Effects of operating parameters on the performance of a zinc-air fuel cell

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Abstract. As a promising energy storage device, the rechargeable Zinc-air fuel cells (ZAFCs) has attracted an increasing attention because of their high energy density, cost-effectiveness, non-toxic (in terms of the manufacturing materials of the cell as well as the products of the reactions), the rich abundance of zinc, compact system design, as well as its environmental benignity. Rechargeable Zinc-air fuel cells (ZAFCs) are investigated as a possible technology for fast responding large-scale electrical energy. A broad study was performed to examine the influence of different ranges of parameters such as electrolyte flow rate (0-250 mL/min), electrolyte concentration (10-60% by weight KOH), electrolyte temperature (26-60°C), active or passive air supply (0-8 L/min), and the effects of each parameter on the cell performance was studied and analysed and the best parameters were chosen to maintain the most effective cell operation.

1. Introduction
The Conversation of climate change and the increasing demands for energy are accelerating the unavoidable shift from fossil fuels to clean renewable energy[1,2]. Additionally the deteriorating fossil-fuel supplies, and the growing global concern over increased greenhouse gases emissions and their effect on global warming and the atmosphere[3]. As well as ,the requirements for energy and power density of power sources for the portable electronic devices and electronics that have been quickly increasing[4].All these issues had raised the international need to invent alternative energy sources such as: Lithium ion batteries, metal-air fuel cells, flow redox cells, and sodium-Sulphur batteries as alternatives that have been proposed to overcome the previous issues[5]. Lithium-ion batteries (LIBs) have dominated the consumer industry due to its high power density and specific capacity[6]. Many studies have been written about LIBs[7,8], but now the (LIBs) are approaching their range limit, since the capacity of the electrode materials limits their power density[1,9]. There are also some excellent recent researches on using Nano spheres[10], nanofibers to enhance LIBs[11]. One of the major drawbacks of LIBs, is it's severe toxicity , high cost and their hazardous nature[12]. One of the most interesting alternatives to traditional power sources is metal/air fuel cells. Since they are reliable, environmentally friendly, and fully renewable, these fuel cells have massive potentials. The positive electrode in these batteries uses oxygen as the reactant, which can be taken from the air outside the cell. Indeed, the metal-air batteries (MABs) use a compatible electrolyte to electrochemically engage an air-breathing positive electrode to a metal negative electrode[6]. These batteries have all the properties of traditional batteries since the negative electrode is made of metal. MABs have a porous positive electrode structure, similar to conventional fuel cells. The positive electrode has an infinite amount of oxygen as the reactant. As a result, MABs may have up to ten times the energy density of LIBs[6,13]. Because of advantages like low cost, safety, exceptionally high energy density, and abundant raw materials, MABs are being considered as an alternative to LIBs. [14]. Metal-air fuel cells can be used for both immobile and portable
applications[15]. The difference between "metal air fuel cell" and "metal air battery" is usually defined as: The system should be referred to as a "metal air fuel cell" if both mineral fuels and oxidizing elements, such as oxygen or air, are introduced from outside the cell. On the other hand, if the mineral fuel's chemical energy is confined within the cell, the device should be classified as a "metal air battery."[16]. Because of its higher specific energy density compared to other energy storage technologies such as Li-ion systems, metal-air batteries are having an increasing attention in both academic and industrial domains. Various metals such as Al [17], Fe [18], Li [19], Mg [20], K [21], zinc [22], and another (metals or alloys) [23] are used for metal air/oxygen batteries. Table 1 compares the theoretical energy density, and nominal cell voltage of various metal air batteries[24].

Table 1. shows a comparison of some metal air and Li-ion batteries [24].

| Battery systems | Li-ion | Li-air | Na-air | Mg-air | Al-air | K-air | Zn-air | Fe-air |
|-----------------|--------|--------|--------|--------|--------|-------|--------|--------|
| Year invented   | 1980   | 1996   | 2012   | 1966   | 1962   | 2013  | 1878   | 1968   |
| Metal price [US$/kg] | 20    | 20    | 2.5    | 2.3    | 1.9    | 1.0   | 2.6    | 0.5    |
| Nominal cell voltage [V] | 3.2-3.85 | 2.96 | 2.27   | 3.09   | 2.71   | 2.48  | 1.65   | 1.28   |
| Theoretical energy density [Wh/kg] | 265   | 3458  | 1106   | 2840   | 2796   | 935   | 1086   | 763    |

Amongst all metal-air batteries, the zinc-air selection represents an environmentally friendly, safe, and possibly simple and cheap way to store and distribute electrical energy for electric vehicles and portable and stationary devices as well [25]. Zn-Air technology has two additional features that make it very appealing (environment and safety): when it comes to safety: A Zn-Air cell is an intrinsically safe battery, in terms of storage, transmission, disposal and usage. And has less danger of fire, explosion or exposure to insecure materials than in other batteries. And in terms of the environment: Zn-Air cells can safely be thrown away with regular garbage because they don't possess added mercury or cadmium that are commonly added to other kinds batteries so it's environmentally friendly [26]. As an anode material, zinc possesses a unique set of properties, including low equilibrium potential, electrochemical reversibility during the charge and discharge cycle, and stability in aqueous electrolytes, strong conductivity, low equivalent weight, high specific energy, and high volumetric energy density. Other benefits of zinc include its abundance, low cost, low toxicity, ease of storage, and safe handling are making the zinc the best choice as an anode in this study[27,28]. The fuel cell uses an electrochemical reaction to convert chemical energy stored in fuels (zinc) and oxidants (oxygen from air) into electric power, and the supporting module (the structural model of the cell) keeps the fuel cell running by electrolyte management, regulating temperature, and fuel supply.[29]. A zinc-air fuel cell is a fuel cell that generates electrical energy by oxidizing zinc metal with ambient oxygen. A zinc-air fuel cell is less expensive than other fuel cell systems, such as lithium-ion, because it does not use expensive metal and is easier to build [30]. Furthermore, the zinc-air cell is particularly not harmful on the environment because it does not employ unsafe materials like lead compounds or emit greenhouse gases. The zinc-air fuel cell is also adaptable, having been employed as an alternative energy source for a wide range of applications, from small button batteries in watches to automobiles and utility-scale power systems in the future[31,32]. Zinc-air batteries have been designed in different forms and shapes, for example flexible batteries[33,34], cable-type batteries [35], and flow batteries[36,37]. Flow batteries offer a significantly greater capacity rating and a considerably wider power range. Furthermore, active materials can be packed or stored outside the cell to increase the cell's power and capacity. To put it another way, flow batteries allow for an independent scaling-up of power and capacity requirements.[38]. Flow batteries outperform other types of batteries in terms of cost, system flexibility, fast reaction, and safety issues for various technologies. [39]. There are two ways to refuel a Zn-air fuel cell (ZAFC): electrical and mechanical recharge [40]. A Zn-air battery that is electrically rechargeable is recharged by directly delivering power to the cell. Zn metal is electrochemically regenerated at the Zn electrode during recharging, whereas oxygen is produced at the air electrode. However, the growth of dendritic Zn during recharging is a serious issue in the Zn electrode. Furthermore, due to the formation of oxygen bubbles and air electrode corrosion, the cathode rapidly declines while recharging [40]. Mechanically rechargeable Zn-air fuel cells (ZAFCs) can be categorized into two basic types: (1) refuel-able ZAFCs and (2) reconstructable ZAFCs. After
the discharge procedure, the Zn plates are entirely replaced and regenerated in the reconstructable kind. The refuelable kind uses aqueous flowing electrolytes in the cells that pass through a packed bed of corroding Zn particles and are drained by gravity. [41]. Anode type (fuel) is a main component in a ZAFC and Instead of Zn plates, Zn particles can be employed as a fuel supply in a flow mode. Porous Zn plates have been employed commercially as anodes for ZAFCs in recent decades. The porous structure has a high active surface ratio, which accelerates the efficiency of reaction by enhancing encounters with electrolyte molecules,[42]. When compared to a Zn plate, the Zn particles had a larger surface area, allowing better interaction between the active metal and the electrolyte[43]. As a result Zn particles have these favorable effects When compared to Zn plates,(i) Zn particles have a greater surface area for reaction, which is desirable; (ii) particle anode with flowing electrolyte is particularly crucial because it can overcome hydrogen evolution reaction (HER) and so boost cell performance and electricity output[41]. Numerous approaches for Zn anodes and fluidic systems have been presented and summarized in the collected works by various research groups[44]. According to Pinto et al. [45],flow configurations of ZAFCs with particle fuel were the most successful configurations of ZAFCs. The Zn powder enhanced the charge and discharge operations of the fuel cell by allowing adequate migration of hydroxyl ions (OH⁻).Vatsalarani et al. [46],demonstrated that using Zn particles as fuel minimized dendritic development in their fuel cell. This might be simply due to the entry of H₂O and OH into the inner Zn/ZnO cores, preventing the discharged zincate ions from diffusing outside of the core. When Zn particles react with the oxygen on the positive electrode zincate ions (Zn(OH)₄²⁻) will be produced, that is dissolvable in the electrolyte. Once the electrolyte gets saturated with zincate ion, zinc oxide (ZnO) is produced. It can be removed from the cell with the flowing electrolyte to preserve the equilibrium of the reaction. another advantage of the Zn particles is its reaction area that is higher than Zn plate reaction area which enhances the productivity of the reaction [1]. Fuel cells require a steady supply of fuel to keep the electrochemical reactions going and produce power. The use of a circulating flow type electrolyte system will result in the removal of the spent Zn anodes, while Zn fuel may be fed to the reaction tank on a regular basis. As a result, the reactant discharge may still be effectively re-supplied without mechanical exchange. [47.] The two electrodes of a zinc-air fuel cell (ZAFC) are a zinc anode and an air cathode. A separator separates both electrodes, allowing ions to flow freely throughout the cell. As an electrolyte, potassium hydroxide (KOH) in aqueous solution is adopted. Zn reacts with hydroxide ions (OH⁻) at the anode (negative electrode) to create zincate ions (Zn(OH)₂⁴⁻), as demonstrated in reaction (1). The zinc oxide (ZnO) precipitation process begins when the concentration of zincate ion hits its solubility limit, as shown in reaction (2). there is also a parasitic undesirable reaction on the zinc anode side that is the Hydrogen evolution reaction (HER).it happens when water receives electrons from the reaction on the anode electrode it will be transformed to hydrogen (H₂) and hydroxide ions (OH⁻), as shown in reaction (3). Zn corrosion occurs when Hydrogen evolution reaction (HER) and Zn dissolution reaction are combined, as shown in reaction (4). At the cathode (positive electrode), oxygen reduction reaction (ORR) consumes oxygen and water to produce hydroxide ions(OH⁻) as described in reaction (5). As the fuel cell discharges, electrons are released from reaction (1) and received by reaction (5). Both reactions proceed and generate electricity.

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\text{Zn anode:} \quad \text{Zn} + 4\text{OH}^- \leftrightarrow \text{Zn} (\text{OH})_4^{2-} + 2\text{e}^- \quad (1) \\
\text{Zn(OH)₄²⁻} \leftrightarrow \text{ZnO} + 2 \text{OH}^- + \text{H}_2\text{O} \quad (2)
\]

\[
\text{Parasitic reaction:} \quad 2\text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{H}_2 + 2\text{OH}^- \quad (3) \\
\text{Zn} + 2\text{OH}^- + 2\text{H}_2\text{O} \rightarrow \text{Zn(OH)₄²⁻} + \text{H}_2 \quad (4)
\]

\[
\text{Air cathode:} \quad 1/2\text{O}_2 + \text{H}_2\text{O} + 2\text{e}^- \leftrightarrow 2\text{OH}^- \quad (5)
\]

In this study, a mechanical rechargeable approach was examined in the type of refuelable ZAFCs, to avoid the obstacles in the electrical charging method. Like: dendrite formation that causes a short circuit between the two electrodes in cell, distortion of the anode, quandary to finding a bifunctional catalyst required for oxygen reduction reactions (ORR) and oxygen evolution reactions (OER)) as well as the catch of cathode corrosion due to the oxygen bubbles generated from the recharging process. In this work, the ZAFC of a mechanical refueling flow type was adopted, combined with a co-cell or electrolyzer for zinc regeneration and electrolyte recharge to the main cell, a practical
study was performed to examine the influence of different ranges of parameters such as electrolyte flow rate (0-250 mL/min), electrolyte concentration (10- 60% by weight KOH), electrolyte temperature (26-60°C), active or passive air supply(0-8 L/min), and the effects of each parameter on cell performance was analyzed and the best parameters were selected to maintain an ultimate cell operation.

2. Experimental Section
2.1. Cell design
The mechanically refuelable flow ZAFC idea was adopted in this study. An effective system of flowing Zn particle fuel cells has been suggested, as depicted in figure 1. Because of the following benefits, Zn particles can be utilized as a fuel source in a flow model: (i) Flowing electrolyte through the reactor is very important, especially for limiting hydrogen evolution reactions (HER). (ii) Zn particles definitely have more functional three-fold vacant sites for reactions than Zn plates, which increases the reaction surface area and improves the interaction between zincate and OH-. The configuration of single-cell included three Perspex material plates as the mainframe because of its resistance to corrosion and also to facilitate frequent disassembling, and apertures were formed on the back and front ends of the cell configuration, respectively, these apertures are considered as an inlet and outlet gates to the electrolyte and air. The dimensions of the cell were (15×15×1cm) length, width and thickness respectively for each Perspex plate. The active area of the air cathode was (10×10) cm, which was on the left clamping plate. To the right of the cathode side towards the Zn anode a cell-dedicated non-woven fabric was placed to function as a separator to prevent the anode and cathode from interjection. The air electrode was fixed to the left side of the Perspex plate by an adhesive material. However, to prevent the electrolyte from leakage, a rubber gasket or lining has been positioned between the acrylic plates to strengthen the cell sealing. The entire cell is held together by 7 bolts securing all sides of the acrylic plates. The electrolyte is circulated between the cell and the supplementary electrolyzer by a pump and the flow is controlled by flow meters. Another pump (an air pump) was applied to supply the cell with air, airflow meters were used to control the air entering the cell. Aqueous electrolytes, mainly alkaline electrolytes, have been adopted by the Zn-air system since the first design approach (in the 19th century). Potassium hydroxide is the most commonly used alkaline electrolyte due to its high conductivity, high activity for both the Zn and air electrodes and good low temperature performance.

100 g Zn granules with a diameter of approximately of 0.5mm were put within a 100-mesh stainless steel pouch that also served as a current collector for the Zn anode. A gas diffusion layer, a cathode current collector, and a catalyst layer made up the three layers of the air cathode plate. The cathode current collector were made of 100-mesh stainless steel.

A slurry mixture of 7 g carbon black in binder soluble solvent was cast to create the gas diffusion layer. 3 g polystyrene-co-butadiene as a binder was dissolved in 50 ml toluene to make the solvent.

Figure (1) Zinc-air fuel cell (ZAFC) integrated with the Zinc electrolyzer
After that, the stainless steel mesh was coated with this slurry mixture and heat-pressed for 15 minutes at 110°C (in this case, in an oven) employing two steel layers as a press means. On the other side of the Stainless steel mesh, the catalyst layer was made-up by dissolving 3 g MnO2 and 7 g carbon black in the binder dissolved solvent. (3 g polystyrene-co-butadiene as a binder was dissolved in 50 mL toluene to make the solvent). The catalyst-coated cathode was heat-pressed at 110°C for 15 minutes in an oven using the same two steel layers. The hydrophobicity of the gas diffusion layer was excellent. The gas diffusion layer's hydrophobicity inhibits electrolyte leakage and water flooding on the cathode side. This layer also permits oxygen gas from the surrounding environment to enter the cell. The cathode's active area was 100 cm². In a zinc air fuel cell, the separator physically separates the positive and negative electrodes and must have low ionic and electrical resistance. Although it is an electrochemically passive element, it has a direct influence on vital battery characteristics. They should have a strong alkaline electrolyte adsorption capability, as well as good chemical resistance to corrosive electrolytes and oxidation. In classic alkaline batteries as well as metal–air systems, nonwoven polymeric separators consisting of polyethylene (PE) and polypropylene (PP) have been frequently used. Their fibrous texture provides high porosity (up to 75% pore volume), which is required for good electrolyte conservation and low ionic resistance.

2.2. Testing methods
The focus in this work was on studying the main parameters that have a direct effect on the cell performance such as electrolyte concentration, temperature, circulation rate, and air supply. The most common way to measure the performance of the cell is to record the voltage and current using a digital multi-meter device at different conditions (with load and without load), different resistances (R) 0-1000 Ω were applied between the anode and the cathode electrodes, a digital multi-meter collected the voltages (V) and the factual current (I) over the exterior resistance every 5 minutes after the ZAFC startup. Polarization curves are used to determine the operative conditions of a fuel cell under exterior resistance. The polarization curve was acquired at different exterior loads by putting various resistances on: from 0 - 1000. By: (multiplying voltage by the obtained current then divide the result on the cathode surface area) the precise values of the power density are calculated. In this work: the effects of many Parameters on ZAFC performances, the power density and the polarization curves were determined.

2.3. Results and discussions
2.3.1. Effect of electrolyte concentration on cell performance
The duty of the alkaline electrolyte is dissolving zinc pellets to Zn²⁺ cations to extract electrons from them. The ionic conductivity of the electrolyte can be upgraded by increasing the alkaline concentration to a specific limit [47], so the effect of Potassium hydroxide (KOH) concentration on the open-circuit voltage (OCV) and the output voltage of ZAFC was examined with 10,20,30,40,50 and 60%wt. KOH. the results were recorded. After the cell reaches its steady-state, that is, after about 30 minutes. As shown in Fig.2(a) the open-circuit voltage (OCV) was increased with incrementing the electrolyte concentration from 10%wt. (1.32 V) up to 40%wt. (1.49 V), but further incrementing, up to 50%wt. (1.51 V) and 60%wt. (1.51 V) had no significant increase in voltage output. Experiments were directed to outline the effect of the concentration of the electrolyte on the performance of the cell by changing the concentration of the electrolyte while the other parameters (electrolyte temperature and electrolyte circulation rate) were fixed. Cell discharging was achieved under variable discharge conditions and by different values of resistors to test the voltage change of cells. The test results are shown in Fig. 2(b); (c) shows the curves of polarization and power density. As shown in Figure 2(b), (c), the power density had increased with the incrementing the Electrolyte concentration from 10 to 40%wt., the maximum power density was recorded at 40%wt. that was 95.45 mW/cm². The observed improvement was due to an increase in the ionic conductivity of the electrolyte, due to the increased KOH concentration that enhances the anode reaction corresponding to the Nernst equation. However, the further increase in KOH concentrations from 40%wt to 60%wt leads to an obvious decrease in power density as recorded 89.06, 85.91 mW/cm² at 50, and 60 % wt respectively. That decrease was achieved because of the viscosity boost in the solution that effects the mobility of ions (or make the ion transfer harder) in the KOH solution. It was noticed that when the concentration of the electrolyte is raised, the cell performance is enhanced, in other words there is a proportional relationship between the electrolyte concentration and the power density to an extent (40%wt). The reason is that a higher electrolytes concentration can offer an enhanced ion
exchange rate throughout chemical reactions within the cell that leads to progressed cell performance. High electrolyte concentration can offer sufficient ions in time to ease fast and efficient ion exchange. These results agreed with Sangeetha(2019) et al.[41].

![Figure (2) (a) KOH concentration vs. open-circuit voltage (OCV). (b) Polarization curve, (c) power curve, at various potassium hydroxide concentrations with constant other parameters such as room temperature T=26°C, air flow rate 6L/min and without electrolyte circulation (no flowing electrolyte).](image)

2.3.2. Effect of air flow rate on cell performance

In ZAFCs, the anode fuel was Zinc metal, and the cathode was Oxygen from the atmosphere. As a result, increasing the inlet airflow velocity rate was a practical way to increase fuel cell efficiency. The purpose of this experiment was to inspect the effect of managing airflow (optimization of airflow velocity) in ZAFC to increase the performance of the cell eventually. This experiment attempted to discover the impact of air-flow conditions on the total discharge capacity of a zinc-air fuel cell (ZAFC). The active material that reacts with Zinc during the reduction reaction was oxygen in the air, which also served as an efficient cathode fuel. An air pump was used to supply the cell with air. The other parameters were fixed as follows: The potassium hydroxide concentration of was 40% wt., without electrolyte circulation (no flowing electrolyte) and at room temperature. Then, the effects of different airflow velocities on the ZAFC were investigated by controlling the airflow by a Flow Meter with Control Valve these velocity ranges: from 0 L/min, 2 L/min, 4 L/min, 6 L/min, to 8 L/min were employed and tested. The results are illustrated in Figure 3(a),(b), and (c) Firstly the cell was experienced without load (OCV condition), and reading was recorded after 10 minutes from each airflow velocity adjustment. The results are shown in Figure 3(a), it was noticed that the ultimate voltage readings increased from no-flow conditions to 6 L/min, where the reading recorded, increased from 1.37 to 1.49 V is, but when the air flow was increased to 8 L/min, a voltage drop was observed to reach 1.33 V. Then the cell was re-tested with load as illustrated in Figure 3 (c) the results indicated that the power density increased with incrementing the air flow rate from 0 to 6 L/min. The maximum power recorded at 6 L/min that was 96.38 mW/cm². Similarly, a decrease in the energy level resulted when the flow rate increased to 8 L/min, where the highest energy level at this flow rate reached 59.16 mW/cm² This can be explained by increasing the air flow rate,
which enhances the oxygen content for more ORR, thus enhancing the cell performance both with
the load during discharge and without discharge (OCV), but with further incrementing of the air flow
to a certain point there was a noticeable decrease in voltage as well as reduced cell performance
during discharge , this decrease in voltage and cell performance was caused by inhibiting the
cathode electrode performance due to pushing the electrolyte solution away from the cathode  back
to the cell towards the anode instead of staying inside the cathode pores that leads to reduce the
surface area for reaction , thus inhibiting the performance of the oxygen reduction reaction on the

cathode electrode. Pichler (2017) et al.[48] Investigated the fact of supplying air to the air electrode
and its impact on the ZAFC performance and discovered that the airflow had increased the fuel cell's
life time as well as its ability to produce constant current, because the improvement in air supply had
increased the oxygen reduction rate which enhanced the cell performance. Cheng (2019) et al.[49].
Revealed that when the velocity rise, the greater air volume could have had an undesirable impact on
all current discharge values, resulting in a drop in voltage output. The obtained results from this
experiment are agreeing with both of them.

Figure (3) (a) air flow rate vs. open-circuit voltage (OCV). (b) Polarization curve, (c) power curve at
various air flow rate. With constant other parameters that are room temperature T=26°C, the
concentration of electrolyte 40%wt. and without electrolyte circulation (no flowing electrolyte).

2.3.3. Influence of circulation rate of the electrolyte on the cell performance
The electrolyte circulation has several effects on the ZAFC components and performance. The
flowing electrolyte can assist in the dissolution of specific products (Zn) and in the disposal of the
final products. in this study KOH is stored in the co-cell (the electrolyzer) or in a small tank that
linked to the discharging cell as discussed in the cell design section , the electrolyzer or the small
tank contain the final products of discharging and the spent electrolyte that was pushed to them .
The electrolyzer was installed by an electrolysis system and, a liquid pump was used to circulate the
electrolyte, a flowmeter with a control valve were used to control the velocity of the circulation, and,
producing a circulating flow. The main aim of this test was to detect how the cell performance
affected the flowing electrolyte. Six different electrolyte flow rates (0, 50, 100,150,200 and 250
mL/min) were tested to examine the transformations in cell performance, as shown in Figure (5). The best parameters obtained in previous experiments were implemented: 40%wt. electrolyte concentration. And the air flow rate 6 L/min. The test results are illustrated in Figure 4(a) OCV output increased from no flow conditions: (1.49 V) till 250mL/min : (1.523V). It was obvious that, the performance was improved in the circulated electrolyte than the cell performance with non-flowing electrolyte.

![Graphs showing electrolyte circulation rate vs. open-circuit voltage (OCV), (b) Polarization curve, (c) power curve at various electrolyte circulation rates, with constant other parameters such as room temperature T=26°C, electrolyte concentration 40%wt. and air flow rate 6L/min.](image)

And when the electrolyte circulation rate was increased the from 50 mL/min to 100 mL/min to 150 mL/min, to 200 mL/min and 250 mL/min the cell performance have increased proportionally; conversely, this enhancement was less noticeable compared with the improvement that was detected when the circulation had changed from non-flow to 50 mL/min. The effect of electrolyte circulation on cell performance at discharge conditions with different loads also had been tested, and results are shown in figure 4(b,c) the cell performance enhanced in terms of current and energy density, but the enhancement was slight, the maximum power recorded was (94.8 mW/cm2) at non-circulation and increased to (108.75 mW/cm2) at 250 mL/min. Depending on these results, a higher electrolyte rejuvenation rate was detected in the circulating electrolyte case than in the non-circulating electrolyte case, the circulating electrolyte had increased the cell voltage by improving the exchange ratio of cations and anions in electrolyte. However, the results of the tests indicate that incrementing the circulation rate over 250 mL/min did not improve cell performance as expected. The calculation curve was plateaued, no obvious change was detected. Because: when the flow rate of the electrolyte increase, the flowing electrolyte pressure within the cell increases too. That leads to the electrolyte diffusion through the catalyst layer of the cathode and obstruct the pores of the porous material as a result of the extremely high pressure leads to limit the oxygen delivery and causing degradation. These results agreed with Yang et al.[50].
2.3.4. The Electrolyte Temperature influence on the cell performance

This testing was directed to observe the effect of KOH electrolyte temperature on the cell performance. The fuel cell was operated with five different temperatures: room temperature (26 °C), 30 °C, 40 °C, 50 °C, and 60 °C and electrolyte solution the other parameters (KOH concentration of 40%wt., airflow rate 6 L/min and electrolyte circulation rate 100 mL/min) were adopted. The results of the experiment indicated that the temperature of the electrolyte had a positive impact on the electrochemical reactions and had improved the chemical activity (Fig. 5a). OCV increased proportionally with the temperature the maximum voltage was obtained at 50 °C where the OCV was 1.527V. But when rising the temperature over 50 °C it was noticed that the cell performance had decreased rapidly until reaching 1.33V. After that, the cell was tested with load as illustrated Figure 5 (b,c) it's obvious that the current and power density had improved with temperature increasing. The supreme power documented for each temperature were: 94.8, 103.7, 106.14, 110.04, 74.1 mW/cm2 respectively, the optimal value 110.04 mW/cm2 was recorded at temp.50°C. a decrease in the energy level was recorded when the temperature was raised to 60°C, the documented power was merely 59.16 mW/cm2. That's because at low temperatures the electrolyte ion diffusivity is reduced which leads to a decrease in the electrolyte activity, thus when the temperature is incremented it leads to the presence of more molecules with high kinetic energy those molecules are allowing the activation energy to be readily overcome. This leads to increasing the activity of the electrolyte as well until reaching the ultimate voltage at 50 °C. With further temperature increase, the energy will be overpowered because of the production of high kinetic molecules which leads to a sharp decrease in the cell performance because all the cathode constituents will be destroyed and lose their unique function due to the high temperature.

![Figure (5) (a) Temperature vs. open-circuit voltage (OCV). (b) Polarization curve, (c) power curve at different Temperature, with constant other parameters such as electrolyte concentration 40%wt. and air flow rate 6L/min., electrolyte circulation rate 150 mL/min](image-url)
3. Conclusions
The study had shown the influence of (electrolyte concentration, air-flow rate, and circulation rate as well as electrolyte temperature) on the Zn-air fuel cell performance. The findings and conclusions of the study were as follows.

With the incrementing of the concentration of the electrolyte the open circuit voltage (OCV) will increase too that increase is from 10% wt. (1.32 V) to 40% wt. (1.49 V), also, the power density had increased with the incrementing of the Electrolyte concentration from 10 to 40% wt. The maximum power densities were recorded at 40% wt.: 95.45 mW/cm². However, the further increase in KOH concentration from 40% wt. to 60% wt. results in a clear decrease in power density the results are recorded 89.06, 85.91 mW/cm² at 50,60 % wt. respectively. Therefore, the optimal KOH concentration for the ZAFC cell is 40% wt.

The open-circuit voltage (OCV) increased with the increased airflow rate from no-flow conditions (1.37 V) to 6 L/min (1.49). The ultimate power density of the ZAFC was at 6 L/min that is: 96.38 mW/cm² This can be explained by increasing the rate of airflow, which enhances the oxygen content for more ORR, thus enhancing the cell performance both with the load during discharge and without discharge (OCV).

The performance of the cell during electrolyte circulation was higher than its performance with non-flowing electrolyte The products of Zn(OH)₄²⁻ can be dissolved in electrolyte and carried away by the circulating electrolyte flow. The Zn anode can be maintained in the best reaction state. By controlling parameters of electrolyte flow, the active polarization, omics polarization, and concentration polarization of the cell reaction were reported to be reduced.

With an electrolyte temperature of 50°C, the best cell performance was accomplished. Since the electrolyte has a low activity at low temperatures, its ion diffusivity drops that leads to accelerating cell polarization to attain the final voltage. The activity of the electrolyte grew as the temperature of the electrolyte rose, resulting in more molecules with high kinetic energy and assisting the overcoming of activation energy.

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