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Improving PEM Water Electrolyser's Performance by Magnetic Field Application

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ABSTRACT

This paper demonstrates the significant and positive effect of applying a magnetic field on the performance of Proton Exchange Membrane Water Electrolysers (PEMWE). A magnetizer and a transparent PEMWE cell are used to observe the effect of the magnetic field at variable water flow rates on the PEMWE performance. The presence of the magnetic field introduces Lorentz force which results in a significant improvement in the electrolyser performance. The magnetic flux density is varied between 0 T and 0.5 T, while the water flow rate is varied from 100 ml min^{-1} to 300 ml min^{-1} to study the effect and relationship between the two parameters and the performance of the PEMWE. Under a 0.5 T magnetic field and 300 ml min^{-1} flow rate, a 33% increase in the cell performance is achieved compared to the conventional operation at the same flow rate. The positive effect is explained by the introduction of Lorentz force from the magnetic field to the operating PEMWE. The improvement here is due to the relaxation and pumping effect of the magnetic field on the electrode surface which results in enhancing oxygen bubbles removal and lowering mass transport polarisation. Moreover, the enhanced oxygen bubbles removal is expected to increase the lifetime of the electrolyser as a result of the reduced contact between the produced oxygen and the anode materials.

Keywords: PEM Water Electrolyser, Water Flow Rate, Magnetic Field, Lorentz Force, Magnetohydrodynamic

1. Introduction

1.1. Background

With the increase in the global energy demand and the urgent need to decarbonise the energy sector in all its applications, the need for an energy carrier to store and carry the energy produced from renewable resources increases. Here, hydrogen provides a solution for both

short and long-term energy storage [1, 2]. Hydrogen can be produced by thermochemical, photocatalytic and electrochemical methods using a wide range of feedstocks, including; water, hydrocarbons and biofuels. However, only through electrochemical water electrolysis using electricity from renewable energy sources (RES), green (carbon free) hydrogen production is possible. It is also the most suitable solution for the production of high purity hydrogen that is required for fuel cell electric vehicles to provide sustainable transport [3].

Moreover, as electrolysers capacity increase, the produced hydrogen may be used to decarbonise industrial processes and residential heating; gradually leading to the realisation of a sustainable hydrogen economy [4]. Thus, studies focused on the production of green hydrogen via more economic and efficient electrolysers are essential for establishing a sustainable clean energy system [5].

There are different types of water electrolysers, namely; alkaline, solid oxide and PEM water electrolysers [6, 7]. By utilising these technologies, hydrogen can be produced at the large scale to meet the energy market demands [8, 9]. PEMWEs have the advantage of high efficiency, fast response to load change, ability to operate at high pressure (increasing the systems overall efficiency) and the production of high purity hydrogen (99.999%) [10]. Moreover, they have proven stability and long-term durability due to the utilisation of a solid polymer electrolyte and novel catalyst materials [7].

The development of PEMWEs has attracted a lot of academic and industrial attention in the last century. The conducted research included experimental and numerical modelling activity aiming to improve the performance and the stability of the electrolyser [11, 12]. This has inevitably led to advancements in the performance and the lifetime of the electrolysers by developing and optimising the different cell components. In the last ten years, the operating

current density increased from 0.6 to 2 A cm^{-2} demonstrating a significant technological development [11, 13].

Despite the increased interest in PEMWE, the use of expensive catalysts in the electrolyser stack has limited the commercial spread of these systems [14, 15]. In addition, the reduced performance due to the liquid - gas phase, diffusion caused by gas crossovers through the electrolyte prevented the systems from reaching the desired performance level [16]. Therefore, further studies focused on reducing cost, increasing efficiency and enhancing durability are very crucial for PEMWE commercialisation [17, 18].

Various physical fields were introduced by researchers in an attempt to increase the performance of water electrolysers. Field effects used to increase the cell performance can be categorised into three main groups: super gravity [19, 20], ultrasonic [21] and magnetic fields [22-25] . Thanks to field effects, the distribution and removal of bubbles from the electrode was enhanced and correspondingly the detrimental effects of bubble coverage on the surface area of the electrode is decreased. These improvements resulted in a reduction in reaction overpotentials and electrolyte resistance, and enhanced mass transfer in the electrolysis cell resulting in a significant increase in the cell efficiency [21, 26]. it was found that the presence of a magnetic field contributes to electrolyser electrochemical performance through enhancing gas removal from the electrode surface. These improvements are due to the magneto hydrodynamic (Lorentz) Force [27, 28] and the magneto aerodynamic (Kelvin) Force [29, 30].

The effect of the magnetic field on electrolysis was studied by researchers with a focus on understanding its effect on alkaline and acidic solutions (concentration, conductivity etc.) [22], electrode materials [27], electrode geometry [31], and its interaction with operating parameters such as; voltage change [32] and the magnetic flux density [29, 33]. For example,

Lida et al. [22] studied the effect of magnetic field on the cell voltage in alkaline (KOH) and acidic (H_2SO_4) solutions. When applying a magnetic field, they observed significant reduction in the cell voltage due to decreased mass transfer losses and reduced electrolyte resistance. They reported that the cell properties depend on the electrolyte concentration and the strength of the magnetic flux density.

Matsushima et al. [31] used transparent electrodes to observe the magnetic field effect on convection and electrodes bubble coverage. The effect of the magnetic field became more significant with increasing the operating current density. Moreover, under the magnetic field working conditions, the bubbles coverage time was smaller with lower number of nucleation. From their experimental results, they created a proportional function to describe the relationship between the contact angle of bubbles and the magnetic field. Lin et al. [34] tested the behaviour of electrode materials, namely; nickel, platinum and graphite, under the magnetic field. Here, the ferromagnetic nickel electrodes obtained 14.6 % current density improvement. In another study, Lin et al.[35] reported that both the magnetic field and the pulse potential remarkably increased hydrogen production efficiency. According to their findings, by the help of pulse potential, bubble removal acceleration and mass transfer ratio is enhanced. Moreover, the introduction of a magnetic field improves the mass transport inside the electrochemical cell by enhancing convection at higher limiting current diffusion values [33, 36-38]. In addition, Yin et al. [39] investigated the effect of magnetic field on Microbial Fuel Cells (MFCs) by studying changes in the performance and electrochemical impedance of the cells. They used 100 mT and 200 mT magnetic flux density values and observed a reduction in the charge transfer resistance (R_{ct}) of the cell.

In our previous studies [27, 40], we investigated the performance of aqueous water electrolysers under magnetic field and a 10% increase in the cell performance was observed. In comparison with the aqueous solution electrolyser cell, PEMWE have smaller electrodes

gap, resulting in a lower proton transfer path through the membrane and therefore higher current densities can be achieved.

As explained above, researchers reported enhanced performance for different solid polymer electrolyte fuel cells through the application of magnetic field. However, according to the authors' knowledge, the effect of the magnetic field on PEMWE has not been studied or reported in the literature. In this paper, the effect of magnetic field on PEMWE was investigated experimentally. The electrolyser was operated and characterised under different magnetic flux densities and at variable water flow rates. Thus, an experimental installation of a transparent Perspex PEMWE cell was used to reduce interference in the magnetic field applied by the magnetizer and observe the magnetic field effect on the PEMWE cell performance. The magnetic flux density was varied between 0 T to 0.5 T while the flow rate was changed between 100 ml min^{-1} to 300 ml min^{-1}. The cell performance was improved by up to 56% at 0.5 T magnetic field. The significant improvement in PEMWE performance through the magnetic field application provides vital evidence for PEMWE technology developers to investigate the inclusion of magnets in large scale electrolyser cells and stacks. Thus, through the implementation of this novel approach, higher efficiency renewable energy storage (in the form of hydrogen) and improved sustainability of the future energy system may be achieved.

1.2. Lorentz Force Theory in PEM Water Electrolysers

In an PEMWE, water is decomposed into oxygen and hydrogen gases at the anode and cathode sides respectively. The anode and cathode reactions are shown in (1) and (2) respectively.

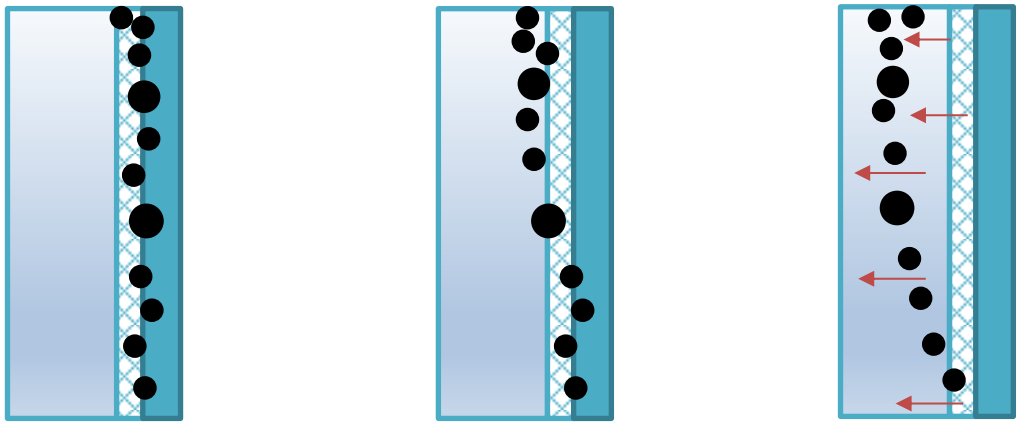
$$2H_2O_{(l)} \rightarrow \mathrm{O}_{2(\mathrm{g})} + 4\mathrm{H}^{+}_{(\mathrm{aq})} + 4e^{-}\left[E_{Ox} = -1.23\ V\right] \quad (1)$$

$$2H^{+}_{(aq)} + 2e^{-} \rightarrow H_{2(g)} \left[E_{Red} = 0.00\ V\right] \quad (2)$$

During these reactions, potential losses take place at the electrodes, the electrolyte and the flow channels. These losses are activation polarizations (V_{act}), ohmic polarizations (V_{Ohm}) and mass transfer polarizations (V_{trans}), and the overall cell voltage is directly related to these losses as shown in (3).

$$V = V_{rev} + V_{act} + V_{trans} + V_{ohm} \quad (3)$$

Here, activation losses are highly dependent on the catalyst material at the anode and the cathode catalyst layers. In PEMWE, IrO_2, RuO_2 are typically used for the anode catalyst, while Pt/C is used for the cathode catalyst to obtain relatively low activation overpotentials. However, the biggest voltage loss is the ohmic polarisation [75]. It is highly dependent on the electrode conductivity, the contact resistances between the cell components and the ionic conductivity of the electrolyte [76]. Mass transfer polarisation at the electrode surface also affects the cell performance especially at high current densities due to the high bubble formation at the surface of the electrode which prevents water from reaching the active catalyst sites. As shown in Fig. 1.a, during the oxygen and hydrogen evolution reactions, bubbles form at the catalyst layer surface. The gas diffuses away from the catalyst layer outwards due to concentration difference (Fig. 1.b), then buoyancy force pushes the bubbles upwards and off the surface of the electrode to leave the cell through the gas flow channels (Fig. 1.c). However, at high current densities, passive bubbles removal by buoyancy force becomes insufficient resulting in mass transfer losses and limiting the possible maximum hydrogen production rate.



(a) (b) (c)

Figure 1. Behaviour of gas bubbles in the PEMWE anode a) gas evolution due to the electrochemical reaction, b) growth and detachment of bubbles from the electrode surface, and c) bubbles removal.

When introducing a magnetic field to the cell, it is possible to reduce the mass transfer losses at the electrodes. This magnetic effect on the electrode is known as magnetohydrodynamic (MHD) phenomenon which is created by Lorentz Force [37]. Lorentz Force effect on the electrode surface is shown in Fig. 2.

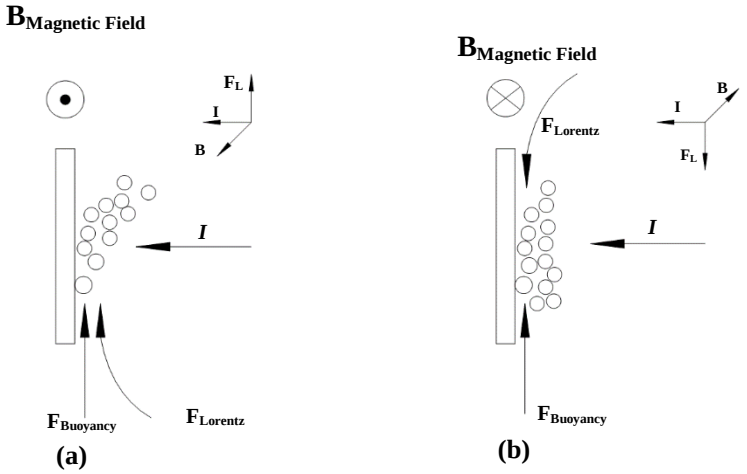


Figure 2. Schematic view of MHD effect, (a) Lorentz Force upward,

(b) Lorentz Force downward [27].

With the magnetic field positioned perpendicularly to the current, an upwards or a downwards Lorentz force effect can be obtained based on the right-hand rule and as shown in Fig. 2.a and Fig. 2.b respectively. Formation of Lorentz force in the vectoral form of current density and the magnetic flux density can be shown in Eq.4 [41, 42] :

$$\overrightarrow{F_L} = \vec{j} x \vec{B} \tag{4}$$

Here $\overrightarrow{F_L}$ demonstrates the Lorentz Force, $\vec{j}$ is the current density and $\vec{B}$ is the magnetic flux density. In the case of upwards Lorentz Force, the force combines with the buoyancy force and accelerates the separation of bubbles off the electrode surface. On the contrary, when Lorentz Force is downward, it produces a counter force to the buoyancy effect which reduces the bubble removal from the surface resulting in an increase in mass transfer losses. These phenomena can be explained by Eq.5 and Eq.6 as below [27, 43]:

$$F_{net} = F_B + F_L \tag{5}$$

$$F_{net} = \left| F_B - F_L \right| \tag{6}$$

Here F_B demonstrates the Buoyancy force. MHD is an effective method to provide additional pumping effect on the gas bubbles which increases the current density inside the cell [44]. In addition, Koza et al. [23] stated that the electrical pathway around the gas bubbles creates vortex convection which helps the separation of bubbles from the surface. Moreover, it is found that the magnetic field has an effect on the bubble dimensions. Lin et al. [35] used a Charge Coupled Device (CCD) camera to observe Lorentz Force effect on the oxygen and hydrogen evolution reactions at the electrodes. They concluded that applying a magnetic field results in smaller bubble diameter and found that moving low diameter bubbles off the electrode surface is easier than larger bubbles. Matsushima et al. [25] and Lida et al. [22] studied MHD effect on the polarisation curve with different electrode distance and electrolyte types in an electrolysis cell. They concluded that low electrode distance, high electrolyte concentration and high magnetic flux density improve the cell performance remarkably.

2. Experimental Setup

2.1. Materials

The electrolyser membrane electrode assembly (MEA) was prepared in house with an anode of IrO_2 with catalyst loading of 3 mg cm^{-2} (Sigma Aldrich-206237) and a cathode of Pt/C catalyst (Fuel Cell Store-Platinum on Vulcan XC-72R - 3151721) with Pt loading of 0.4 mg cm^{-2}. Toray TGP-H-120 PTFE was used as the cathode GDL and platinized Ti mesh is used as the anode GDL (Fuel Cell Store- 592770). Nafion 115 (Fuel Cell Store-591139) was used for the polymer electrolyte membrane which is 127 µm thick. The anode catalyst layer was coated on the membrane using an airbrush with the assistance of a vacuum table, and the cathode catalyst layer was applied on the GDL using the same method. The MEA is then prepared by hot pressing the anode GDL, the anode catalyst coated membrane and the cathode

catalyst coated GDL. The cell had an active surface area of 5 cm^2. A transparent Perspex PEMWE cell was used to allow more magnetic permeability through the cell.

2.2. The application of the Magnetic field in the PEMWE cell

In Fig. 3, a schematic of the experimental setup of the electrolyser with the magnetic field source is shown. DI water is delivered to the electrolyser cell using a variable speed pump. The electrolyser cell is placed in the magnetic field generated through a controllable magnetizer by Newport Instruments ® and the produced gases from the anode and the cathode are collected in glass tubes. It is important to note that constant Magnetic field can also be obtained from a permanent magnet; however by the help of electromagnets, it is easy to control the magnetic flux densities without changing experimental parameters. Thus, in this study, an electromagnet is used to obtain variable magnetic flux density and observe the change in the electrolyser performance. A Versastat 3 Potentiostat-Galvonastat system was used to drive the electrolyser and conduct the measurements. All experiments are repeated at least three times to test reproducibility of the results.

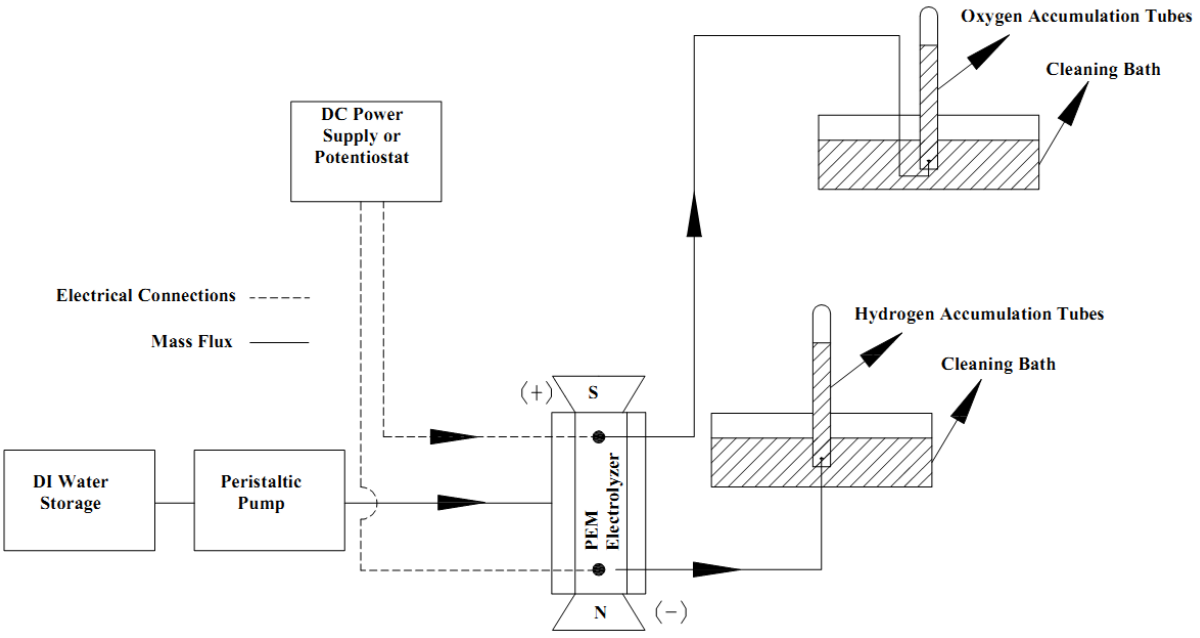


Figure 3. Schematic view of the experimental setup of the electrolyser operation under a magnetic field [43].

As can be seen in Fig. 3, the magnetizer poles North (N) and South (S) are positioned to generate a magnetic flux density perpendicular to the direction of the current flow through the electrolyser cell. The magnetic flux density generated was measured using a LakeShore 455 DSP gauss meter. The cables of the potentiostat were fixed on the insulated region of the magnetizer to avoid any interference in the measurement. Linear Sweep Voltammetry (LSV) measurements were conducted to obtain the V-I curves at the different operating conditions. The cell voltage was changed between 0 to 2.5 V at a scan rate of 10 mV s^{-1} to obtain the LSV. The PEMWE was operated at room temperature. Fig. 4 shows the experimental setup as installed in the laboratory.

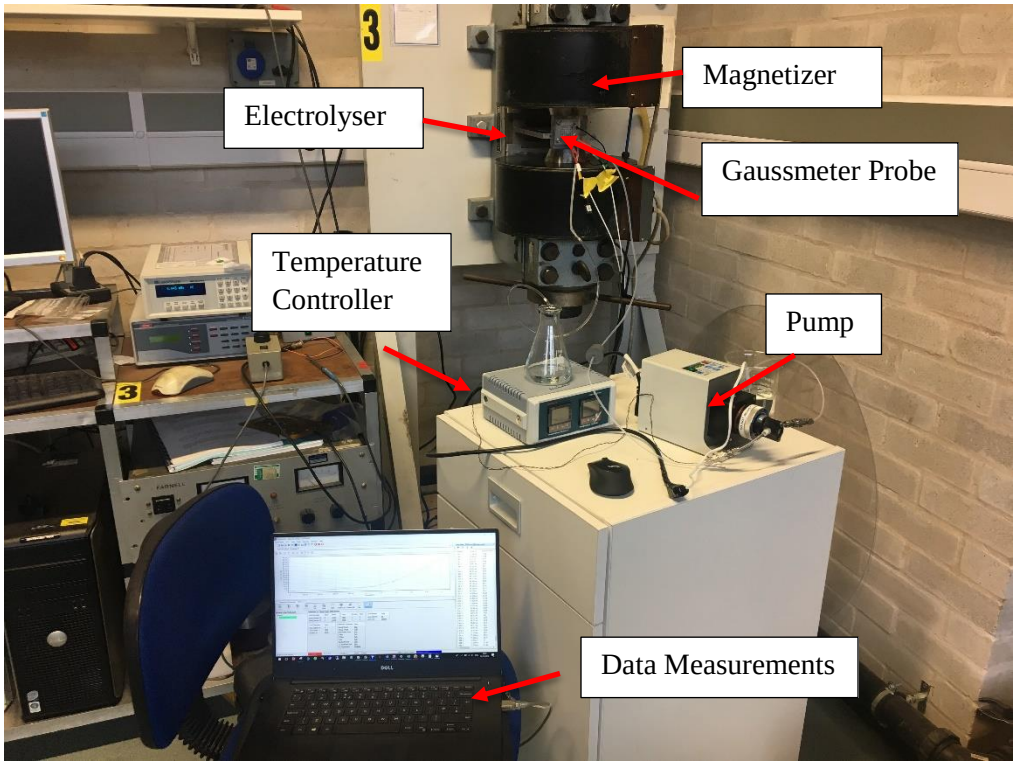
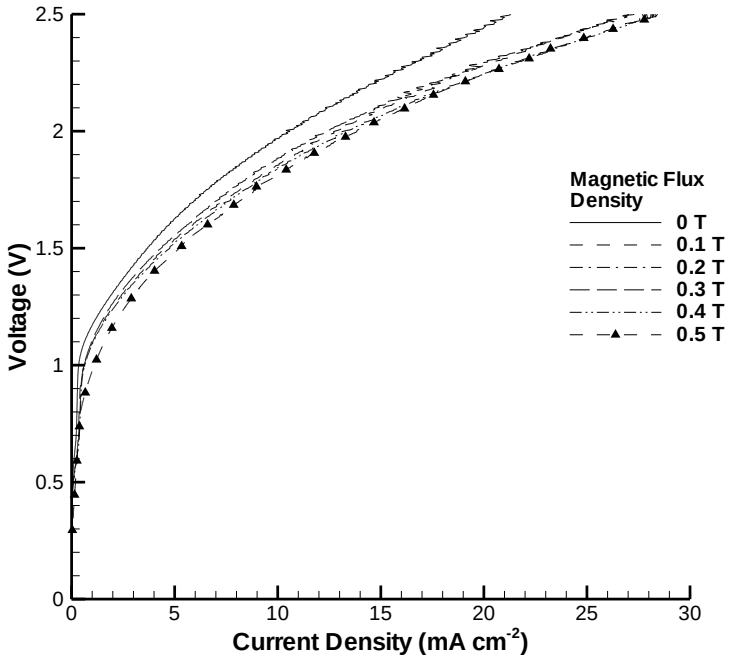


Figure 4. Experimental Setup for the Magnetic Field Experiments of PEMWE

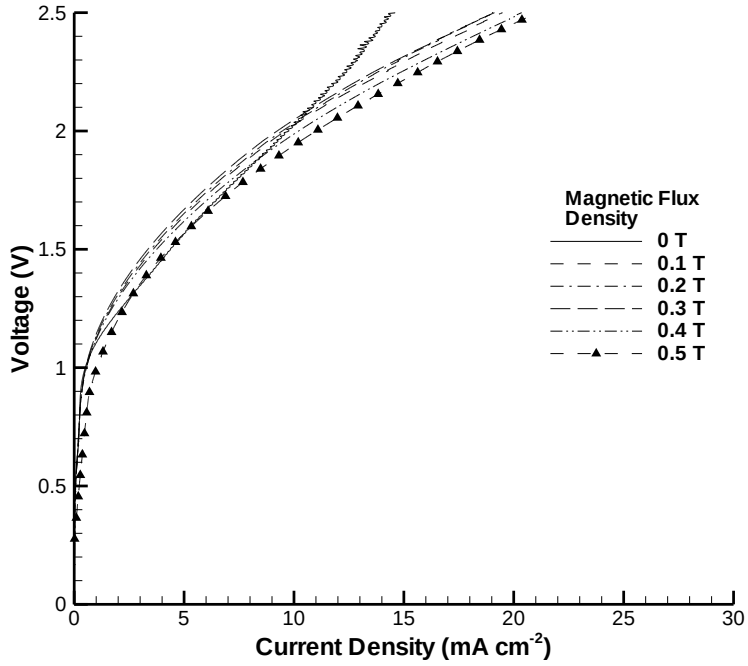
Experiments were conducted to study the effect of water flow rate and magnetic flux density on the PEMWE performance. The water flow rate was varied between 100-300 ml min^{-1} while the magnetic flux density was varied between 0.1 T to 0.5 T and an V-I curve was obtained for each combination. The results were then analysed to identify the effect of each parameter.

3. Results and Discussions

Fig.5a shows the effect of the magnetic flux density change on the PEMWE when operated with 300 ml min^{-1} water flow rate. When increasing the magnetic flux density from 0 T to 0.1 T, a significant step up in the cell performance is observed. However, when increasing the value of magnetic flux density from 0.1 T to 0.5 T, small change in the performance is observed with a linear increase in the current density with the magnetic flux density. It is important to note that at 0.5 T magnetic flux density the PEMWE current density is increased by almost 32% at 2.5 V.



(a)



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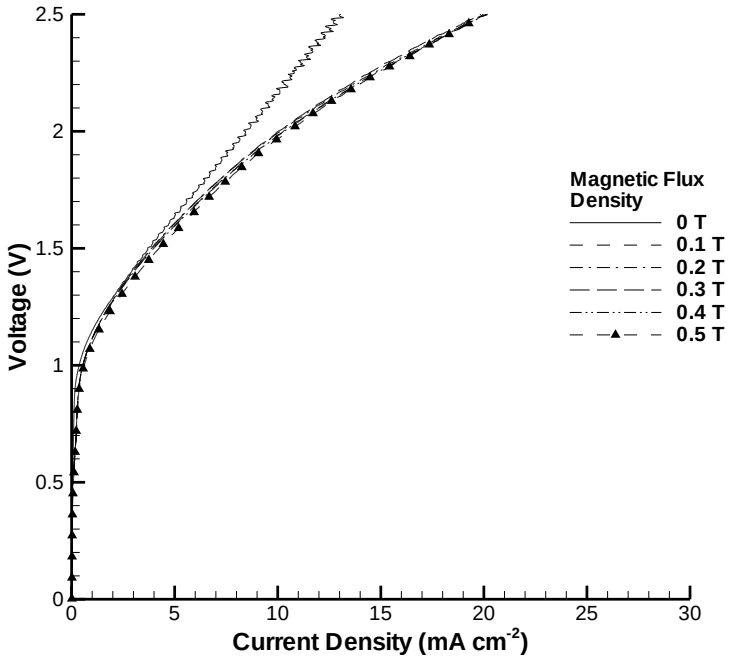


(c)

Figure 5. Effect of Magnetic field on PEMWE at water flow rates of (a) 300 ml min^{-1} (b) 200 ml min^{-1} and (c) 100 ml min^{-1}.

The improvement in the performance is notably seen in the ohmic and mass transport regions of the polarisation curve. This improvement is in agreement with the above-mentioned theory on the effect of the magnetic field in the electrochemical cell [41]. On the other hand, no change is seen in the activation region with the change of magnetic flux density.

In Fig. 5b, the effect of magnetic flux density on the PEMWE can be seen at 200 ml min^{-1} water flow rate. Again, it can be observed that by changing the magnetic flux density from 0 to 0.1 T, the performance of the cell is improved significantly (46% increase in current density at 2.5V). Again, a linear increase in the performance is noted with increasing the magnetic flux density from 0.1 T to 0.5 T. However, the rate of increase in performance in different magnetic flux density is higher than that observed at 300 ml min^{-1} flow rate. The flow rate value is then further reduced to 100 ml min^{-1} to confirm the observed relationship between flow rate and magnetic flux effect.

In Fig. 5c, the effect of the magnetic flux density on PEMWE at 100 ml min^{-1} water flow rate is shown. Here the same trend can be seen, as at the lowest flow rate of 100 ml min^{-1} the change in performance is the most significant. Here, the cell current density at 2.5 V is increased by 56%. However, no further improvement in the performance is observed with varying the magnetic flux density between 0.1 T to 0.5 T. Table 1 shows a summary of the change in PEMWE current density with the change in the magnetic flux density.

Table 1. The change in PEMWE current density with the change in the magnetic flux density.

Water flow rate (ml min^{-1})	Current density increase at 2.5V		
	0.0T vs 0.1T	Total (0.0T vs 0.5T)	Current density increase rate with magnetic flux change from 0.1 T to 0.5T
100	55%	56%	1.5 %

200	35%	46%	18.5 %
300	27%	33%	23.17 %

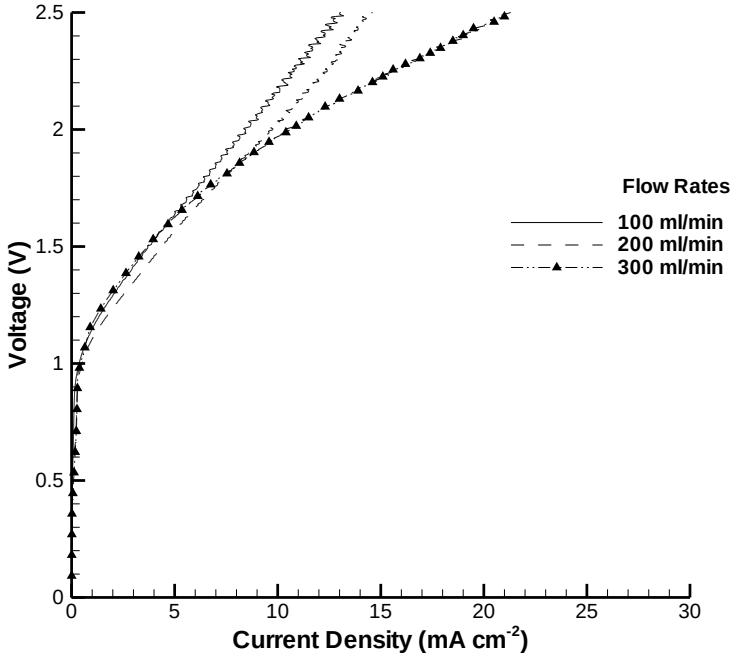
Table 1 highlights the significant increase in current density at 2.5 V; indicating an increase in hydrogen production rate, with the introduction of the magnetic field. The main performance enhancement is achieved in the step change from no magnetic field to 0.1 T, after which lower increments are observed especially at low water flow rate. It is also clear that at increased water flow rate, the stronger magnetic flux starts to have a more significant effect on the performance. This can be due to the limited time for the interaction between the magnetic field and the gas bubbles at high water flow rate and so a higher magnetic flux is required to observe Lorentz force effect. In the gas phase, due to the paramagnetic property of O_2, gas bubbles change their direction through the magnetic field [45]. Moreover, the ratio of the flow induced by Lorentz force to that induced by natural buoyancy is larger. Weier et al. [28, 46, 47] investigated the effect of magnetic field on the convection in the electrolysis cell. They observed similar results in the copper electrolysis and concluded that the flow ratio induced by Lorentz force improves the convection inside the cell.

Fig. 6 shows the effect of water flow rate on the cell performance without and with a magnetic field (0.5 T) applied. The effect of water flow rate on the ohmic and mass transport regions is apparent for both cases; as the mass flow rate increases the losses in both regions decrease. The main difference between the two cases is noted in the mass transport region. The magnetic field seems to eliminate the effect of mass transport completely at all flow rates, and therefore highlights the change in the ohmic resistance with increasing water flow rate. It is well-known that bubbles stuck on the electrode surface increase the through-plane surface area resistance due to lowering the contact area with the catalyst layer. Thus, both, mass

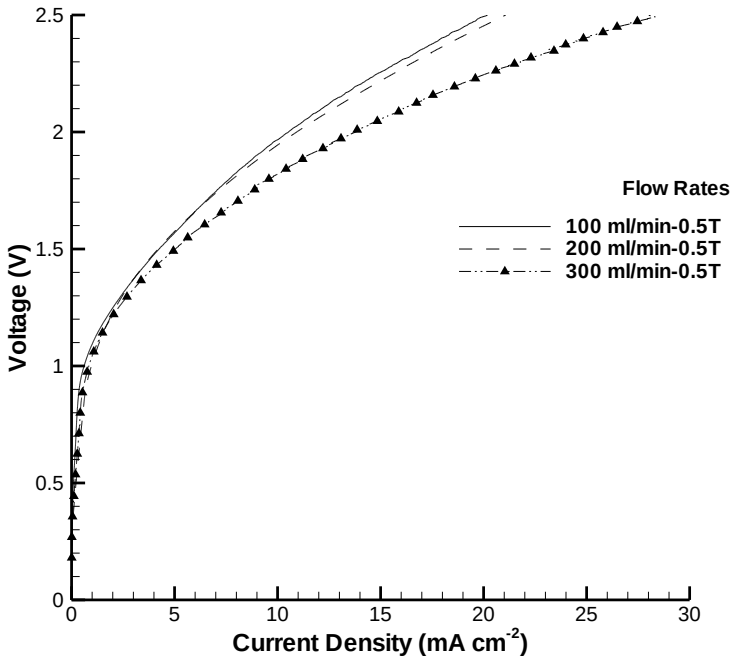
transfer losses and the ohmic resistance are affected by the magnetic field [30, 48, 49]. The lower ohmic loss under magnetic field is also reported by Yin et al.[39] using EIS studies.

The effect of the water flow rate has been discussed in the literature [50-52]. It is explained that the increase in flow rate results in a reduction of ohmic resistance due to removal of non-uniform distribution of gas bubbles between the electrolyte and electrode interface [53, 54]. Moreover, the higher flow rate allows faster product gas removal from the electrode surface and therefore reduces mass transport losses [52, 55].

At low water flow rate, the gas phase is more dominant inside the cell. Due to the higher magnetic permeability in the gas phase than liquid phase [56, 57], the change in the cell performance at lower flow rate in the fixed magnetic field is higher than that at higher flow rates. This further confirms the positive effect of the magnetic flux in reducing the mass transport losses in PEMWE.



(a)



(b)

Figure 6. Effect of flow rate on the performance of the a) non-magnetized and b) 0.5T magnetized PEMWE cell.

Finally, Table 2 summarises the change in the electrolyser current density with the various operating conditions of water flow rate and magnetic flux values.

Table 2. Current Density value at 2.5 V for magnetized and non-magnetized cells

	Magnetic Flux Density					
	0 T	0.1 T	0.2 T	0.3 T	0.4T	0.5T
Flow Rate (ml min^{-1})	**Current density at 2.5 V (mA cm^{-2})**					
100	13.068	20.26	20.224	20.076	20.286	20.414
200	14.552	19.711	19.223	19.246	20.573	21.287
300	21.245	26.981	26.425	27.333	28.245	28.3319

4. Conclusion

This study demonstrates experimentally a significant improvement in PEMWE performance achieved via the application of magnetic flux at various operating conditions. The results show that at all water flow rate values, the performance of the cell is improved significantly under magnetic field working conditions. The performance improvement is especially noted at lower water flow rates (100 and 200 ml min^{-1}) where the buoyancy force is more dominant for gas bubbles removal, and therefore Lorentz force effect can be easily observed. At higher water flow rate (300 ml min^{-1}) similar performance improvement is observed but with higher enhancement shown at higher magnetic flux density.

It was demonstrated that at 300 ml min^{-1} and 0.5 T magnetic flux density working conditions, the current density value of the cell is increased by 33% at 2.5 V. These results show that the application of a magnetic field on PEMWE can easily and significantly increase the hydrogen production performance. Furthermore, similar effect can be obtained in commercial systems by employing constant magnets which may result in enhanced overall system efficiency with little capital and no operational cost. The DOE has set a target to lower the hydrogen production cost below 2.3 $/kg. Thus, the significant 33% improvement achieved in the electrolyser performance by introducing the magnetic field is an important step towards this target [43].

Finally, the stationary nature of renewable energy powered PEMWEs allows designing high-performing magnetized PEMWE stacks for green hydrogen production. In our future studies, a Multiphysics numerical model for magnetised PEMWE will be developed, and gas flow observation techniques will be employed to further study the effect of magnetic field on PEMWE operating under other operating conditions.

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Nomenclature

Superscripts and subscripts

F_L	Lorentz Force, N
F_B	Buoyancy Force, N
j	Current Density, mA.cm^{-2}
B	Magnetic Flux Density, Wb.m^{-2}
V_{act}	Activation Polarizations, V
V_{Ohm}	Ohmic Polarizations, V
V_{trans}	Mass Transfer Polarizations, V

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