Applied Thermal Engineering 128 (2018) 1579–1587

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Hold current effects on the power losses of high-speed solenoid valve for common-rail injector

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HIGHLIGHTS

- Analyze distribution characteristics of the different losses such core loss, solid loss, copper loss and mechanical energy.
- Reveal the influence of hold current I on dynamic response time of solenoid valve.
- Determine interrelation between dynamic response and effective energy utilization of solenoid valve.

ARTICLE INFO

Article history:
Received 17 June 2017
Revised 15 August 2017
Accepted 23 September 2017
Available online 28 September 2017

Keywords:
Hold current
Dynamic response
Power loss
High-speed solenoid valve
Common-rail injector

ABSTRACT

In the present investigation, a simulation of the dynamic response of a high-speed solenoid valve (HSV) has been performed. The influences of hold current I on the dynamic characteristics and power losses of a HSV have been investigated through the finite-element methods (FEM). The simulation results show that as the driving current I decreases, the opening response characteristics of a HSV deteriorate, the proportion of different power losses decrease in different levels, the energy utilization efficiency of a HSV increases. In the energy distribution of a HSV, core loss accounts for the highest proportion, followed by solid loss and copper loss. Useless energy is mostly due to core loss. It can be concluded that there is a possibility of achieving an optimal balance between the opening response time and energy distribution of a HSV when choosing hold current I properly.

1. Introduction

As environmental pollution is becoming severe and oil resources are drying up, fuel economy and low emission of diesel engines are urgently required. Developing diesel engines with efficient combustion and low emissions is a new challenge for academics and engineers in the field of internal combustion engine. A high-pressure common-rail system with flexible control is very important for improving and optimizing the comprehensive performance of diesel engines. A High-speed solenoid valve (HSV) is the key control unit of a common-rail injector. A HSV with high dynamic response characteristics is necessary to ensure precise and flexible control of the fuel injection timing, fuel injection quantity, and injection rate shape [1–4].

A HSV is crucial for the precise control of a solenoid injector in common-rail injection systems. There have been researched about the working performance of a solenoid valve. Wang et al. [5] tested the effects of Al-Fe soft magnetic material on the performance of a solenoid valve and determined that this material can effectively reduce the magnetic resistance and improve the electromagnetic force. Cheng et al. [6] adopted a new soft magnetic material to design the magnetic circuit of a HSV and analyzed its magnetic flux density distribution characteristics. Liu et al. [7] analyzed the main structure parameters of an electromagnetic valve and the influence of the relationship among the parameters on the electromagnetic force of a HSV using the response surface method. Sun et al. [8] performed simulation of a solenoid valve in the unit pump with electrical control and determined that the driving current has a significant influence on the electromagnetic energy conversion of the HSV. C. Marco et al. [9] established a mathematical model of a common-rail injector solenoid valve using the zero-dimension method and studied the influences of driving current on the electromagnetic force of a HSV under different air gaps. SMA. Jaber [10] and Nitu et al. [11] studied the influence of driving voltage on the electromagnetic force and pointed out that the electromagnetic force increased proportionally with the increase in driving voltage.

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https://doi.org/10.1016/j.applthermaleng.2017.09.123
1359-4311/

The dynamic response of a HSV in a fuel injectors is significant for the precision control of a fuel injection. The working process of a solenoid valve involves a multi-field process coupled with elec tric-magnetic-mechanical-thermal fields. Therefore, the corresponding energy conversion determines the opening and closing response characteristics of the solenoid valve. Cvetkovic et al. [12] developed a theoretical model of a solenoid valve to research multi-field coupling relations. Andadi et al. [13,14] tested the impact of temperature and driving current on the reliability of a solenoid valve, established a theoretical model to improve the dynamic characteristics, and predicted the reliability of a solenoid valve. Cheng et al. [15] analyzed the influence of four different driving circuits on the energy loss and dynamic response of solenoid valves and stressed the importance of driven strategy on the response characteristic of a solenoid valve. Zhao et al. [16] investigated relationship between the boost voltage, opening response time and power losses of a solenoid valve.

It can be observed that the majority of the aforementioned literature investigated the influences of structural parameters or driving current on the electromagnetic characteristics and dynamic response of a solenoid valve using experimental and simulation methods. However, there are few reports about the function of hold current I in the driving circuit with two-order hold current and the analysis of the influence of hold current on the distribution of energy inside a HSV. Therefore, from the viewpoint of energy distribution inside a HSV, the reasons for the impact of hold current I on the dynamic response of the HSV should be studied by analyzing the influences of hold current I on the effective electromagnetic energy.

2. Description of models and methodology

2.1. Electromagnetic and mechanical model

Many factors determine the dynamic response of a solenoid valve such as the electromagnetic force, pre-load force of spring, mass of moving parts, and friction. In this article, the effect of the hold current I on a HSV was studied without considering the hydraulic characteristic and load in working condition, thus, the Eq. (1) did not include the fuel oil resistance, additionally, frictional resistance during the motion of moving parts of a solenoid valve was ignored. According to Newton's second law of motion, the movement equation of moving parts of a solenoid valve can be obtained as follows:

$$F_{\mathrm{mag}} - F_{\mathrm{sp}} - m \cdot g = m\frac{d^2x}{dt^2}, \tag{1}$$

where F_{mag} represents the electromagnetic force, F_{sp} denotes the pre-load force of the spring, m represents the mass of the moving components, and x denotes the displacement of the armature.

The electrical behavior of a solenoid valve can be described by Kirchhoff equilibrium equations [17]:

$$V - i \cdot R - N\frac{d\phi}{dt} = 0 \tag{2}$$

where V represents the voltage source, i denotes the electrical current, R represents the resistance of the solenoid valve, ϕ denotes the magnetic flux through each turn, and N is the number of coil turns.

Based on the energy conversion equation, the energy equation of the magnetic circuit can be expressed as:

$$V \cdot i \cdot dt = i^2 \cdot R \cdot dt + F_{mag} \cdot dx + dU_m, \tag{3}$$

where Vi represents the power input, $F_{\mathrm{mag}}dx$ denotes the mechanical work of the electromagnetic force, and dU_m represents the variation of magnetic energy in a working solenoid valve.

Considering Eqs. (2) and (3) with the expression of the magnetic energy U_{m}, the mechanical work can be expressed as:

$$F_{\mathrm{mag}} \cdot dx = \frac{1}{2}(N \cdot i \cdot d\phi - N \cdot \phi \cdot di). \tag{4}$$

Based on Hopkinsow's law, the following expression for the magnetic force is derived:

$$F_{\mathrm{mag}} = \frac{1}{2} \cdot \phi^2 \cdot \frac{dR}{dx}. \tag{5}$$

The derivative of ϕ depends on the displacement x and geometrical parameters. By recording current and voltage time histories, the magnetic flux as a function of time can be derived via the integration from Eq. (2). Therefore, the electromagnetic force can be calculated from Eq. (5).

2.2. Power losses model within solenoid valve

2.2.1. Core loss

Core loss includes hysteresis loss, eddy current loss, and excess loss. Core loss depends on parameters such as the magnetic field frequency and saturation magnetic flux density. Core loss is used to evaluate the power loss of magnetic materials owing to hysteresis and eddy current in high-frequency working conditions. Core loss is obtained based on the calculations of the multi-frequency loss curves. The core loss is determined as follows [18]:

$$P_{\mathrm{Coreloss}} = P_{\mathrm{h}} + P_{\mathrm{c}} + P_{\mathrm{e}} = k_{\mathrm{h}} \cdot f \cdot B_{\mathrm{m}}^2 + k_{\mathrm{c}} \cdot (fB_{\mathrm{m}})^2 + k_{\mathrm{e}} \cdot (fB_{\mathrm{m}})^{1.5}, \tag{6}$$

where P_{h}, P_{c}, and P_{e} represent the hysteresis loss, eddy current loss, and excess loss, respectively. Further, k_{h}, k_{c}, and k_{e} denote the hysteresis loss coefficient, classical eddy current loss coefficient, and excess loss coefficient, respectively. Furthermore, f represents the frequency of the magnetic field and B_m denotes the saturation magnetic flux density.

2.2.2. Solid loss

Solid loss represents the resistive loss of a solid volume, a resistive loss calculated for excitation with solid conductor. The accurate prediction of solid loss is important for the high-speed conductor. There are two main contributors to the solid loss: one is the on-load solid eddy current loss resulting from the harmonics of the magnetomotive force of the windings, which is also called space harmonics; the other is the on-load solid eddy current loss caused by the time harmonics of the phase currents owing to pulse width modulation [18]. Solid loss can be calculated using the following equation:

$$P_{\mathrm{Solidloss}} = \int_V \frac{J^2 dV}{\sigma}, \tag{7}$$

where σ represents the conductivity of the magnetic materials, J denotes the eddy current density, and V represents the volume of the material. The solid loss was simulated using the transient solver with motion, where in the actual measured motor/generator current waveforms were applied.

2.2.3. Copper loss

Copper loss is generated by the driving current in the winding coils, which can be determined using the following formula:

$$P_{\mathrm{Copperloss}} = i^2 \cdot R \tag{8}$$

where i represents the solenoid coil current and R denotes the resistance of the solenoid winding coils.

2.2.4. Mechanical energy

When current was applied to the solenoid valve, the armature moved upward overcoming the effect of spring pre-tightening force by the electromagnetic force. When the armature is at the highest position, it is still maintained at this position under the electromagnetic force. In the opening process of a solenoid valve, the electromagnetic force and displacement of the armature are transient. Therefore, the mechanical energy of a solenoid valve is defined as follows:

$$P_{Mechanical} = \int_0^t F_{mag}(t) \cdot x(t), \tag{9}$$

where $F_{mag}(t)$ represents the electromagnetic force and $x(t)$ denotes the displacement of the moving component of the solenoid valve.

2.3. Simulation model and basic settings

The electromagnetic energy conversion and power loss in the solenoid valve are complex, which is coupled with the electrical-magnetic-mechanical field [13–15]. The three-dimensional finite element method (FEM) is suitable for analyzing the complex energy conversion, and a detailed analysis can be carried out for the solenoid valve. Therefore, in this study, FEM was applied. Fig. 1 illustrates the simulation model of a HSV and its assembly location within the common-rail injector. The dynamic simulation model of a solenoid valve includes the iron core, armature, and coil winding. The detailed parameters including the specified pre-load force of the spring, stiffness of the spring, mass of the moving components, number of coil turns, initial resistance value, B-H magnetization curve of the iron core and armature (Fig. 2), and initial inductance value are presented in Table 1.

2.4. Simulation results and model validation

Fig. 3a shows the test bench of the dynamic response of the HSV, which contains a power control unit, driving current control unit, and the lift test unit of the armature. The boost voltage, hold current I, and hold current II can be flexibly set using the driving current control parameters as shown in Fig. 3b. It is usual to supply high voltage (called as boost voltage) to open a solenoid valve quickly, after opening the solenoid valve, low hold current is generally provided. In this study, a driven strategy with a two-order hold current (peak-hold-hold) was used to drive the HSV. Hold current I ensured that the armature reliably reached the position of the maximum lift. Hold current II was used to maintain the armature at the maximum lift position. Hold current II was usually lower than hold current I.

Fig. 4 shows the comparison between the solenoid experimental armature lift curves and simulation results. Overall, the lift curve obtained from simulation showed a good agreement with the experimental results. Although between the calculated value and experiment results there is a relatively large deviation at the closing process of the solenoid valve, the deviation did not exceed 10%. The reason for the errors at the closing process was that the effects of factors such as mechanical fiction of the moving parts (e.g., armature) were ignored during the moving process in the case of simulation. Therefore, in this condition, the simulated falling velocity of the armature was faster, and thus, the armature returned to the initial position in advance.

3. Results and discussion

3.1. Influence of hold current I on the dynamic response characteristics of HSV

Seen in Fig. 5, the increasing hold current I has an impact on the opening response time of the solenoid valve, but does not affect its closing response characteristics. It is clear that the closing response of a HSV depended on the hold current on the premise of the structural parameters of a HSV remain unchanged. In this article closing response of the HSV depended on hold current II as shown in Fig. 3

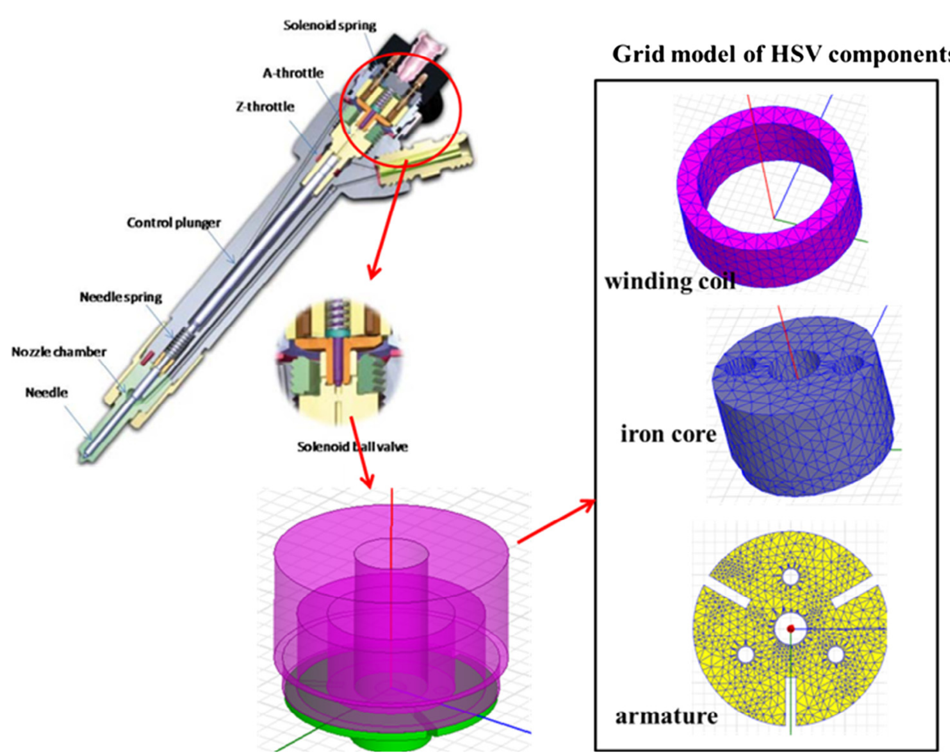


Fig. 1. Simplified 3D simulation model of solenoid valve of common-rail injector.

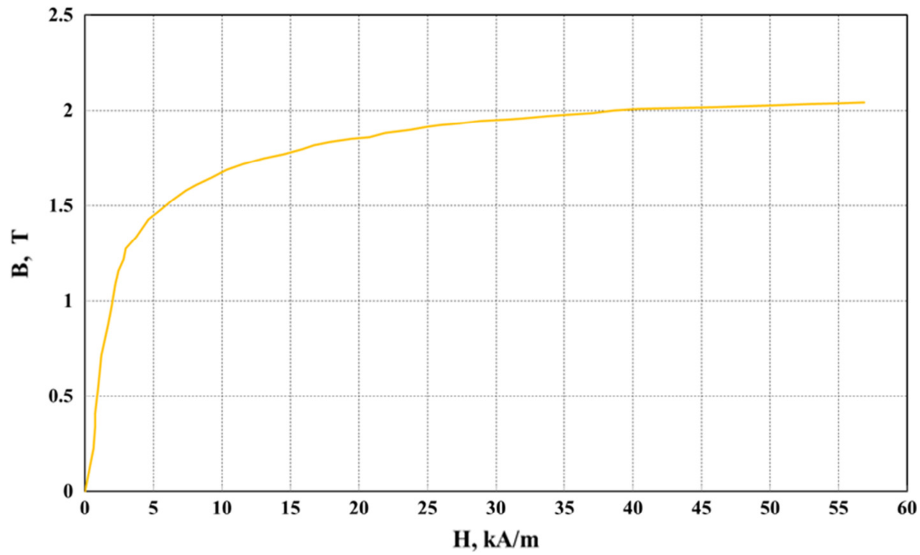


Fig. 2. B-H magnetization curve of soft magnetic materials for the solenoid valve.

Table 1
Detailed information of 3D simulation model.

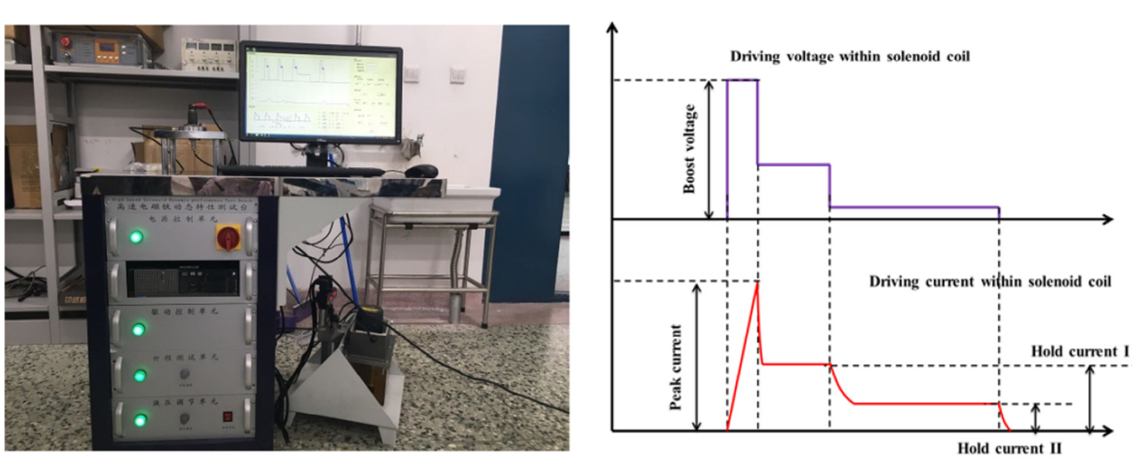
Classification	Setting value
Pre-load force of spring/N	70
Stiffness of spring/(N/mm)	57
Mass of moving components/g	5.3
Number of coil turns	52
Maximum moving displacement of armature/μm	70
Total air gap between iron core and armature/μm	120

(b). The hold current I was studied in the condition that the peak current was 24 A and the hold current II was 5 A constantly. Although an increase of the hold current I enlarged the power in a HSV, but at closing process the constant of the hold current II kept the power constant, thus, the closing response time did not change.

As hold current I increased, the opening response time decreased from 340 μs to 300 μs, indicating that the opening response characters were improved. However, with the increase of hold current I, the power consumption of the winding coil rapidly increases, which raises the temperature of a solenoid valve. After the temperature exceeded the critical value, the insulating layer within winding coil of a solenoid valve melted and was damaged, which was the main reason for the lower service life of a solenoid valve [16,17]. The essence of the impact of hold current I on the opening response time of the solenoid valve was its influence on the energy conversion and distribution in a HSV. Therefore, it is necessary to analyze the significance of hold current I in the driving circuit of a solenoid valve from the viewpoint of energy conversion and distribution, which will be presented in Section 3.2.

3.2. Influence of hold current I on the energy distribution within HSV

As evident in Fig. 6, the total loss within the solenoid valve was different and its distribution was not uniform under different hold current I. When hold current I was 14 A, the total loss inside the solenoid valve was low, and it was mainly distributed in its magnetic area. As hold current I increased, the total loss of the solenoid valve gradually increased and the range of loss distribution enlarged. As hold current I continued to increase, the total loss expanded to the magnetic area out of the solenoid valve and the total loss increased.



(a) (b)

Fig. 3. (a) Test bench to measure the dynamic response characters of the solenoid valve; (b) The schematic of driving current control for the HSV.

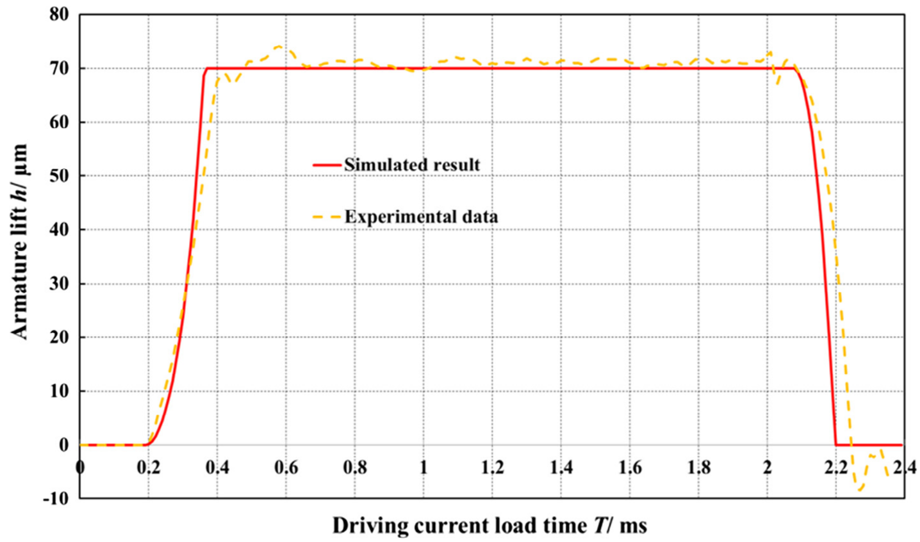


Fig. 4. Comparison between armature lifts of simulation results and experimental data (boost voltage = 70 V, 150 μs, hold current I = 14 A, hold current II = 5 A).

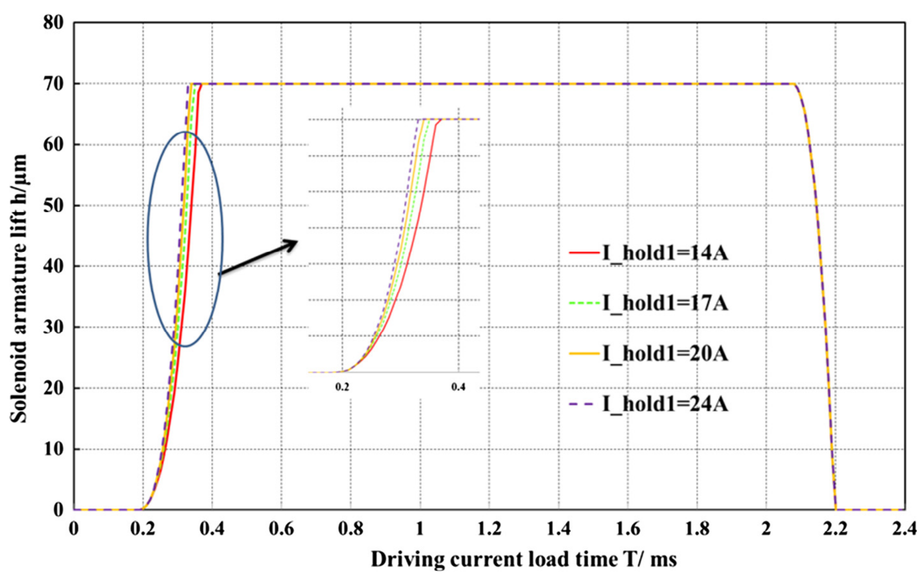


Fig. 5. Influences of hold current on the lift curve of solenoid valve armature.

Fig. 7 shows the changes of the solid loss, copper loss, and core loss of the solenoid valve with the driving current load time in a working cycle. As evident in this figure, rapid changes of the driving current occur at three periods: the period of transition from peak current to hold current I, period of transition from hold current I to hold current II, and phase of hold current II reduces to zero. Core loss occurs during the above three periods. The core loss during the latter two periods is very large. The peak core loss occurs at the transition period from hold current I to hold current II and the peak value exceeds 1600 W. When the driving current increases from zero to the peak current, the solid loss increases and reaches the maximum value when the driving current achieves its peak. When the driving current transits from the peak current to the hold current I, the solid loss decreases significantly. Subsequently, the solid loss remains at a low value during the hold current I. When the driving current transits from the hold current I to hold current II, the solid loss rises rapidly and reaches a peak that is much smaller than the previous one. When the hold current transits from the hold current II to zero, the solid loss increases. The above results demonstrate that the solid loss changes with the driving current in the peak-hold-hold driven strategy. Copper loss depends on the change of driving current.

Fig. 8 illustrates the power distribution at the hold current I equaling 14 A. Core loss constitutes the majority of power, i.e., approximately 50%, which indicates that the maximum power of the solenoid valve is consumed by the iron core. The solid loss constitutes approximately 23% in the power distribution. The solid loss is produced owing to the strong eddy effect inside the solid volume of the solenoid valve, which is caused by the transient driving current. The copper loss accounts for approximately 17%, which mainly arises from the consumption of the winding coil resistance. Based on the above results, the proportion of the copper loss is small compared to those of the core loss and solid loss, which indicates that the copper loss is not the main contributor to the power loss of the solenoid valve. The mechanical energy constitutes the least proportion with a value of 14%. The result of the mechanical

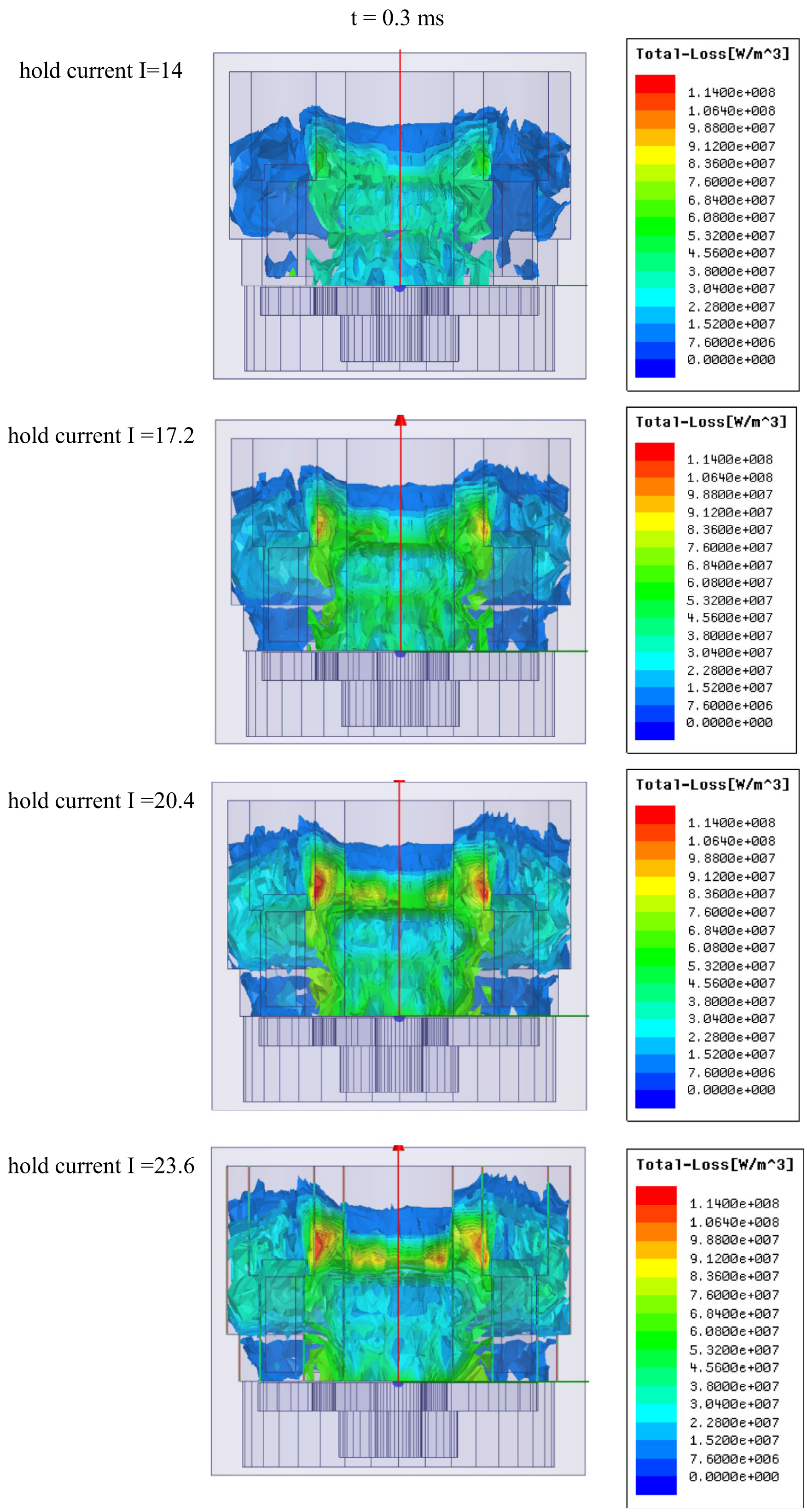


Fig. 6. Total loss distribution within the iron core of the solenoid valve.

energy indicates that only 14% of the total input energy to the solenoid valve is used to drive the solenoid valve move, and the remaining 86% of the power is not used effectively.

Based on Fig. 9, under different hold current I, the power distribution inside the solenoid valve demonstrates similar trends. As the hold current I decreases from 24 A to 14 A, the percentage of

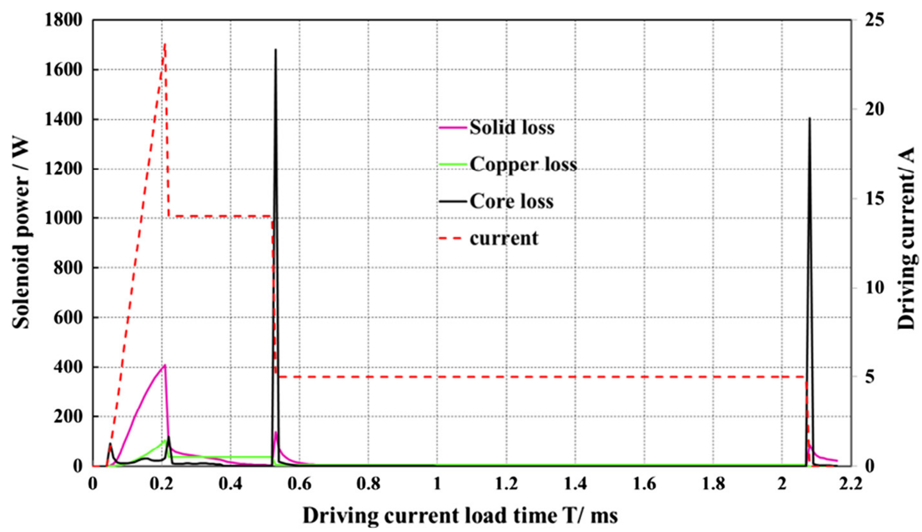


Fig. 7. Influence of different hold current I on the eddy current power loss (hold current I = 14 A).

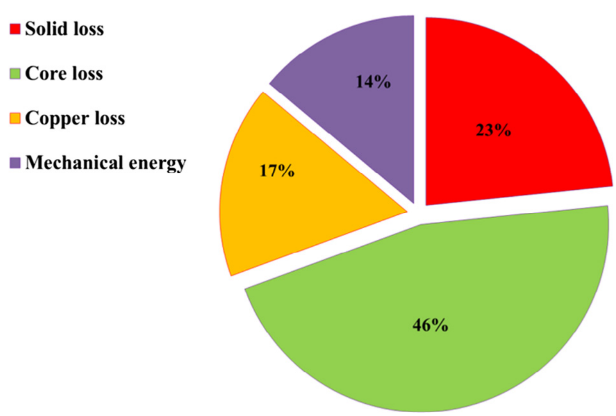


Fig. 8. Power distribution at hold current I = 14 A.

the core loss increases whereas those of the solid loss and copper loss decrease. The core loss decreases by 7.43%, which indicates that the percentage of the core loss is more evidently affected than the mechanical energy. When the hold current I decreases, the percentage of mechanical energy increases but it only increases by approximately 1%. The above results indicate that the change of the hold current I directly affects the power distribution inside the solenoid valve whereas the impact on the mechanical energy is not evident owing to the changes in hold current I.

Fig. 10 shows the energy variation as the hold current I decreases from 24 A to 14 A. The value of core loss increases by 0.14 J whereas the copper loss, solid loss, and mechanical energy decrease. The decreasing amounts of the solid loss and copper loss were similar and less than 0.8 J. The amount of decrease of the mechanical energy was the least which is only 0.08 J. The copper loss, solid loss, and core loss constitute the useless energy of the solenoid valve. As evident in Fig. 10, the useless energy reduces by 1.23 J, which indicates that the hold current I in the peak-hold-hold driving circuit reduces the energy loss. As shown in Fig. 11, as the hold current I decreases, the opening response time of a solenoid valve increases and its conversion efficiency of total energy into mechanical energy increases. The increase in the energy efficiency of a solenoid valve is beneficial for promoting reasonable power distribution and utilization, and plays an important role in improving the reliability and controlling the temperature of the solenoid valve.

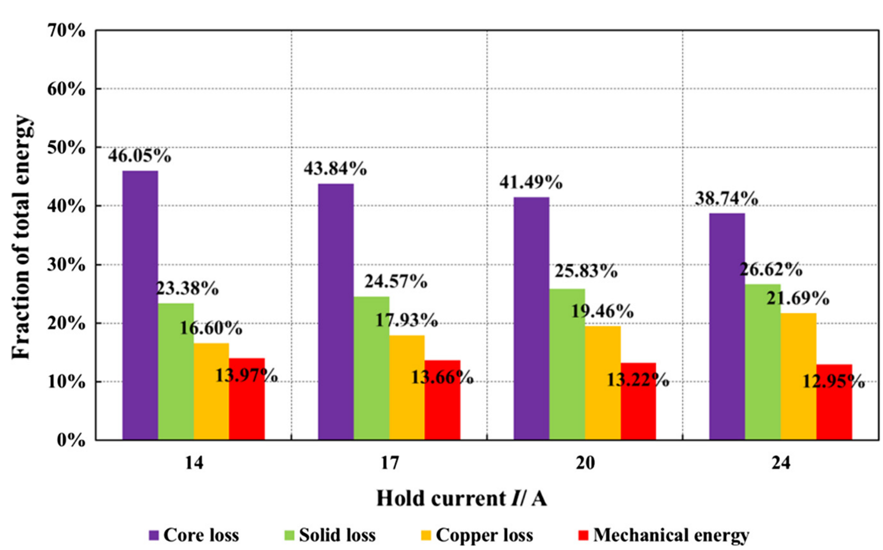


Fig. 9. Power distribution at different hold current I.

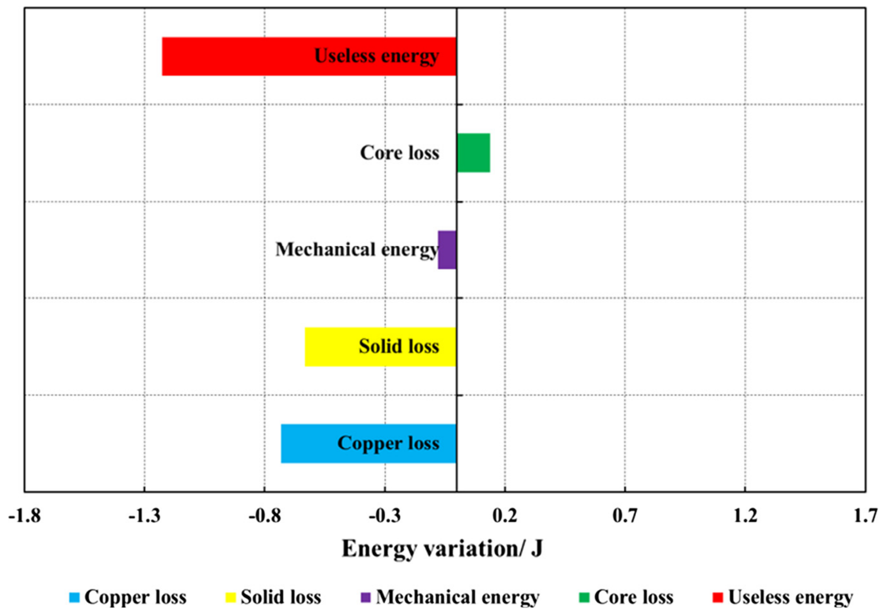


Fig. 10. Energy variation when the hold current I reduces from 24 A to 14 A.

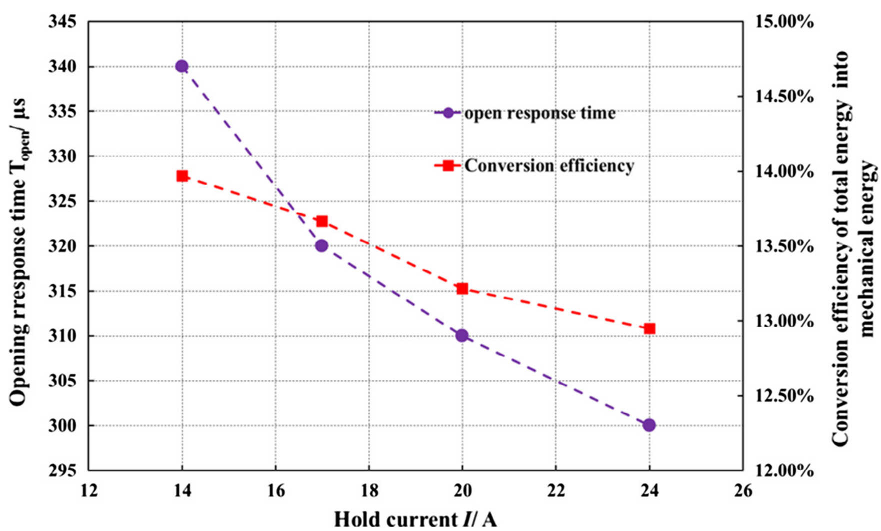


Fig. 11. Influence of hold current I on the opening response and conversion fraction.

4. Conclusions

In this study, FEM was used to investigate the electromagnetic field and power loss distributions of a HSV. The main conclusions are listed as follows:

(1) In the energy distribution of a HSV, core loss accounts for the highest proportion, followed by solid loss and copper loss. Notably, useless energy loss is mostly due to core loss. Useless energy loss directly influences the conversion efficiency of the electromagnetic energy of a HSV.
(2) The change in hold current I influences the proportion of different types of loss in the energy distribution. The proportion of solid loss, copper loss, and mechanical loss decrease by different levels along with the decrease of hold current I. In contrast, the proportion of core loss increases.
(3) As driving current decreases, the opening response time of a HSV increases, useless energy decreases. Therefore, to choose an appropriate hold current, the useless energy can be decreased and the effective energy utilization of a HSV can be increased subsequently.

Acknowledgement

This work is supported by the Fundamental Research Funds for the Central Universities (Grant No: HEUCFM170302), the National Natural Science Foundation of China (Grant No: 51475100) and China Marine Low Speed Engine project-phase 1 (Grant No: CDGC01-KT0302,CDGC01-KT0802). The Authors are all indebted to their generous support.

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