite element method (CFEM). It has

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been utilised to model fatigue fracture formation in the membrane and mechanical damage of the ionomer and catalyst coated layer. Thus, it able to match their simulated results well with experimental data. The fatigue fracture formation of the membrane during humidity cycles in a PEMFC was modelled to investigate the effects of crack position, clamping displacement magnitude, channel geometry (location and shape), and humidity cycle amplitude. It is discovered that raising the humidity amplitude may increase the membrane's tensile in-plane stresses, which would be harmful to its longevity.

Structural damage and fatigue failure of PEMFC may also induced by vibration during operating conditions. Using a 3-axis vibrating platform, Rajalakshmi et al. (2009) performed a sine sweep and random vibrating test and found that the torque given to some tightening bolts was decreased from 14 to 6 N m. Structural failures such irreversible plastic deformation (Jiang et al., 2004) and joint wear under vibration may be the source of the bolt torque release (Basava & Hess, 1998). According to the experimental findings, PEMFC fatigue life increases exponentially as cyclic stress decreases (Khorasany et al., 2015). These studies, however, mostly concentrate on the individual components. It provided with several numbers of experimental data, which served as the foundation for computational FEA and did not take into consideration how different components interacted with one another or specific geometrical structure, like the channels. This could have an impact on the stack's local and overall vibration responses. Consequently, numerical modelling at the stack level is another crucial technique for assessing the fatigue life of a stack under operating conditions (Liu et al., 2017). The research also examined the slippage between unit cells under impact using FEM. Researchers looked on the quantitative effects on the impact acceleration's direction and amplitude slippage (Wu et al., 2015). Liu et al. (2017) assessed component damage (bolts, gaskets, and PEMs) and fatigue life based on the Miner fatigue damage theory. Stack FEM models taking into account the structure details such channels and the non-linear mechanical component qualities was developed in order to increase the analysis precision and provide fine fatigue life contours of components with adequate details. Four operating conditions were used for the fatigue life analysis: single-axial (in the x-, y-, and z-axes independently) and multi-axial random vibrations. Fig. 3 shows the fatigue life distribution of the bolts in 4-clamping and 6-clamping stacks under different directions of applied vibrations. The 6-clamping stacks exhibited longer fatigue life in comparison to 4-clamping stacks. The increasing number of bolts can increase the rigidity of the of the end plate, leads to the decrease of cyclic stress induced at on the outside area of gasket and PEM.

4. DESIGN OPTIMISATION OF PEMFC STACK

Fuel cells are regarded as a strong contender for use in the transportation and automotive sectors due to the growing usage of environmental pollutants and the way they offer a new method of utilising compatible clean energy sources. Compared to combustion engines and batteries, the cost of producing fuel cells is now higher. Reduced assembly costs and increased fuel cell power density through optimisation are necessary for the commercialization of fuel cell stacks (Wang et al., 2024).

The previous research study proposed a mathematical correlation for metallic bipolar plate geometrical parameter optimisation. Reaching the maximal forming limit and completing the bipolar plate formation without breaking the plate in crucial regions are two important benefits of optimising the bipolar plate's geometrical characteristics. Performance of the cell and mass transport are impacted by channel width and depth. In this study, integration of design of experiment (DOE) and FEA was implemented. The findings indicated that the parameters that have the biggest effects on plate thinning were corner radius, draft angle, and channel depth. Furthermore, the maximum channel depth is most influenced by the corner radius and the draft angle. Finally, a mathematical equation can be used to forecast the filling depth and the thinning percentage given other geometrical parameters (Khatir et al., 2021).

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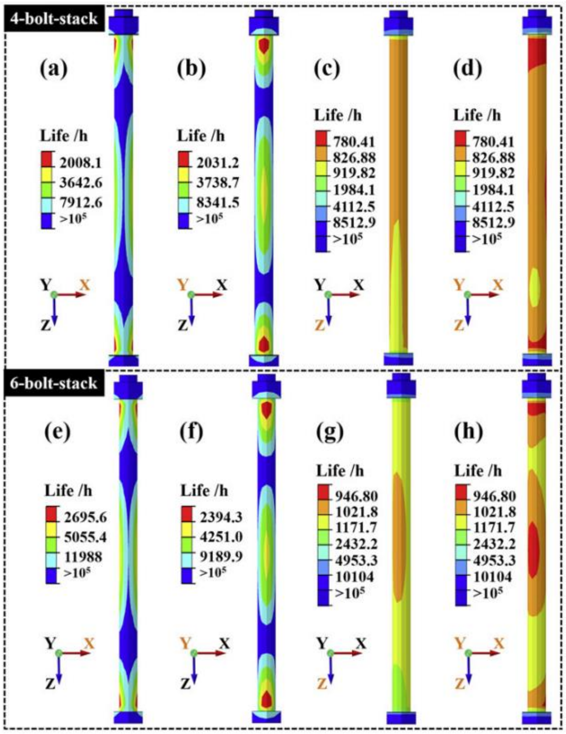

Fig. 3. Contours of fatigue life distribution of the bolts: (a) – (d) for four-bolt clamping, (e) – (h) for six-bolt clamping with application of vibrations in (a) & (e) in x-direction, (b) & (f) in y-direction and (d) & (h) in multi-direction

Source: Liu et al. (2017)

In other work, Habibnia et al. (2020) reported the optimisation of end plates in polymer membrane fuel cells to generate low content and uniform pressure on the gas diffusion layer. The end plates and the impact of factors on the pressure of the gas diffusion layer were studied for this purpose. The thickness of the end plate, the depth of the BPP groove, and the clamping pressure applied to the end plates were the investigated parameters. The stress distribution on the gas diffusion layer was analysed using FEA. A numerical relationship between the influencing values and the outputs was obtained by extracting the FEA data and importing them into the Adaptive Network-based Fuzzy Inference Systems. The effective parameters of the ideal fuel cell state were assessed in this study using the bee algorithm. They proposed the optimised parameters were 12 mm for end plate thickness, 0.1077 mm for BPP groove and the optimum clamping pressure was 11.0199 MPa. Fig. 4 shows the suggested optimised geometrical design of the end plate. The end plate thickness and the depth of the BPP grove can affect the deflection of BPP after applying clamping pressure. Excessive deflection of end plate and BPP cause ununiform pressure distribution in PEMFC, leads to leakage and high electrical contact (Jo et al, 2020). Meanwhile, the excessive clamping pressure can reduce the removal of produced water in PEMFC (Yan et al, 2020).

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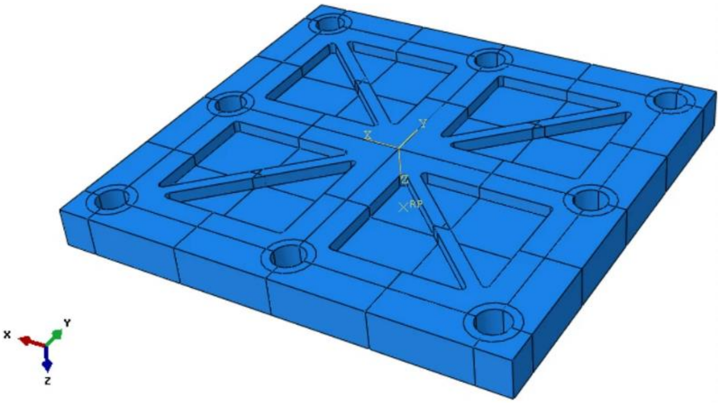

Fig. 4. Optimal proposed geometric structure of the end plate

Source: Habibnia et al. (2020)

Flow field design also play an important role in PEMFC. Flow field is crucial to the performance of PEMFC and can be summarized by several key functions: ensuring uniform distribution of reactants, facilitating the efficient removal of products, promoting effective transport of electrons and protons and maintaining an appropriate pressure drop (Arvay et al., 2013). The design of flow field plates has evolved from simple structures with basic functionalities to more complex multidimensional configurations that can enhance performance, especially in terms of mass transfer. In the early stage, conventional flow field designs such as straight, serpentine, integrated and meandering flows were proposed and implemented (Li and Sabir, 2005; Marappan et al., 2021). While some of these designs have demonstrated practical success, most simple flow designs have primarily been utilised for mechanism studies investigating performance dependence on flow field design (Boddu et al. 2009). Zhang and Tu (2024) have critically summarized the everal typical types of flow-field designs, namely porous material of flow plate, pin type, parallel flows, criss-cross flows, serpertine flows and radial and arc-shaped flow channels. Each design has given significant effect on the performance of PEMFC. For instant, porous material of flow plate has good water removal and uniform mass transfer, while parallel flows design has low pressure drop in both reactant and coolant flows.

5. CONCLUSION

In conclusion, the application of FEA has proven invaluable in understanding the mechanical characteristic of PEMFC FEA has become a powerful numerical tool in optimising the design of PEMFC structure to enhance its performance. This brief review highlights the development of numerical model of PEMFC structure for evaluation of pressure distribution in BPP and end plate, fatigue analysis of PEMFC due to vibration using FEA and numerical optimisation of PEMFC design with application of FEA.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

Abdul Muhaimin Abdul Aziz: Conceptualisation, and writing-original draft; **Ng Wei Shi**: Conceptualization, and draft preparation; **Rozan Mohamad Yunus**: Supervision, writing- review and editing, and validation; **Mohd Afzan Mohd Anuar**: Project administration, conceptualisation, final review, editing, and validation.

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