Research of Heat Dissipation Technologies for Electromagnetic Linear Actuator

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Abstract. As the core drive component of Electromagnetic Driven Valve Train (EDVT), Electromagnetic Linear Actuator (ELA) directly determines the performance of EDVT, and thus affects the dynamic performance and fuel economy of the engine. During high-velocity motion, ELA produces heat that will negatively affect its property or even make some damages. On the basis of analysis of temperature rise and temperature distribution of ELA, three heat dissipation technologies were proposed in this study, and relevant experimental test was carried out for each of the three technologies. Through comparing data of temperature rising test and considering factors such as noise and space usage, the method of silent fan equipped with cooling fin was selected as optimal heat dissipation scheme. This study provides sound test data on heat dissipation technology of ELA and is of important engineering significant.

1. Introduction

Compared with Cam Driven Valve Train (CDVT) in conventional engine, EDVT can realize fully flexible regulation of valve movement law within the entire operating range, which makes the engine working at optimum performance and thus significantly improve the dynamics and fuel economy of the engine [1-4]. The core drive component of EDVT is ELA. The energy consumption and performance of ELA directly influence the energy consumption, high-speed adaptability and long-time work stability of EDVT, and thus affects the dynamics and fuel economy of the engine [5]. Therefore, research on ELA energy consumption and heat dissipation technologies of ELA is of theoretical significance and practical engineering value.

Figure 1. ELA structure and experimental prototype
In this work, the ELA is basically a cylinder type moving coil linear motor [6], of which the structure and experimental prototype are shown in Figure 1. On the basis of previous energy consumption analysis and temperature rise test of ELA [7, 8], this paper proposes three heat dissipation technologies of ELA and carries out in-depth analysis and comparison.

2. Temperature rise of ELA

Previously, we have carried out in-depth analysis of heat transfer process of ELA and established mathematical models of radial and axial heat transfer. On this basis, the finite element model of ELA was constructed with the aid of Ansoft Maxwell and Ansys Workbench, and bidirectional coupling dynamic simulation of energy consumption and temperature rise was performed [8]. Through simulation, the temperature rise and distribution can be obtained, as shown in Figure 2 and Figure 3, respectively.

![Figure 2. Temperature rise curve of ELA’s internal measuring point at engine speed of 3000r/min](image2)

![Figure 3. Temperature distribution cloud chart of ELA at initial and final stable state when engine speed is 3000 r/min](image3)

As shown in Figure 2, the temperature of ELA gradually increases with working time, and eventually reaches a stable state (where the temperature maintains at a constant value and ELA enters into stable working state). However, when the engine speed is 3000r/min, ELA enters into stable working state with maximum temperature reaching over 115 °C and minimum temperature reaching at point F reaching about 70 °C. If continuing working under such high temperature, the permanent magnet material...
NdFeB in ELA will be demagnetized, some plastic parts show deformation and aging, and the working performance of ELA will be reduced or even damaged. In the case when the engine speed is more than 3000r/min, the situation will be even worse. Therefore, heat dissipation of ELA is of engineering significance to guaranteeing the working stability and service life of ELA under high-intensity workload.

Figure 3 shows the comparison of temperature distributions of ELA under initial state and final stable state. It can be seen that the high-temperature zones of ELA are mainly concentrated at inner yoke and coils. In the vertical direction, the temperature gradually increases from bottom to top, and the temperature is the most concentrated especially at the top position. As for heat dissipation and cooling measures for ELA, the heat dissipation near the position of inner moving coils and at the position of upper cover should be concerned the most.

3. Heat dissipation scheme of ELA
According to the temperature rise and temperature distribution of ELA in section 2, the high-temperature zones of ELA are mainly concentrated near moving coils and at top cover, so heat dissipation at these positions are very important. Through in-depth analysis, three heat dissipation schemes were proposed in this study.

3.1. Reed valve pumping
The working principle of reed valve pumping is shown in Fig.4. The inner moving coil of ELA produces air flow, which drives the reciprocating motion of reed valve, resulting in pump suction effect. Therefore, rapid flow of air and heat convection can be realized. In such innovative design, only installation of a reed valve rather than other complex devices is needed, which is basically a minor structural alteration of ELA. Dr. Fan Xinyu has made in-depth analysis on this issue and achieved certain results [9], which will not be reiterated here.

![Figure 4. Working principle of reed valve pumping](image)

Through conducting temperature rise test of ELA with reed valve pumping and comparing it with the temperature rise results of ELA without reed valve pumping, temperature variation curve of ELA at measuring point B can be obtained, as shown in Fig.5. Since point B was the point where the highest external temperature value was measured except for point A and subsequent two scheme cannot measure the temperature at point A, point B was selected as the unified comparison point in this study.

According to Figure 5, the adoption of pump suction leaf valve has certain but not significant inhibition effect on temperature rise of ELA. When the engine speed exceeds 4000r/min, it is still difficult for ELA to reach stable state at temperature of 110°C. If the engine speed is even higher, the temperature for stable state will be increased accordingly. When the temperature exceeds 120°C, the
performance of ELA will get worse, and ELA will be easily damaged under such high-temperature and high-intensity working condition.

In conclusion, reed valve pumping has compact structure and innovative design, but has worse heat dissipation effect, with limited amount of heat being brought away.

![Figure 5](image)

**Figure 5.** Comparison of temperature variation at measuring point B

3.2. Fan+ flange support
ELA is an executive device of the EDVT in engine, of which the surrounding space is compact, and the external heat absorber cannot fully cover it. Through analysis of ELA temperature distribution, we decided to install a heat absorber at top cover of ELA.

Considering the temperature at ELA moving coil is the highest, it is of vital significance to lower the temperature at the position of inner moving coils and air gap. However, according to the analysis result of pump suction leaf valve scheme, the convection effect produced by ELA movement itself is not enough. So we were wondering if installation of an external forced air blast device can have sound cooling effect on ELA? In this study, we considered to employ "fan + flange support" scheme to perform forced cooling with the aid of the air vent at top of ELA, as shown in Figure 6.

![Figure 6](image)

**Figure 6.** Layout of "fan + flange support" heat dissipation scheme
To allow air penetrate via air gap to lower end of ELA, the wind power of fan must be strong enough so as to achieve sufficient forced air cooling effect. In this scheme, the fan adopted was SANYO fan PCRA0412P4K03, with parameters listed in Table 1.

| Parameter                  | Duty cycle | Rated voltage | Rated current | Rated power input | Rated speed (Inlet) | Rated speed (Outlet) | Static pressure | Operating temperature range |
|----------------------------|------------|---------------|---------------|-------------------|--------------------|----------------------|-----------------|---------------------------|
| 100%                       | 12V        | 1.6A          | 19.2W         | 17500min⁻¹        | 11700min⁻¹         | 650Pa                | -10℃~70℃        |
| 0%                         | 0.19A      | 2.28W         | 5250min⁻¹     | 3510min⁻¹         | 58.5Pa             |                      |                 |

Since measuring point A was occupied, the data measured at other 5 points were obtained, as shown in Figure 7. Through performing force-air cooling for ELA with a powerful fan, the temperature rise of ELA was significantly inhibited. When the engine speed is lower than 5000r/min, temperature at all external measuring points can be finally maintained within 90℃; even when the engine speed is 6000r/min, the temperature can be finally maintained around 110℃, indicating a significant decrease of temperature of ELA.

![Figure 7. Temperature rise curves of ELA at 5 measuring points after adoption of “fan+ flange support” heat dissipation scheme](image)

However, such scheme is subjected to some defects. The dimensions of fan and flange are large, which will increase the overall height of ELA after installation of fan and flange. When ELA is in high-speed movement, inertia shaking will be inevitably resulted. In actually application, some problems will be caused due to dimensional limit of engine cylinder head. In addition, there is a loud noise during the operation of the powerful SANYO fan, which is a significant noise pollution.

3.3. Silent fan + cooling fin

Regarding external heat dissipation at top cover of ELA, there is another scheme using silent fan and cooling fin, as shown in Figure 8. To reduce the noise of external installed fan, a silent fan is adopted in
this scheme. Moreover, the employment of cooling fin enlarge the heat dissipation area at top cover of ELA, thus realizes effective cooling effect.

Through experimental test of such scheme, temperature rise curve can be obtained, as shown in Figure 9. When the engine speed is 6000r/min, the temperature of ELA at all external measuring points can be finally maintained within 100 ℃. This indicates that the scheme of silent fan + cooling fin effectively reduce the operating temperature of ELA and improve the reliability and stability of ELA during long-time operation.

Figure 8. Layout of air cooling device using silent fan and cooling fin

Figure 9. Temperature rise curves of ELA at 5 measuring points using silent fan and cooling fin

4. Comparison of three heat dissipation schemes

Through analysis and comparison of three different heat dissipation schemes, an optimal one was finally determined. By collecting and analyzing test data of three schemes, the comparison of temperature rise curves of ELA at measuring point B by three different schemes can be obtained, as shown in Figure 10-a.
Figure 10. Comparison of data of three different heat dissipation schemes

As shown in Figure 10-a, the three schemes exert cooling effect on ELA in different degrees. Among them, the cooling effect of pump suction leaf valve scheme is relatively unsatisfactory, whereas the other two schemes using fan have significantly cooling effect as the final temperature of ELA at measuring point B can be maintained within 65 °C when the engine speed is 3000r/min. Of two schemes using fan, the scheme of silent fan + cooling fin has better cooling effect.

Figure 10-b shows the temperature values at different measuring points under different schemes when ELA reaches stable state. The results of Figure 10-b are consistent with the results in Figure 10-a, from which other laws can be obtained. All three schemes can reduce the temperature values measured at different points at stable state of ELA, wherein the cooling effect at point A, B, C is significantly better than that at point D, E, F. The two schemes using fan have better cooling effect, which make the final stable temperature at point B and C (at the two points, the temperature used to be high) lower than that at point D. The satisfactory cooling effect is associated with the installation site of fan and also the consequence of comprehensive analysis of ELA temperature distribution.

Through compressive analysis of three heat dissipation schemes, diagram of comprehensive performances of three schemes can be obtained, as shown in Figure 11. It can be seen that the three schemes were compared in terms of cooling effect, noise intensity and space occupation. The scheme
of silent fan + cooling fin has the best comprehensive performance. The scheme of powerful fan + flange support has significant cooling effect, but has excessive noise and space occupation, which limits its comprehensive performance. In contrast, the scheme of reed valve pumping has advantages in noise and space occupation, but has unsatisfactory cooling effect. Moreover, it does not require external air cooling power supply, which is the most distinguished feature compared with the other two schemes. Pump suction leaf valve has various advantages, which is of great research value. If the cooling effect can be improved, the comprehensive performance of pump suction leaf valve can be significantly improved. Therefore, further researches on pump suction leaf valve are needed. According to comparison of three schemes at present, the scheme of silent fan + cooling fin has the best comprehensive performance.

5. Conclusion
Three heat dissipation schemes for ELA were analyzed and compared in this study, and following conclusions can be obtained:

1. High-temperature zones of ELA are mainly concentrated near inner moving coils. In vertical direction, the temperature gradually increases from bottom to top, therefore the heat dissipation at the position of moving coil and top cover should be concerned the most for cooling treatment of overall ELA.

2. Through comparing temperature rise data and evaluation from cooling effect, noise intensity and space occupation, the scheme of silent fan + cooling fin was selected as optimal heat dissipation scheme.

3. Although reed valve pumping scheme has limited cooling effect, it has various advantages including innovative design, extremely small space occupation, no requirement of external air cooling power supply, which is worth of further researches.

This study provides test data and analysis basis for further development of ELA heat dissipation technologies, which is of engineering application value.

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