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A novel strategy to enhance the generating power of ionic polymer metal composites through magnetoelectricity

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Abstract

In this paper, we put forward a method to enhance the output power of ionic polymer metal composite (IPMC) through a magnetic field by combining the ion-electronic and magnetoelectric effects. Firstly, we confirmed that the total output voltage of IPMC deformation originates from the vector superposition of ion-electronic and magnetoelectric effects when applied a magnetic field. The open circuit voltage and output power of IPMC were experimentally investigated by adjusting the deflecting frequency and magnetic field intensity. As the frequency and magnetic field intensity increase, the increased voltage and output power caused by the magnetic field show an upward trend. Then, the experimental results were analyzed and verified through the piezoelectric and magnetoelectric theory. The results show that the increased voltage has a linear relationship with the frequency and magnetic field intensity and has nothing to do with the inherent parameters of IPMC itself. Finally, we performed simulation and practical tests to verify the energy harvesting effect of this strategy. During the energy harvesting test of water flow fluctuation, the open circuit voltage was increased by 41.91% and the output energy was increased by 110.03%, which indicates that this strategy has excellent performance in practical applications. By this study, the power generation performance of IPMC was explored and improved through multiple physical mechanisms.

Key words: IPMC, Magnetic field, Power enhancement, Multiple physical mechanisms

1 Introduction

Ionic polymer metal composite (IPMC)[1-3] is a class of flexible smart material that can realize electromechanical energy conversion[4,5]. With the maturity of preparation process and optimization of performance in recent years[6-9], IPMC has had a wide range of applications in various fields, including underwater propeller[10], micro-fluid pump[11], deformation sensing[12], micro gripper[13] and energy harvesting systems[14-16]. IPMC typically consists of an ionomeric layer (usually Nafion) plated by two electrode layers (noble metal) on both sides to form a sandwich structure. Inside the ionomer, the anions are covalently bound to the polymer chain while the cations can migrate through the nano-ion channels. Once the IPMC is deformed, the uneven stress distribution inside the ionomer will lead to the redistribution of the cations, triggering a voltage between the two electrodes, which is called the ion-electronic effect of IPMC.

As a result of the characteristic of converting mechanical energy into electrical energy, IPMC has a potential in the field of energy harvesting. Compared with traditional energy harvesting materials such as piezoelectric materials[17-19], IPMC has better flexibility and higher conversion efficiency at low frequency. Therefore, in some special occasions, such as energy harvesting from water flow fluctuation, IPMC will present a better effect than other energy harvesters. The research of IPMC for energy harvesting started early in 2007, *Dogruer D* et al.[20] experimentally confirmed that IPMC is an attractive candidate for potential energy harvesting application. Then in 2009, *Aureli M* et al.[21] analytically and experimentally study the energy harvesting capability of submerged IPMC in the fluid environment. In 2013, *Cha Y* et al.[22] studied underwater energy harvesting from torsional vibrations of an IPMC with patterned electrodes and proposed an electromechanical model to predict energy harvesting from the IPMC as a function of the shunting resistance. In 2017, *Vinh N D* et al.[23] designed an energy harvesting system based on IPMC to gather the kinetic energy of the ocean waves, by which the average power density generated reached approximately 245 μW/m^2. Recently in 2020, *Duy V N* et al.[24] conducted a study of the movement, structural stability, and electrical performance for harvesting ocean kinetic energy based on IPMC. However, the low power generation limits the wide application of IPMC energy harvesting systems. In order to overcome this limitation, two strategies were developed that one is to optimize the transducing performance of IPMC itself while the other is to improve the efficiency of the energy harvesting circuits[25, 26]. In this paper, we try to increase the output power of IPMC by optimizing the external working environment.

Compared with other transducing materials, an outstanding feature of IPMC is that its electrode layers on both sides are made of conductive metals. According to the law of electromagnetic induction proposed by *Michael Faraday* in 1831, an induced electromotive force will be generated when a metal conductor moves in a magnetic field. So far, magnetoelectric technology has been quite mature, such as the widespread use of generators. In the field of energy harvesting, magnetoelectric technology also has a wide range of applications. For example, in 2015 *Gutierrez M* et al.[27]designed and characterized the first completely orientation-independent magnetic levitation energy harvester for low power and low frequency applications. In 2018, *Rui X* et al.[28] designed a magnetic coupled piezoelectric energy harvester to increase the output and bandwidth. In 2021, *Lee J* et al.[29] proposed a new magnetically coupled method to efficiently transfer the vibrational energy from a source to a piezoelectric energy harvester. Compared with other energy generation mechanisms, magnetoelectric technology has great advantages in terms of high efficiency and frequency.

Therefore, in this paper, we propose a novel method of integrating ionic electric and magnetoelectric effects to enhance the generating power of IPMC. The rest of this paper is arranged as follows. The experimental configuration is described in section 2. In order to verify the energy harvesting strengthening effect of the strategy we proposed, a series of experimental and model analysis were conducted in section 3. And in section 4, we set up a magnet device to test the energy harvesting effect of IPMC for water flow fluctuation. Some important conclusions were highlighted in section 5.

2 Experimental section

We suspect that the power generated by the deflection of IPMC in a magnetic field may originate from three mechanisms. (1) The deflection of the IPMC causes the migration of cations to generate electrical signals, and here we call it ion-electric (IE) effect. (2) The metal electrode cutting the magnetic lines leads to an induce electromotive force, which is named magnetoelectric (ME) effect. (3) The movement of the cations inside the IPMC under the action of the magnetic field potentially generates the voltage, which is called after ion-magnetoelectric (IME) effect.

In order to verify the three mechanisms that we proposed, a series of experiments were implemented on an IPMC sample with the dimension of 25 mm in length, 3 mm in width and 0.2 mm in thickness. The IPMC sample was fabricated using the simplified process developed by our group through a combination of immersion reduction plating and electroplating method[30], the electrode of which is palladium-gold composite electrode. Firstly, the IPMC sample was clamped to form a cantilever beam structure, and a displacement of 10 mm was applied to the end of the IPMC by an exciter at a frequency of 1 Hz without a magnetic field. The voltage between the two electrodes of the IPMC was measured at the same time (Fig.1 (a)). Secondly, the IPMC was fixed on a flat plate at the end of the exciter with double-sided tape, and one side of the IPMC was completely attached to the flat plate. We made the IPMC do a reciprocating cutting motion with a displacement of 10 mm in a magnetic field by the exciter, and measured the voltage generated between the two electrodes (Fig.1 (b)). The realization of the magnetic field is to align two plate magnets in a mutually attractive manner, and the intensity of the magnetic field can be changed by adjusting the distance between the two magnets. It is worth noting that when IPMC cuts the magnetic induction line, the wires need to be arranged at both ends along length direction. Thirdly, on the basis of the configuration in Fig.1 (b), we changed the connection type of wires to the same end of the IPMC (Fig.1 (c)). Thus the voltage generated by the two electrodes was neutralized, and the measured voltage can be used to determine whether the internal cations have generated electrical signals under the attendance of the magnetic field.

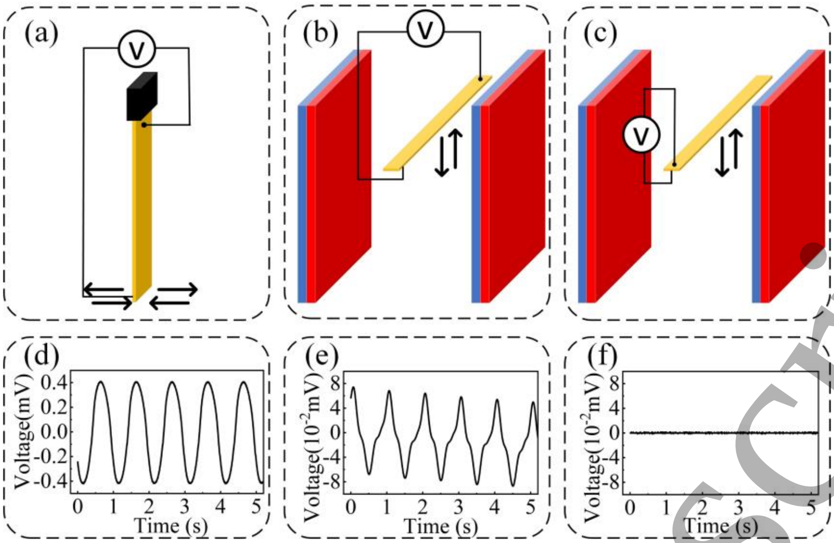

Fig.1 Experimental configuration and test results. (a) The method of testing the voltage of IE effect. (b) The method of testing the voltage of ME effect. (c)The method of testing the voltage of IME effect. (d) The measured voltage of IE effect. (e) The measured voltage of ME effect. (f) The measured voltage of IME effect.

3 Results and discussions

The measured electrical responses of the three comparative experiments are shown in Fig.1 (d)-(f). It is obvious that the IE effect and ME effect generated a voltage while the IME effect did not present visible response. It indicates a fact that the cations did not migrate along the thickness of the sample under the action of the magnetic field. In fact, for the Nafion-based IPMC, the ion channel diameter of the interlayer is on the nanometer level[31], and the radius of ion clusters formed by side chain of sulfonic acid groups is also about 4.5 nm[32], so the large resistance seriously limits the migration of the cations together with several water molecules. In fact, when applied a changing magnetic field, the ions in the salt solution will migrate[33]. Therefore, with the reduction of ion migration resistance in the matrix polymer, the IME effect is a process from scratch. For special ionomers with low ion migration resistance, such as ion hydrogels, the possibility of IME effect cannot be ruled out. Although we have not observed the voltage of IME effect in the IPMC we prepared, it is still worth of further studying and investigating in other polyelectrolytes due to its feasibility in principle.

After illuminating the electrical response of IPMC deformation in the magnetic field, we studied the voltage change caused by the magnetic field. In fact, there are two ways to exert the magnetic field on IPMC. When the direction of the magnetic field is shown in Fig.2 (a), the voltage generated by the ME effect and the IE effect is coupled to decrease, which is called the negative magnetic field. When the direction of the magnetic field is reversed as shown in Fig.2 (b), the voltage generated by the ME effect and the IE effect is coupled to enhance, which is named the positive magnetic field. The voltage comparison of IPMC deflection in different conditions is shown in Fig.2 (c) (the end displacement is 10 mm, the Frequency is 8 Hz, and the magnetic field intensity is 20 mT). It can be concluded that the voltage of IPMC deformation will be enhanced when a positive magnetic field is applied.

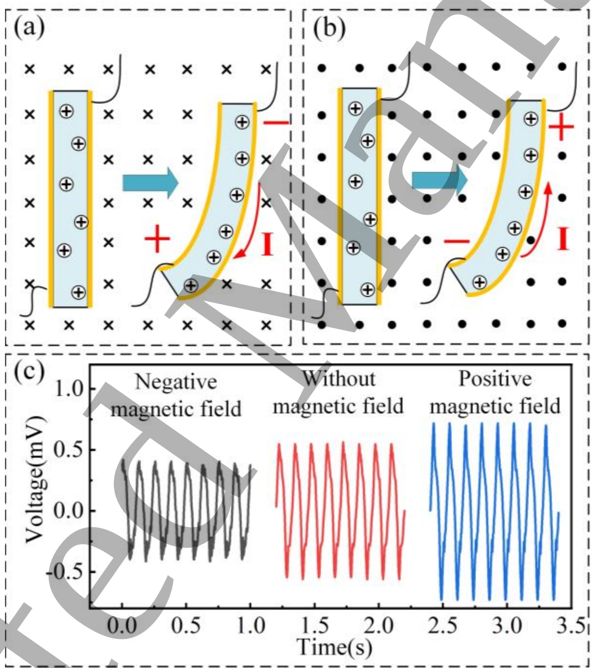

Fig.2 The mode and trend of the IPMC electrical response under magnetic field. (a)The voltage attenuation when a negative magnetic field is applied. (b) The voltage enhancement when a positive magnetic field is applied. (c) The voltage comparison of IPMC deflection in the negative magnetic field, positive field and the field without magnetism at the frequency of 8 Hz and the magnetic field intensity of 20 mT.

In the state of applying a positive magnetic field, we further studied the voltage and power evolution of the IPMC with an increase of frequency and magnetic field intensity, respectively, when connected to different load resistance. We defined the open circuit voltage as V, the power of the load resistance as P when no magnetic field applied. When applied a positive magnetic field, the open circuit voltage was defined as V_1 and the power of the load resistance was defined as P_1. Therefore, the increased voltage and power can be defined as $\Delta V=V_1-V$ and $\Delta P=P_1-P$, respectively. The relationship between ΔV, ΔP and frequency, magnetic field intensity is shown in Fig.3. As the frequency (Fig.3 (a)) and the magnetic field intensity (Fig.3 (b)) increase, the ΔV presents an approximately linear rising trend and so as the rate of the voltage rise ($\Delta V/V$). When the magnetic field intensity reaches 100 mT and the frequency is 8 Hz, the open circuit voltage is increased by 158.2%. And for ΔP, when the applied load remains constant, as the frequency (Fig.3 (c)) and the magnetic field intensity (Fig.3 (d)) increase, it also presents an upward trend. When the load resistance comes up to 10 kΩ, the IPMC has the maximum outout power. It means that the internal resistance of IPMC is approach to 10 kΩ，by which the output power of the IPMC power supply will reach the highest as well.

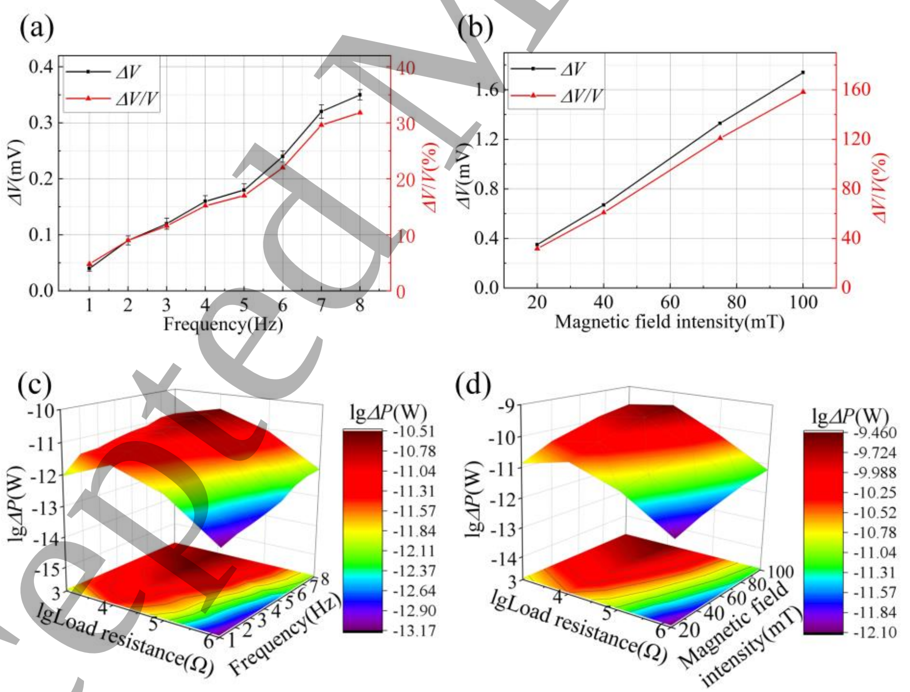

Fig.3 (a) The relationship between ΔV, $\Delta V/V$ and the frequency at 20 mT. (b) The relationship between ΔV, $\Delta V/V$ and the magnetic field intensity at 8 Hz. (c) The relationship of ΔP, load resistance and frequency at 20 mT. (d) The relationship of ΔP, load resistance and magnetic field intensity at 8 Hz.

To shed light on our experimental findings, the experimental results are further explained through the IPMC piezoelectric and magnetoelectric theory. As shown in Fig.4 (a), according to the piezoelectric theory of IPMC proposed by *Lee S* et al. [34], the length of the cantilever beam is defined as L, the thickness is H and the end displacement is defined as S, then the ionic electrical response V_I of IE effect satisfies the formula as follows.

$$V_I = \frac{2H^2 d}{3L^2} S \tag{1}$$

In this formula, d is a constant, which is determined by the ratio of Young's modulus and the electromechanical coupling coefficient of IPMC, it can be calculated by measuring the relationship between the generated voltage and the displacement. The voltage generated by the IE effect of IPMC is only related to the end displacement apart from its own parameters. Therefore, the voltage of the ion-electric effect will not change if the end displacement keeps constant.

The magnetoelectric theory of IPMC in Fig.4 (b) is proposed on the basis of Faraday's law of electromagnetic induction. When an irregular conductor moves in a magnetic field, it can be regarded as a straight conductor rod from the start point to the end point. Therefore, the deflection of IPMC in a magnetic field can be regarded as a variable-length conductor rod rotating and cutting the magnetic line of induction. Because the IPMC sample has two electrodes, its instantaneous induced electromotive force V_M can be expressed as follow.

$$V_M = 2B\omega l^2 \tag{2}$$

In the formula, B represents the magnetic field intensity, ω represents the angular velocity of the equivalent conductor rod, and l represents the instantaneous length of the equivalent conductor rod. If the length of IPMC is defined as L, the end displacement is S and the deflection angle is θ. Then ω and l can be calculated as follow.

$$\begin{cases} \omega = \dfrac{\dot{S}\cos\theta}{L/\cos\theta} \\ l = \dfrac{L}{\cos\theta} \end{cases} \tag{3}$$

Substituting formula (2) into formula (1), the expression of V_M can be obtained as follow.

$$V_M = 2B\frac{\dot{S}\cos^2\theta}{L}\left(\frac{L}{\cos\theta}\right)^2 = 2B\dot{S}L \tag{4}$$

In terms of this formula, the voltage generated by the ME effect of IPMC is related to the deflection velocity of the cantilever beam and the magnetic field intensity while the generated voltage of the IE effect is dependent on the end displacement. Since we have demonstrated that the voltage generated by the IME is almost invisible, the induced electromotive force V_M of the IPMC electrode should be equal to ΔV in value. That's to say, the increased voltage ΔV due to ME effect has a first-order linear relationship with both frequency and magnetic field intensity.

Substituting the various parameters in the experiment into formula (4), the theoretical V_M under different experimental conditions was calculated and compared with the actual measured ΔV. As shown in Fig.4 (c), (d), the theoretical voltage has a first-order linear relationship with the frequency and magnetic field intensity. The actual voltage is slightly lower than the theoretical voltage, which is possibly ascribed to the energy loss caused by the experimental device and the circuit.

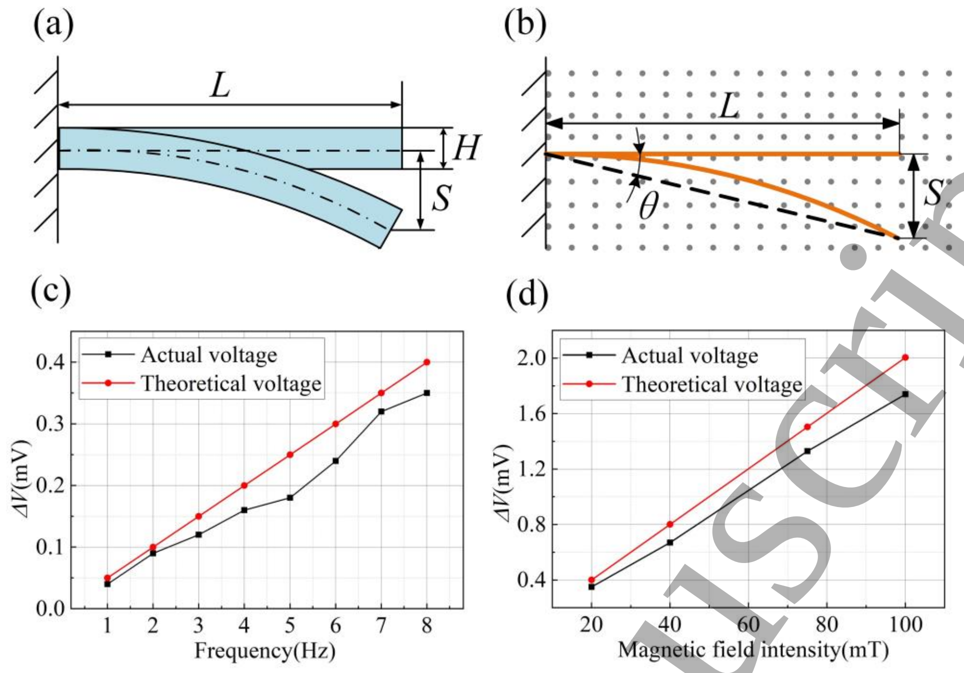

Fig.4 (a) The piezoelectric model of IPMC. (b) The magnetoelectric model of IPMC. (c) The trend of theoretical voltage and actual voltage as the frequency increased at 20 mT. (d) The trend of theoretical voltage and actual voltage as magnetic field intensity increased at 8 Hz.

4 Energy harvesting verification

In order to verify the feasibility of the strategy we proposed, a set of simulation and practical tests have been carried out by water flow fluctuation for energy harvesting.

Considering that the presence of the magnet device will affect the water flow in practical applications, we firstly used the Fluent software to simulate the pressure distribution of the flow field in different scenarios. In order to simplify the calculation, the simulation was performed in a two-dimensional state. The result of the simulation is shown in Fig.5. For a rectangular flow field without magnet device, the pressure at its middle position is 956 Pa (Fig.5 (a)). When a magnet was set on each side of the middle position of the flow field, and the pressure in the middle position is about 995 Pa (Fig.5 (b)), which is 4.08% higher than that without magnet device. For this flow field, it can be regarded as a pipeline water flow field. The distribution of magnets on the pipe wall reduces the cross-sectional area of the pipe, thereby increasing the water flow pressure. Therefore, in the pipeline water flow environment, the presence of the magnetic field device both increases the water flow pressure and the output voltage, which will theoretically have a better application effect on the output voltage of IPMC. As shown in Fig.5 (c), when the distance between the two magnets is further reduced, the pressure in the middle position is reduced to 951 Pa. It can be regarded as an open flow field at this time, and the presence of the magnet device divides the water flow, so that the pressure of the water flow in the middle position is reduced. However, the pressure reduction caused by the magnet device is about 0.6%, which is insignificant compared to the voltage increase it brings. Therefore, compared to the state without a magnetic field, the enhancement of the output voltage can still be achieved.

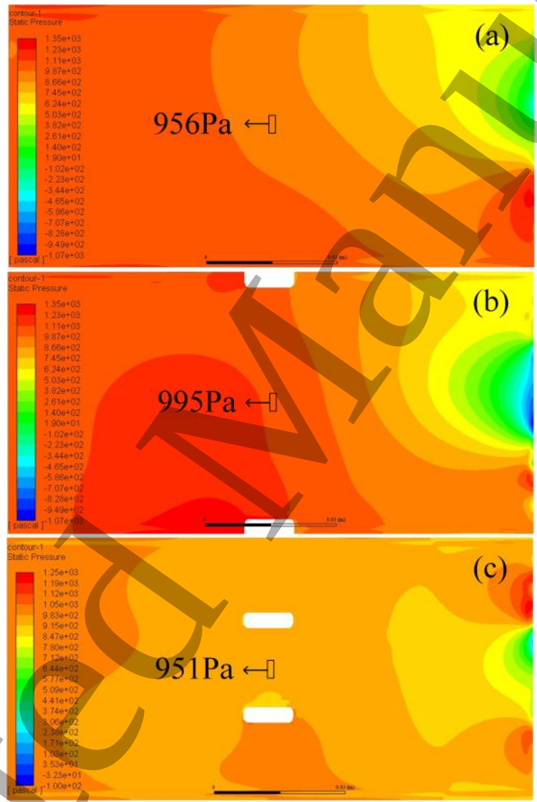

Fig.5 (a) Pressure distribution of the flow field without a magnetic field device. (b) Pressure distribution of the pipeline flow field in the presence of a magnetic field device. (c) Pressure distribution of the open flow field in the presence of a magnetic field device.

In order to further verify the effect of energy harvesting, some practical tests were conducted in a water flow environment. As shown in Fig.6, the IPMC sample was fixed laterally in a tank full of water. In the absence of a magnetic field, the sample was only simply clamped (Fig.6 (a), (c)), and in the presence of a magnetic field, a magnet device was designed to set two magnets on both sides of the IPMC in a manner of mutual attraction (Fig.6 (b), (d)). The distance between the two magnets is 23 mm and the magnetic field strength is 90 mT. We used a vibration exciter to put a flat plate to oscillate in the water to obtain water flow fluctuation, and the frequency of the vibration exciter is 1 Hz.

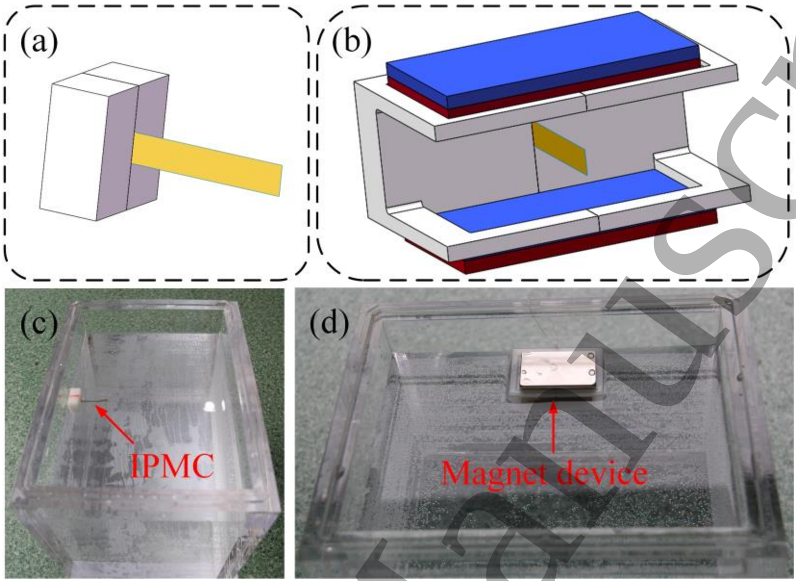

Fig.6 (a) The clamping method of the IPMC in the absence of a magnetic field. (b) The clamping method of the IPMC in the presence of a magnetic field. (c) Actual installation of the IPMC sample without magnetic field. (d) Actual installation of the magnet device.

The open circuit voltage measured under a magnetic field or not is shown in Figure 7. It can be seen that the maximum voltage amplitude is 0.22 mV in the absence of a magnetic field. And when exerting a magnetic field on IPMC, the maximum voltage reaches 0.31 mV, which is increased by 41.91% compared to that of no magnetic field. However, despite the maximum voltage is increased under the magnet device, we can still see from the enlarged picture that the voltage fluctuations of the IPMC sample in one cycle are reduced in the presence of a magnetic field. It indicates that although the presence of the magnet device did not significantly weaken the water pressure, it had a negative impact on the water flow fluctuation.

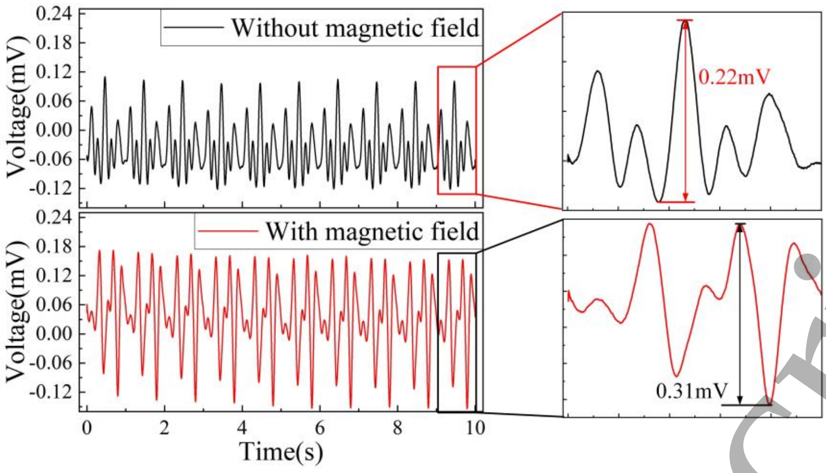

Fig.7 The open-circuit voltage caused by the water flow fluctuations measured in the absence and presence of a magnetic field.

Therefore, we continued to evaluate its effect from the energy perspective. It is well known that the electrical energy can be expressed as the product of the square of the voltage and time divided by the load resistance. So we studied the energy of one cycle by squaring the open circuit voltage, the results of which are shown in Fig.8. The electric energy generated by IPMC in one cycle can be expressed as the ratio of the integral area to the load resistance. The integral area without magnetic field is about 3.53 and that with a magnetic field is about 7.42. Since the load resistance is equal, we can calculate that the energy generated by the IPMC sample with magnetic field is 110.20% higher than that without magnetic field.

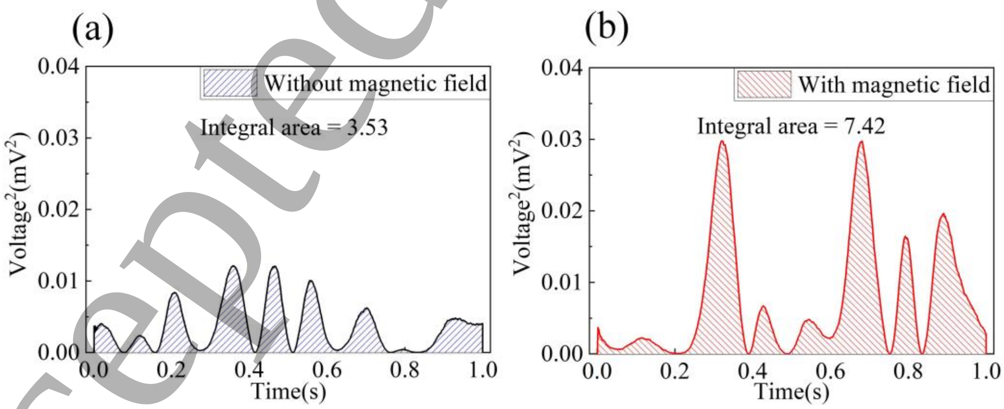

Fig.8 (a) The integral area of squared voltage over time in the absence of a magnetic field. (b) The integral area of squared voltage over time in the presence of a magnetic field.

Through the above test, we can conclude that the strategy we proposed has excellent performance in practical case. In fact, here we only performed a low-frequency test for energy harvesting of IPMC. As the frequency increases, the magnetic field can provide a higher output voltage and energy increase. At the same time, in the case of high frequency, the ME effect can also well compensate for the voltage relaxation phenomenon of the IE effect. In addition, this strategy not only has a good effect on the IPMC with palladium-gold composite electrode, but also has general applicability to ionic transducer with conductive electrode.

5 Conclusions

In this work, we proposed a novel strategy to enhance the output voltage and power of IPMC via combining ionic migration and induced electromotive force when IPMC deflect in the magnetic field. By adjusting the direction of the magnetic field, we successfully achieved the coupling increase of generated voltage and power of IPMC. Through the experimental and theoretical analysis, we concluded that as the frequency and magnetic field intensity increase, the increased voltage and the increased output power caused by the magnetic field will correspondingly show a linear upward trend. The open circuit voltage of IPMC has been increased by 158.2% when the magnetic field intensity reached 100 mT at the frequency of 8 Hz. In the practical application tests of water flow fluctuation energy harvesting, the magnet device we designed achieved a voltage increase of 41.91% and an energy increase of 110.20%. By this work, we improved the power output performance of IPMC through double physical mechanisms, which potentially opens another door toward the engineered performance of IPMC energy harvesting through the integration of multiple mechanisms. In future work, we will focus on exploring the ME effect to increase the operating frequency of IPMC and evaluating the feasibility of the IME effect for energy harvesting in other ionic polymers.

Acknowledgments

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