Study on improving efficiency of a plasma synthetic jet through dynamic pressure supplemental air

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Abstract. To improve efficiency of a plasma synthetic jet (PSJ) under the high frequency actuation mode we investigated the effect of the pressure of supplemental air on efficiency of a PSJ actuator. First, the analytic model of the air supplement PSJ is established to analysis the effect of the air supplement pressure on the jet velocity of the PSJ. The theory analysis shows that the jet peak velocity and average velocity is increased dramatically. Furthermore, to reflect the efficiency performance of a PSJ in such mode, the average transform efficiency of the energy is used as an index which is calculated by the measured average jet speed and average discharging power consumption. The results show that the discharging parameters fluctuate dramatic in different actuation cycles in the high frequency actuation mode. And the average transform efficiency can be used to evaluate the efficiency in such mode. As the pressure of supplemental air increase, the average discharging power consumption decrease by up to 45.3\% while the jet enhancement rate remains above 9\% constantly. Overall the average transform efficiency is boosted by 1-2 orders of magnitude. The research reveals that the supplemental air can keep the gas discharging stable to improve the jet performance, and increase the efficiency of the PSJ.

1. Introduction
Plasma synthetic jet (PSJ) was first proposed by the Applied Physics Laboratory of Johns Hopkins University in 2003 [1]. Compared with piezoelectric synthetic jet and mechanical synthetic jet, PSJ uses the heat generated by spark discharge plasma as the excitation source. It has a higher excitation frequency and its speed is up to hundreds of meters per second. PSJ has no moving parts. PSJ has a good application prospect in shock wave and boundary layer control [2-4], flow separation control [5-7], increasing lift and reducing drag [5-7], aerodynamic torque control [8-9], etc.

In the past ten years, Reedy used PIV technology to measure the flow field of PSJ [10]. Anderson used numerical simulation to study the interaction between PSJ and supersonic crossflow [11]. Greene used experiments to study the inhibition of shock boundary layer separation [12]. Chedevergne studied the effect of PSJ on high Reynolds number jet [13]. Song Huimin studied the matching characteristics of PSJ electrode layout and power supply system [14]. Han Lei developed a multi-frequency pulse power supply for PSJ [15]. Zhang proposed a multichannel discharge PSJ actuator [16]. Dong explored the evolution of flow structure in nanosecond discharge PSJ cavity [17]. Zhang explored the jet structure of porous PSJ at different pressures [18]. Sun Jian studied aerodynamic force and torque control of flying wing model by using parallel discharge PSJ array [19].
In order to meet the demand of low power consumption in future practical applications, more and more scholars begin to pay attention to the energy efficiency characteristics of plasma synthetic jet actuators [20-26]. Wang Lin compared the three-dimensional modeling simulation and experimental results under different electric heating efficiency [20]. Golbabaei Asl proposed a new method to calculate the discharge efficiency based on the theoretical prediction and the results of measuring the impulse response of plasma synthetic jet in the pendulum gravimeter experiment [21]. Zong used the improved theoretical model [22] and PIV technology [23] to study the energy efficiency characteristics of the actuator. He also studied the effect of dimensionless heating volume on efficiency and established a preliminary nonlinear program model to optimize the actuator parameters [24]. Zhang Zhibo established a new model by combining the electromagnetic dynamics equation and the resistance-inductance-capacitance equation, and analyzed the effect of shell energy and radiation loss on efficiency [25]. Zhou Yan studied the discharge and electrothermal efficiency of the two-electrode plasma synthetic jet actuator under the single excitation mode with circuit parameters and actuator structure parameters [26]. The above researches mainly focus on the energy efficiency characteristics of single discharge mode or similar single discharge mode. There are few researches on the high-frequency continuous excitation mode, especially when the excitation frequency is equal to the natural frequency of the cavity. In this mode, the internal components of the cavity are greatly affected by the discharge [11]. The instantaneous parameters of single cycle discharge vary greatly, so it is difficult to use the transient quantity to study. Therefore, a new characterization method is needed. In addition, the absolute energy efficiency of the plasma jet is generally $10^{-5}$ ~ $10^{-4}$ by optimizing the structure parameters of the actuator and the discharge circuit. It is urgent to consider how to use other methods to improve the energy efficiency.

The plasma jet produced by spark discharge is a high-speed plasma synthetic jet. It formed at the outlet of the actuator cavity, which is caused by the discharge in a closed cavity to heat up and expand the gas in the cavity, forcing the gas to extrude from the only outlet. In the working cycle, only the jet outlet is used for suction recovery, and the amount of backfill gas is limited. Especially when the excitation frequency is equal to the natural frequency of the gas renewal in the actuator cavity [11], the gas parameters in the cavity are greatly affected by the discharge. With the increase of the working time of the actuator, the time required for the inspiratory recovery stage is prolonged, the inspiratory capacity is insufficient, the jet speed is significantly reduced, the working frequency of the actuator is limited, the jet energy generated is reduced, and the flow control ability is weakened.

In order to solve the problem that the jet energy is reduced and the flow control ability is greatly weakened when the jet is operated for a long time, the scholars put forward some solutions. Based on the existing actuator and the principle of high-speed gas stamping, Luo Zhenbing et al. invented a kind of pneumatic synthetic jet actuator which can make full use of the high-speed flow environment. Its working principle is to introduce a high-speed flow through the air inlet of the actuator. The high energy jet for flow control is synthesized by the action of "force" (high-speed flow stamping) and "relay" (gas heating of spark discharge). Lin Qi et al. put forward a kind of air replenishing spark discharge plasma jet actuator, which uses a one-way valve to expand the intake channel in the recovery stage, increase the intake volume and shorten the recovery time. When working for a long time, the energy utilization efficiency of the gas discharge in the cavity is improved, thus greatly improving the jet energy and continuity [27]. All of the above schemes are to improve the performance of the discharge chamber through various ways of air supply. Previous studies focused on the influence of the parameters of air replenishment on jet velocity, but few on energy efficiency.

Due to the different flow states on the aircraft surface, the surface pressure distribution is gradient. The idea of using the flow pressure to supplement the plasma synthetic jet actuator is proposed [28]. As shown in Figure 1, taking the wing surface as an example, the air flow velocity at the stagnation point of the leading edge of the wing drops to zero, and the pressure at the stagnation point is the maximum, which is the total incoming pressure. In other locations, as the flow accelerates along the airfoil surface, the dynamic pressure increases and the static pressure decreases. The pressure in the cavity of the plasma synthetic jet actuator is equal to that in the jet hole. The air is drawn from the stagnation point of
the wing leading edge and sent to the air filling port of the actuator, which can improve the air filling pressure of the actuator, accelerate the recovery speed of the suction when the actuator is working, make the gas state in the cavity recover to the initial state as soon as possible, maintain the stability of the gas discharge, and improve the speed.

![Diagram](image)

**Figure 1.** Improving the performance of PSJ by using flow pressure air supplement.

Therefore, this paper studies the energy efficiency characteristics of the high frequency excitation mode, that is, the continuous operation mode with the excitation frequency equivalent to the natural frequency of the discharge chamber, and explores the effect of different air supply pressure on the energy efficiency characteristics of the two electrode inductive discharge plasma synthetic jet actuator. Firstly, the theoretical model of dynamic pressure air supplement is established. Secondly, the discharge experimental device and measurement method of the study on the energy efficiency characteristics of the air supplement plasma synthetic jet are introduced, and the definition of the index average energy conversion rate which measures the energy efficiency characteristics is given. Finally, the effect of the air supplement pressure on the average jet velocity, average discharge power and average energy conversion rate is analyzed.

2. Experimental system

In order to explore the effect of air supplement pressure on the energy efficiency of plasma synthetic jet, an experimental system is built as shown in Figure 2, including plasma synthetic jet actuator, programmable high-voltage pulse power supply, pressurized air supplement system, oscilloscope, power meter, U-tube manometer, current probe and voltage probe.

![Diagram](image)

**Figure 2.** Experimental system structure.

2.1. Plasma synthetic jet actuator

The structure of the designed plasma synthetic jet actuator is shown in Figure 3, and its structural parameters are shown in Table 1. The main body of the actuator is made of zirconia ceramic. The main body of the actuator is $a = 24$ mm long and $b = 27$ mm wide. A cylindrical hole with internal thread of 8 mm in diameter is arranged on the main body as the discharge cavity, and a jet hole with diameter of $d = 1.2$ mm and a pressurized filling hole with diameter of $D = 6.5$ mm are respectively arranged in the
vertical direction of the discharge cavity. Two ends of the discharge chamber are screwed into the steel studs with a diameter of $M = 8$ mm and sealed with silica gel. Through holes are opened in the center of the steel studs, and tungsten copper alloy needles with a diameter of $m = 2$ mm are inserted as cathode and anode electrodes. The anode and cathode of the actuator are respectively connected with the positive and negative pole of the high voltage output of the programmable high voltage pulse power supply. The power supply is a program-controlled four channel high-voltage pulse power supply developed by our research group. The model is XMU-PTAL-DY-03. The output pulse voltage amplitude of each channel is 0-20 kV, the frequency is 0-20 kHz, and the duty cycle is 0-99%. The basic accuracy of the power meter is 0.2%. The air supplement one-way valve is a diaphragm type medical one-way valve. Its air inlet diameter $D_c$ is 2.5 mm, and the opening pressure $p_k < 3$ kPa.

Figure 3. Plasma synthetic jet actuator.

| Table 1. Actuator parameters. |
|-------------------------------|
| Parameter                      | Value  |
| Actuator length $a$/mm         | 24     |
| Actuator width $b$/mm          | 27     |
| Cavity diameter / Steel stud diameter $M$/mm | 8     |
| Cavity height $H$/mm           | $0 - 24$ |
| Jet throat length $h$/mm       | 9.5    |
| Jet throat diameter $d$/mm     | 1.2    |
| Air supplement throat diameter $D$/mm | 6.5 |
| Anode and Cathode diameter $m_c$/mm | 2   |
| Opening Pressure of the Check valve $p_k$/kPa | 0-2 |
| Entrance Diameter of the Check valve $D_c$/mm | 2.5 |

2.2. Pressurized air supplement system

In order to simulate the dynamic pressure of incoming flow for air supplement (as shown in Figure 1), an air supplement system is designed, including high-pressure air bottle, pressure reducing valve, pipeline and switch (as shown in Figure 2). Open the high-pressure air bottle, adjust the pressure to 0.3-0.4 MPa, reduce the pressure to kPa level through the pressure reducing valve, and then supply the air into the plasma synthetic jet actuator cavity, with the air supplement pressure $p$, range of 3-11 kPa.
2.3. Measurement system

In order to obtain the energy efficiency characteristics of the plasma synthetic jet actuator (see Sec. 3.1 for the definition), the average discharge power $P_a$ and the average jet velocity $v_a$ were measured. $P_a$ is measured by a power meter (CP-240), which is connected between the input end of the high-voltage pulse power supply and the commercial power to measure the average power of the whole system (as shown in Figure 2). $v_a$ is measured by a U-tube manometer, which is aligned with the jet hole of the actuator, and the measurement distance is 1 mm from the jet hole. According to Bernoulli equation, the jet dynamic pressure $p_m$ is obtained by U-tube manometer, and the average jet velocity $v_a$ is calculated by Eq. (1), where $\rho$ is the air density at room temperature (288 K), taking 1.22 kg.

\[ v_a = \sqrt{\frac{2p_m}{\rho}} \]  

(1)

3. The effect of air supplement pressure on the energy efficiency of PSJ

3.1. Definition of average energy conversion rate

In relevant documents at home and abroad, the definition of the energy efficiency of plasma synthetic jet in the related references is mainly to compare the single discharge energy with the jet energy, less considering the energy efficiency characteristics in the case of continuous discharge. The discharge of plasma synthetic jet actuator has strong dynamic characteristics. Especially when the discharge frequency $f_d$ of the actuator is close to the Helmholtz natural frequency $f_h$ [29] of the actuator, the discharge energy of each cycle of continuous discharge is quite different (as shown in Figure 4). The main reason for this phenomenon is that under continuous excitation, due to the very short jet duration ($\sim 100 \mu s$) and large waveform, the breakdown voltage and discharge current required for each discharge are different, and the gas composition in the actuator cavity changes greatly [30]. For example, the jet temperature predicted by Narayanaswamy rises rapidly from the ambient temperature of 300 K to more than 1000 K [31].

It is difficult to measure the transient parameters by experiments. In order to reflect the energy efficiency characteristics of the actuator under continuous excitation, the average discharge power $P_a$ and the average jet velocity $v_a$ of the actuator in a period of time are used as the measurement indexes to study the effect of the air supplement pressure on the energy efficiency of the actuator. Therefore, the dimensionless average energy conversion rate $\varepsilon_a$ can be defined as the ratio of the average kinetic energy $E_a$ of the jet to the average discharge energy $E_d$. The average kinetic energy of the jet can be calculated by the average jet velocity $v_a$ and the average discharge energy can be calculated by the average power $P_a$ measured by the power meter, as shown in Eq. (2) to Eq. (4).

\[ E_a = \frac{1}{2} m_a v_a^2 = \frac{1}{2} \rho A v_a^2 t v_a^2 = \frac{1}{2} \rho A v_a^3 t \]  

\[ E_d = P_a t \]  

\[ \varepsilon_a = \frac{E_a}{E_d} = \frac{1}{2} \frac{\rho A v_a^3 t}{P_a t} = \frac{\rho A v_a^3}{2 P_a} \]  

(2) \hspace{1cm} (3) \hspace{1cm} (4)

In the above equations, $m_a$ is the mass of the gas ejected by the jet in time $t$, and $A$ is the area of the jet hole. By using the dimensionless average energy conversion rate $\varepsilon_a$ defined above, the effect of the air supplement pressure on the energy efficiency of the PSJ actuator is studied.

3.2. Effect of air supplement pressure on energy efficiency of the actuator

As shown in Eq. (5), the Helmholtz natural frequency of the actuator is related to the volume of the cavity [31].
In the above equations, \( L_{th} \), \( V_{ca} \), \( P_0 \) and \( \gamma \) are the length of the jet outlet, the volume of the cavity, the pressure of the external environment and the specific heat ratio respectively. In order to study the effect of frequency, dimensionless frequency is defined as shown in Eq. (6). \( T_d \) represents the discharge period and \( T_h \) represents the cavity oscillation period (1/\( f_h \)) between jet ejection and suction recovery [14].

\[
f^* = \frac{f_d}{f_h} = \frac{T_h}{T_d}
\]

When \( f^* \ll 1 \), the excitation period is enough to restore the actuator to its initial state. Therefore, the jet characteristics of the actuator in continuous excitation mode are almost the same as that in single operation mode. On the contrary, when \( f^* \) is close to or greater than 1, the gas density in the cavity will decrease, resulting in the change of the characteristics of the pulsed jet [14, 31].

This paper focuses on the energy efficiency characteristics of the actuator when the discharge frequency \( f_d \) is similar to the natural frequency \( f_h \) of the actuator, and the effect of air supplement on the energy efficiency characteristics of the actuator. When the discharge frequency is high (tens to hundreds of Hertz), the change of \( f_d \) will change the output energy of the power supply. Therefore, in order to ensure that the discharge output energy is consistent during the experiment, \( f^* \) is not adjusted by changing the discharge frequency, but by adjusting the natural frequency \( f_h \) of the discharge cavity of the actuator. From Eq. (3), it can be seen that adjusting the volume of cavity \( V_{ca} \) is easier to achieve rapid adjustment of \( f_h \), so adjusting \( V_{ca} \) is selected to change \( f^* \). According to the structure of the actuator, \( V_{ca} \) and its corresponding natural frequency \( f_h \) are shown in Table 2. \( V_{ca} \) is 500 mm\(^3\), 600 mm\(^3\), 700 mm\(^3\) and 800 mm\(^3\) respectively, and the corresponding actuator \( f_h \) is 837.6 Hz, 764.6 Hz, 707.9 Hz and 662.2 Hz respectively. When the discharge frequency \( f_d = 250 \) Hz, the corresponding \( f^* \) under each volume is shown in Table 2. The air supplement pressure \( p_s \) range from 0 to 11 kPa (surface pressure). In addition, the electrode distance of the actuator \( d = 5 \) mm, the amplitude of the loading pulse \( U_C = 17.5 \) kV, duty cycle \( \tau = 20\% \).

| \( V_{ca} / \text{mm}^3 \) | \( f_d / \text{Hz} \) | \( f_h / \text{Hz} \) | \( f^* \) |
|-----------------|------------|------------|------|
| 500             | 250        | 837.6      | 0.30 |
| 600             | 250        | 764.6      | 0.32 |
| 700             | 250        | 707.9      | 0.35 |
| 800             | 250        | 662.2      | 0.38 |

**Figure 4.** Changes in discharge peak voltage and peak current under different \( f^* \).
Firstly, in order to verify the phenomenon that the discharge characteristics of plasma synthetic jet actuator change when the discharge excitation frequency is close to the natural frequency, the instantaneous peak voltage $U_{\text{max}}$ and peak current $I_{\text{max}}$ of the discharge under different $f^*$ conditions without air supplement are measured. The results are shown in Figure 4. It is found that $U_{\text{max}}$ and $I_{\text{max}}$ fluctuate greatly under different dimensionless frequency $f^*$ when there is no air supplement. And the result data obtained by repeated measurements are discrete. Taking the average value as the reference quantity, the maximum fluctuation range of $U_{\text{max}}$ is 13.8% and the maximum fluctuation range of $I_{\text{max}}$ is 33.8%. When $f^*$ is equal to 1, that is, the discharge frequency $f_d$ is close to the natural frequency $f_h$ of the actuator, the inspiratory recovery time is very short. Therefore, the next cycle of discharge begins when the gas parameters in the cavity haven't yet been restored to the initial state. In this way, with the increase of the discharge time, the gas discharge in the cavity becomes more unstable, and the transient parameters of discharge change dramatically, especially the discharge current. It can be seen that the discharge parameters and jet characteristics of the actuator in a single cycle cannot truly reflect its working characteristics when $f^*$ is equal to 1. Therefore, this paper proposes to use the average as the measurement index. By measuring the average jet velocity and average discharge power of the actuator in a long period of time, the energy efficiency characteristics of the plasma synthetic jet are measured, as shown in Eq. (4).

3.2.1. Average jet velocity. First of all, Figure 5 shows that the average jet velocity $v_a$ varies with the filling pressure $p_s$ at different dimensionless frequencies $f^*$. When there is no discharge excitation ($f^* = 0$), under the action of air supplement pressure, when the pressure in the cavity is greater than the external pressure, there will be a certain jet velocity, which increases with the increase of air supplement pressure, from 25.8 m/s to 61.9 m/s, increasing by nearly 1.4 times. When there is discharge excitation and $f^*$ is equal to 1, the average velocity of the jet produced by the actuator increases linearly with $p_s$, which is basically parallel to the velocity change curve without excitation. And $v_a$ is approximately equal under each filling pressure, but it is significantly higher than that without excitation. When air supplement pressure $p_s = 11$ kPa, the average velocity of the jet produced by the actuator with different $f^*$ is about 68 m/s, which is about 9% higher than that without excitation. It shows that the jet energy generated by the actuator comes from the energy generated by discharge and the energy of pressurized air supplement.

![Figure 5. Effect of supplemental gas pressure on jet average velocity under different $f^*$.](image1)

![Figure 6. The growth rate of average jet velocity produced by discharge under different air supplement pressures.](image2)

In order to further analyze the contribution of energy generated by plasma spark discharge to the jet, let the average velocity of the discharge jet under different supplemental gas pressure be $v_a$, the average velocity of the jet without discharge excitation is $v_0$, so the growth rate $\Delta v = \frac{v_a - v_0}{v_0}$, as shown in Figure 6.
With the increase of $p_s$, when $p_s < 7$ kPa, $\Delta \delta$ decreased gradually. When $p_s > 7$ kPa, $\Delta \delta$ remained stable. In the early stage, the jet energy generated by the air supplement pressure is low, and the jet increase generated by the discharge energy is considerable. When the air supplement pressure is increased to a certain extent, the total energy occupied by the discharge is basically unchanged. The results show that the air supplement can stabilize the discharge and control the decrease of the growth rate. It is also noted that when $p_s < 7$ kPa, the jet growth rate $\Delta \delta$ in the state of $f^* = 0.30$ is significantly higher than that in the other three states of $f^*$. It indicates that when the excitation frequency is more and more close to the natural frequency of the cavity, because the gas density in the cavity cannot be restored to the initial state before the next discharge, the jet strength is greatly affected, which also confirms the conclusion of literature [14, 29]. However, with the increase of $p_s$ above 7 kPa, the gas renewal in the cavity is accelerated, and the growth rate of the other three $f^*$ states is basically the same as that of $f^* = 0.30$. It shows that the discharge performance of the actuator can be improved and the stability of the jet can be enhanced by increasing the air supplement pressure to a certain extent.

According to the results of Figure 5 and Figure 6, the average jet velocity after pressurization is mainly generated by pressurization. And the energy generated by discharge is added to further improve the energy of jet. When $f^*$ is equal to 1, the contribution of the discharge to the jet decreases when the air supplement pressure $p_s$ is small. But when $p_s$ increases to a certain extent, the speed of external air backfill is enough to keep the discharge in the cavity relatively stable, keep the jet stable, and keep the jet velocity growth rate relatively stable.

### 3.2.2. Average discharge power

In order to obtain energy efficiency, while measuring the average jet velocity under the above conditions, another important indicator to measure the average energy efficiency characteristic of the exciter is the average discharge power $P_a$, as shown in Figure 7. Obviously, as the supplemental gas pressure $p_s$ increased, the average discharge power showed a downward trend, and after being pressurized by supplemental gas, they all decreased to about 38 W. The most significant decrease was in the state of $f^* = 0.38$. From no supplemental gas, $p_s = 0$, $P_a = 70.7$ W decreased to 38.7 W ($p_s = 7$ kPa), the power was reduced by 45.3%, $p_s$ increased again, and $P_a$ remained basically stable at around 38 W. This shows that when the discharge frequency of the actuator is close to the natural frequency of the actuator cavity, that is, $f^*$ is close to 1, the discharge power is greatly affected by $f^*$ without air supplement. The closer $f^*$ is to 1, the higher the discharge power is, and the slower the power decreases with the increase of air supplement pressure.

![Figure 7. Effect of air supplement pressure on average power of actuator under different cavity volume.](image_url)

![Figure 8. Variation of exciter discharge average power with $f^*$ at different supplemental air pressures.](image_url)

In order to further investigate the relationship between dimensionless frequency $f^*$ and discharge power, with $f^*$ as the abscissa, the change of power $P_a$ with $f^*$ under different pressure $p_s$ is plotted, as shown in Figure 8. After the gas supplement, the $f^*$ range of low power consumption is significantly
expanded, and as ps increases, the frequency range of low power consumption is wider. When ps only increases to 3 kPa, the power consumption is below 40 W in the range of $f^*$ from 0.30 to 0.35; when ps increases to 7 kPa, the discharge power in the range of $f^*$ from 0.30 to 0.38 is all below 40 W. Without air supplementation, when the frequency $f^*$ is equal to 1, the gas parameters in the cavity change drastically, and the gas state of the cavity cannot be restored to the initial state of the discharge in time after the discharge, and then the next discharge, so that the discharge power is affected by $f^*$ very large, in general, the closer $f^*$ is to 1, the higher the discharge power will be. After the air supplement, the gas recovery in the cavity is accelerated, and the gas in the cavity can be quickly restored to the initial state. The gas parameters remain relatively stable to meet the next discharge, which can maintain the stability of the discharge, significantly reduce the discharge power, and improve its working performance.

3.2.3. Average energy conversion rate. Although the jet will also be produced under the action of air supplement pressure, the jet energy of this part is not the effect of discharge. So when calculating the average energy conversion rate of discharge, it is necessary to subtract the energy produced by the air supplement pressure and only consider the increase of jet kinetic energy brought by the energy produced by the discharge part. According to Eq. (4), the formula for calculating $\varepsilon_a$ under air supplement pressure is converted into Eq. (7).

$$
\varepsilon_a = \frac{E_{a1} - E_{a2}}{E_0} = \frac{\rho A(v_{a1}^2 - v_{a2}^2)}{2Ps}
$$

In the formula, $v_{a1}$ is the average jet velocity of the actuator when the pressure air supplement and discharge are working at the same time, and $v_{a2}$ is the average jet velocity of the actuator only when the pressure air supplement is working.

Using the measured average jet speed and discharge power, according to the Eq. (7), the change curve of the average energy conversion rate $\varepsilon_a$ of the plasma synthetic jet with the air supplement pressure $p_s$ is shown in Figure 9. As a whole, with the increase of $p_s$, $\varepsilon_a$ increases gradually under each $f^*$. Especially when $p_s$ is more than 7 kPa, the discharge energy efficiency of the actuator is improved significantly and more discharge energy is converted into the kinetic energy. When $p_s = 0$, the magnitude of $\varepsilon_a$ is $o(10^{-4}) - o(10^{-5})$, which is consistent with the result in reference [29], $o(10^{-4})$ and $o(10^{-5})$ refer to the magnitude of discharge energy conversion. After air supplement, the gas in the cavity can be recovered faster, the parameters of the gas can be kept stable, and the discharge power is reduced (Figure 7 and Figure 8). At the same time, the kinetic energy of the jet maintains a certain growth (Figure 5). The above comprehensive effect makes the overall average conversion rate continue to increase. When $p_s = 11$ kPa, $\varepsilon_a$ reaches the order of $o(10^{-3})$, which is 1-2 orders of magnitude higher than that without air supplement. The results show that the discharge energy efficiency of the actuator is significantly improved after air supplement.

![Figure 9. Variation of exciter average energy conversion rate with $p_s$ at different $f^*$.](image)
4. Conclusion
(1) When the discharge frequency of plasma synthetic jet actuator is close to the Helmholtz natural frequency of the cavity, the instantaneous discharge characteristics of a single cycle under the continuous frequency excitation change dramatically. The average energy conversion rate can be used as the index to evaluate the discharge energy efficiency.

(2) With the increase of dimensionless frequency $f^*$, the increase of the average jet velocity caused by the discharge of the actuator decreases when the air supplement pressure is less than 7 kPa. When the air supplement pressure is increased to 7 kPa, the filling speed of the outside air is enough to keep the gas discharge in the cavity relatively stable. This can improve the discharge performance of the actuator, enhance the stability of the jet, and stabilize the jet growth rate at about 9%.

(3) When $f^*$ is between 0.3 and 0.4, the average discharge power is greatly affected by $f^*$ when there is no air supplement. Generally speaking, the average discharge power increases sharply with the slow increase of $f^*$. With the increase of air supplement pressure, the gas recovery speed in the discharge chamber increases, the gas parameters remain relatively stable, and the discharge power decreases rapidly. When the air supplement pressure reaches 7kPa, the power consumption of the actuator is kept at about 40W, and the power consumption is reduced by 45.3% at most.

(4) In the case of air supplement, the average discharge power consumption of the actuator is greatly reduced, while the average jet velocity is still relatively high. Therefore, the average energy conversion rate is greatly increased with the increase of the air supplement pressure, from $o \times (10^{-5}) - o \times (10^{-4})$ without air supplement to $o \times (10^{-3})$, increasing by 1-2 orders of magnitude. It shows that it is a feasible way to improve the energy efficiency of plasma synthetic jet actuator by air supplement.

(5) In the future, in the application of actual flow control, it is necessary to further explore the layout of the air filling port on the aircraft model, so as to increase the air supplement pressure as much as possible and improve the discharge effect.

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