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TECHNICAL PAPER

Study on electromagnetic force of the new micro digital valve

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Abstract

Electromagnetic force is crucial to the performance of the micro digital valve. The bigger electromagnetic force is needed to improve the rapidity of the micro digital valve. In the light of the traditional electromagnetic structure, which layouts the spring at the middle of the electromagnet, a new electromagnetic structure which sets the spring at the top of the electromagnet is studied. The relevant parameters and material are researched in the paper. The cross-sectional area of air gas and the electromagnetic force have a positive correlation relationship. The bigger driving current and the more turn of coil can increase the electromagnetic force in a certain range. The magnetic field would get the saturated state while driving current get a bigger value. At the moment, the magnetic force would not increase. Influence of magnetic material and non-magnetic material for valve seat is tiny. Electromagnetic force has a little difference between the two installation shells in the process of demagnetization. The simulation model is accurate and reliable. Using the simulation model, the electromagnetic cross section area, the different shell materials and the magnetic saturation phenomenon are simulated.

1 Introduction

Digital Hydraulics technology has a potential to replace the proportional systems and the servo systems because of their superiority, such as their favourable programmability, lower power losses and so on (Mikko and Andreas 2010). The high-speed on/off valves are the key components of Digital Hydraulics on account of they have some advantages on rapidity, higher reliability and lower cost. Furthermore, fast response is one key factor of the high-speed on/off valves. And, electromagnetic force decides the response velocity of the high-speed on/off valves. Many works of the mechanism of static electromagnetic characteristics of the solenoid valve are studied (Lisowski et al. 2013; Tsai and Tseng 2010; Fan et al. 2014; Mutai and Yamasawa 1995; Sung and Kim 2012; Kong and Li 2014).

Tao et al. achieved the larger magnetic force and consumed the lower power by selecting different soft magnetic materials and by changing the structure parameters of the electromagnetic valves (Tao et al. 2002). Kajima studied influence of coil turns and electromagnet diameter of electromagnetic performance, and put forward the corresponding solutions (Kajima 1995). Eyabi et al. studied a nonlinear magnetic model which considered magnetic saturation and hysteresis of the materials (Eyabi and Washington 2006). Fu et al. researched the parameters which have influence on dynamic characteristics of a servo proportional valve (Fu et al. 2008). The optimal parameters were selected to improve the response characteristics. Liu et al. analyzed the electromagnetic force of the high speed valve by numerical method and experiment (Liu et al. 2010, 2013). Topcu et al. researched the effects of driving current on switching speed of a fast response valve (Topcu et al. 2006). Nitu et al. (2007) and Taghizadeh et al. (2009) researched the effects of driving voltage and pulse width modulation frequencies on the static electromagnetic force of solenoid valve. The researched result shows that driving parameters have significant effects on the solenoid valves' dynamic behavior. Wang et al. studied effects of magnetic circuit's structure on the magnetic characteristics of a solenoid valve with Al–Fe soft magnetic material, and get the rapid response and strong magnetic force (Wang et al.

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2011). Angadi et al. studied effects of electronic circuit on the magnetic field and temperature field of a solenoid valve (Angadi et al. 2009a, b). Miller et al. studied the effects of coil's parameters on the electromagnetic performance of a novel solenoid valve (Miller et al. 2014).

The above literatures have do a lot of research work on electromagnetic force. According to them, structure parameters and the material are crucial to the micro digital valve. The aim of the paper is to research the structure parameters and material to improve the electromagnetic force. Therefore, the relevant parameters and the experiment method are discussed in the paper. The contrast tests are finished to verify the theory.

2 Mathematical model and testing rig

2.1 Structure of the novel micro high-speed digital valve

In order to study influence of different electromagnetic structure, a new micro high-speed digital valve which used the top spring arrangement plan was presented in this paper, as shown in Fig. 1. In addition, a traditional micro high-speed digital valve which adopted the central spring arrangement plan was also designed to do comparative study, as seen in Fig. 2. Compared with the traditional valve, the novel valve can get the bigger cross-sectional area of air gap. More specifically, diameter of spring chamber of the traditional valve is 2.8 mm, diameter of the spring rod of the new valve is 1.6 mm, diameter of the valve spool is 5 mm. The equivalent area of the novel

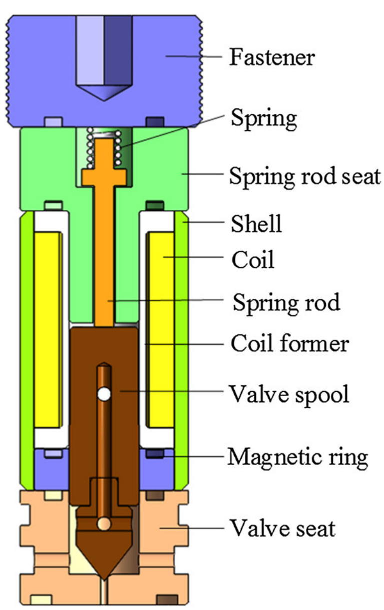


Fig. 1 Novel micro high-speed digital valve

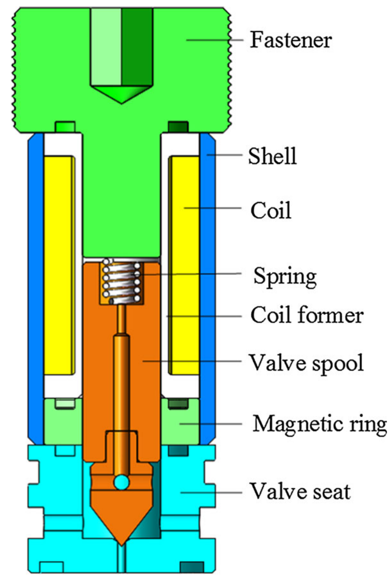


Fig. 2 Traditional micro high-speed digital valve

valve core (iron core) is 16.37 mm^2, and that of the traditional valve core is 13.48 mm^2.

2.2 Mathematical model and simulation setting

Electrical behavior of the micro high-speed digital valve can be implemented by Kirchhoff equilibrium equation (Wang et al. 2016):

$$U = \frac{d\psi}{dt} + iR = \frac{d(N\phi)}{dt} + iR = N\frac{d(\phi)}{dt} + iR, \quad (1)$$

where U is voltage of the valve, ψ is magnetic chain of the magnetic circuit, i is coil current, R is resistance of the coil circuit, N is the coil number, φ is magnetic flux of the coil circuit.

The energy equation of the magnetic circuit can be obtained on the basic energy conversion equation (Sun et al. 2016):

$$Uidt = Ri^2dt + F_e dx + dU_m, \quad (2)$$

where U_i is power input, F_e is electromagnetic force, $F_e$dx is mechanical power, dU_m is the variation of the magnetic energy.

By Kirchhoff' s law of magnetic circuit:

$$Ni = \phi R_m, \quad (3)$$

where Rm is the total magnetic resistance of the magnetic circuit.

By Maxwell' s electromagnetic force formula:

$$F_e = \frac{\phi^2}{\mu_0 S_0} = \frac{B^2 S_0}{\mu_0}, \quad (4)$$

where μ_0 is permeability of vacuum, S_0 is cross-sectional

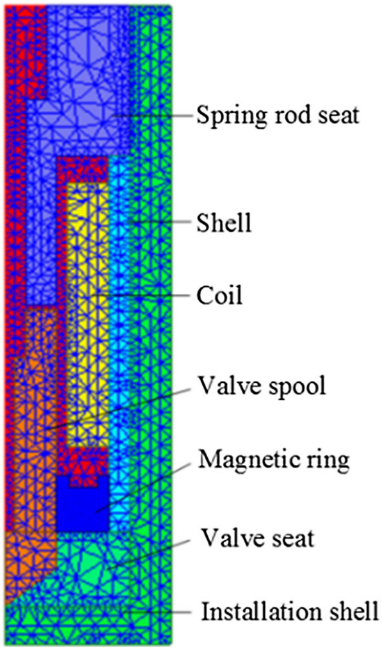


Fig. 3 Mesh model of the traditional valve

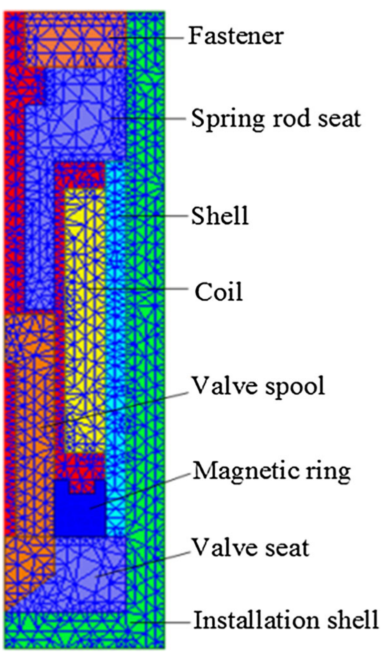


Fig. 4 Mesh model of the novel micro high-speed digital valve

area of air gap, B is the magnetic intensity. The magnetic force equation can be written as:

$$F_e = \frac{\mu_0 S_0 (NI)^2}{4x^2}, \tag{5}$$

where x is the displacement of the armature.

Table 1 Detailed information of Maxwell computation

Item	Classification	Setting
Physical properties		
Armature	Material property	DT4
	Air gap	0.1 mm
	Outer diameter	5 mm
Valve shell	Material property	DT4
Coil	Material property	Copper
	Wingding type	Standard
	Turns	Variable
	Height of coil	14 mm
	Inner diameter of coil	7.5 mm
	Outer diameter of coil	10 mm
Initial boundary		
Other components	Material property	Al or 316L
Motion field	Material property	Air
Solving domain	Material property	Air
Driven condition	Direct current	Variable

Numerical analysis of electromagnetic force which needs to consider many factors (i.e. size, materials, structure and current) is one complex calculation process. The finite element method has been applied in the present researches (Wang et al. 2016; Chen et al. 2014; Moaveni 2007; Sun et al. 2007). ANSYS Maxwell has been adopted to the simulation study (Liu et al. 2010; Dean et al. 2008). Figures 3 and 4 show the grid models of the traditional vale and the novel valve. Table 1 describes the detailed information required in the simulation. Figure 5 shows the components of the micro valve. Figure 6 shows the whole structure of the micro valve.

2.3 Selection of materials

Rapidness is one important characteristic of the micro digital valve. Bigger electromagnetic force can help to obtain the design aim. Magnetic materials which use in the micro digital valves have many kinds. But they should accord to the principles: higher saturation magnetic induction intensity B_s, higher permeability μ_m, lower remanence intensity B_r and lower coercive force H_c. Base on these basic requirements, DT4C is selected in the paper. The basic physical properties are given in Table 2.

DT4 has higher saturation magnetic induction intensity, so it can obtain bigger electromagnetic force than other soft magnetic material when they reach to magnetic saturation. Table 3 shows the detailed information of the micro digital valve.

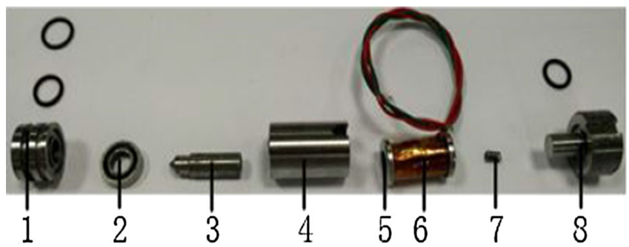


Fig. 5 Components of the micro valve

Fig. 6 Whole structure of the micro valve

Table 2 Physical properties of the soft magnetic materials

Materials	B_s (T)	B_r (T)	μ_m (H/M)	H_c (A/M)
DT4	1.8	1.2	6	32

Table 3 Detailed information of the micro digital valve

Item	Classification	Setting
Physical properties		
Armature	Material property	DT4
	Air gap	0.3 mm
	Outer diameter	5 mm
Coil	Material property	Copper
	Wingding type	Standard
	Turns	Variable
	Height of coil	14 mm
	Inner diameter of coil	7.5 mm
	Outer diameter of coil	10 mm
Other components	Material property	Al or 316L
Motion field	Material property	Air
Solving domain	Direct current	Air
Initial boundary		
Driven condition		Variable

3 Results

3.1 Testing method and electromagnetic testing platform

In order to get accurate measurement data, one testing method is adopted, which insulate influence of spring. As

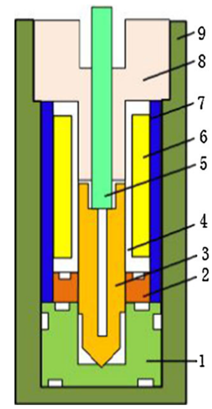


Fig. 7 Central spring arrangement testing plan

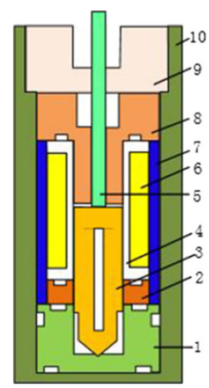
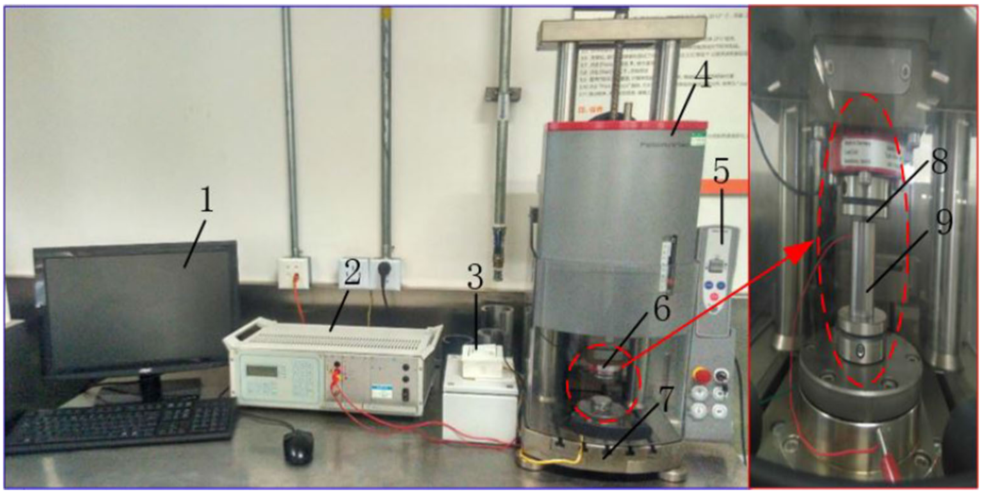


Fig. 8 Top spring arrangement testing plan

in seen in Figs. 7 and 8, the springs are removed and the guide rods are added. Electromagnetic force of valve is transmitted from the micro valve to the force transducer of the electromagnetic testing platform.

As is seen in Fig. 9, the electromagnetic testing platform is made up of host computer, transducer, controller, collector and so on. The testing platform can provide different driving signals. Electromagnetic force of the micro valve is measured by the force transducer under different lengths of air gap and currents. In the testing process, electromagnetic force is transmitted form the valve spool to the guide rod. Then, it is acted on the end of the force transducer through touch between the guide rod and the force transducer.



1.Industrial Personal Computer 2.Intelligent current controller 3.Current collector 4.Host computer 5.Control panel 6.Force transducer 7.Foundation 8.Guide rod 9.Micro valve

Fig. 9 Electromagnetic testing platform

3.2 Analysis of experimental results

3.2.1 Influence of turns

In order to research influence of turns, turns are varied from 200r to 400r. The testing current is 0.5A. Diameter of the enameled wire is 0.08 mm. The valve for central spring arrangement is selected to testing. Material for the installation shell is 2A12. Material for the valve seat is Cr12MoV.

Figure 10 shows influence of turns on electromagnetic force F_e Each curve has two processes, the curve of the bigger value is the magnetization process, the other is the demagnetization process. As can be seen, F_e and turn vary in proportion, and they have approximate linear relationship. According to Kirchhoff' s law:

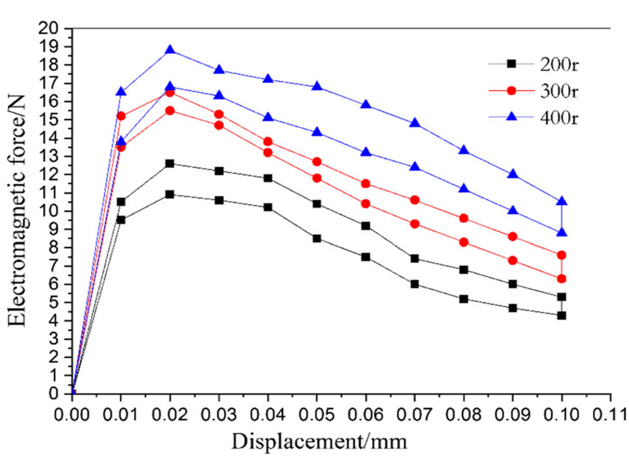


Fig. 10 Electromagnetic force for different turns

$$\Phi = Ni/R_m. \tag{6}$$

The magnetic flux ϕ increases with the rise of turns while other testing condition has no adjustment. Along with the turns, magnetic field intensity will strengthen. Accordingly, the magnetic flux ϕ will enhance.

3.2.2 Magnetic saturation testing

Because of the limitation of electromagnetic characteristic of soft magnetic materials, the magnetic field intensity can not increase infinitely. When the magnetic field reaches to a level, the electromagnetic performance comes to the limitation. Different current are adopted as so to verify the assumption. Diameter of the enameled wire is 0.08 mm. Turns of the enameled wire are 400r. Material for the installation shell is 316L. Material for the valve seat is Cr12MoV. Exciting current varies from 0.5A to 0.8A. Figure 11 is the F_e curves of different exciting current. In Fig. 11, while current varies from 0.5A to 0.7A, electromagnetic force F_e and current vary in proportion, and they have approximate linear relationship. When the current reaches to 0.8A, electromagnetic force doesn't increase. Under this case, the magnetic field has reached the saturated state. Electric energy does not transform to magnetic energy, so electromagnetic force does not increase. Redundant electric energy will produce thermal energy, which causes energy loss. If thermal exceed the certain range, resistance of the enameled wire will change, even burn down the wire.

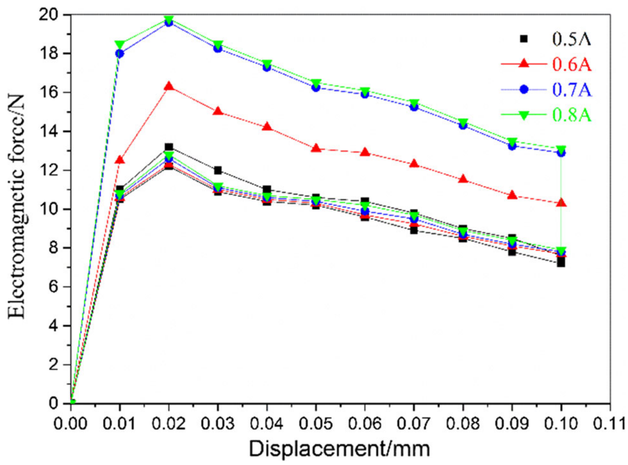


Fig. 11 Magnetic saturation for different current

3.2.3 Influence of cross-sectional area of air gap

Electromagnetic force can reflect the magnetic characteristics and can be measured through the testing platform. Therefore, electromagnetic force was used as the comparison parameter between the simulation analysis and the testing work. In the testing process and simulation research, the driving current is 0.8A, number of the coil turns is 300, displacement of the iron core is 0.1 mm. As shown in Fig. 12, four curves represent the testing results and the simulation results of the two valves respectively. From Fig. 12, it can be concluded that electromagnetic force increases along with decrease of the air gap. Under the same displacement of the iron core, the testing results of electromagnetic force of the novel micro high-speed digital valve were about 1.33 times as that of the traditional valve. According to formulation (6), ratio of the testing results was in good agreement with the area ratio of the two valves. The simulation results were much closed to the testing values, and the maximal relative deviation was approximately 4.3%. Therefore, the simulation is in agreement with the actual results, and the simulation model is reasonable and correct.

3.2.4 Influence of different materials for valve seat

The micro digital valve is a poppet valve. Therefore, endurance of the valve seat should be considered deeply. Material of valve seat is usually magnetic material. Influence of magnetism of the valve seat need to be researched. In order to solve the problem, comparison tests are studied. Testing current is 0.5A. Diameter of the coil is 0.08 mm. Number of coil turns is 300. Material for the installation shell is 2A12. Figure 13 shows the curves of the electromagnetic force under different materials of valve seat. Comparison materials are 2A12 and Cr12MoV. 2A12 has little magnetism and Cr12MoV has some magnetism. In Fig. 13, electromagnetic forces of the materials are nearly uniform. Therefore, influence of different materials for valve seat is tiny. Endurance of Cr12MoV is better than that of 2A12. So Cr12MoV should be used as the material of the valve seat.

3.2.5 Influence of different materials for installation shell

Material for installation shell is crucial for the experiment. Because the material of the installation shell may affect the distribution of the magnetic field, experiment of different materials of installation shell need to be done. In this testing, 2A12 and 316L are selected to verify the different influence. The testing current is 0.8A. Number of coil turns is 300r. Diameter of the coil is 0.08 mm. Material for the valve seat is Cr12MoV.

2A12 has little magnetism and 316L has weak magnetic properties after they are processed. Figure 14 shows the

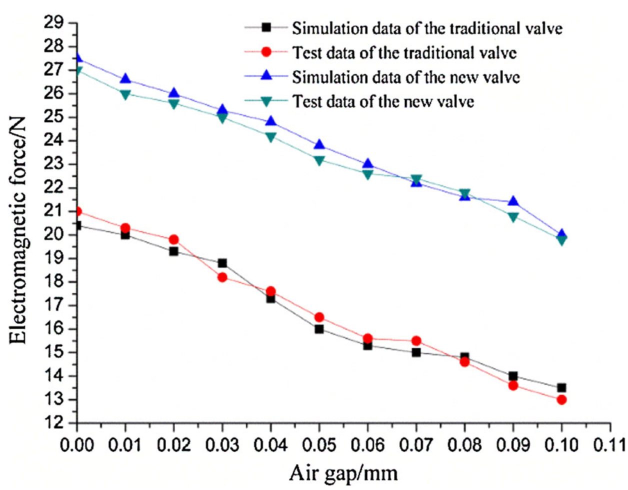


Fig. 12 Electromagnetic force for different arrangement

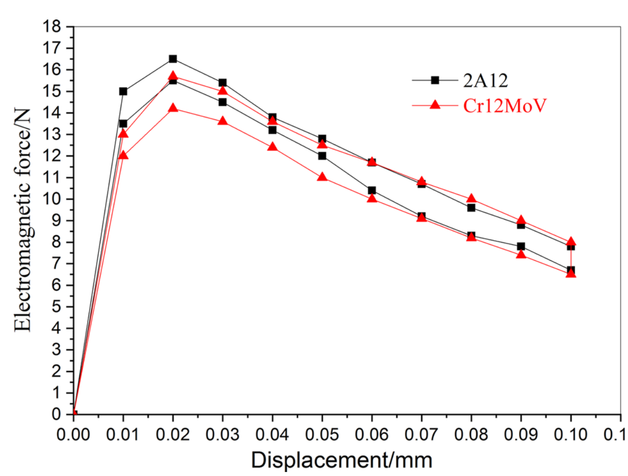


Fig. 13 Electromagnetic force for different materials for valve seat

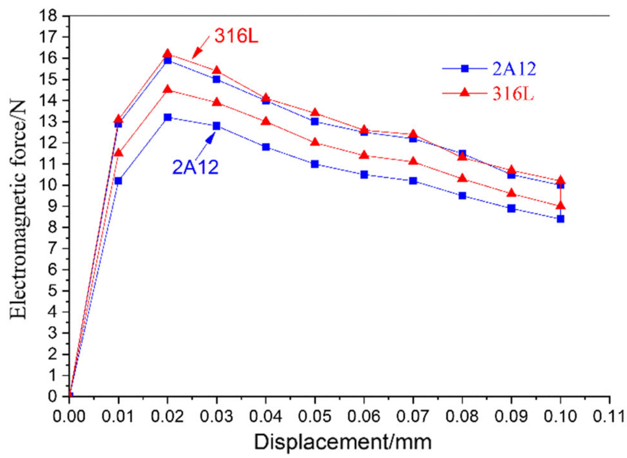


Fig. 14 Electromagnetic force for different materials for installation shell

curves of the electromagnetic force under different materials for installation shell. As is seen in Fig. 14, electromagnetic force has little difference between the two installation shells in the process of magnetization, and has a little difference between the two installation shells in the process of demagnetization. Electromagnetic force of installation shell of 316L is bigger than that of 2A12 in the process of demagnetization. Smaller electromagnetic force would be needed in the process of demagnetization. So 2A12 should be used as the material of installation shell.

4 Simulation results and analysis of multi parameters

4.1 Influence of cross section area of iron core

The two kinds of micro valves studied in this paper, the valve spool is equivalent to the moving iron core, fasteners (traditional valve) and spring rod seat (new valve) is equivalent to the static iron core. The area of the iron core of the electromagnet influences the distribution of the magnetic line and the density of the magnetic flux, and then determines the magnitude of the electromagnetic force. Area of the iron core of the electromagnet influences the distribution of the magnetic line and the density of the magnetic flux, and then determines the magnitude of the electromagnetic force. Figures 15 and 16 show the distribution of magnetic field lines and magnetic induction intensity images for the two valves. Magnetic flux density and magnetic induction intensity were greater than that of the traditional valve. This is due to increase of the iron core area, the effective volume of the electromagnet increases, more magnetic lines can be used to enhance the magnetic induction intensity. As shown in Fig. 17, the energy

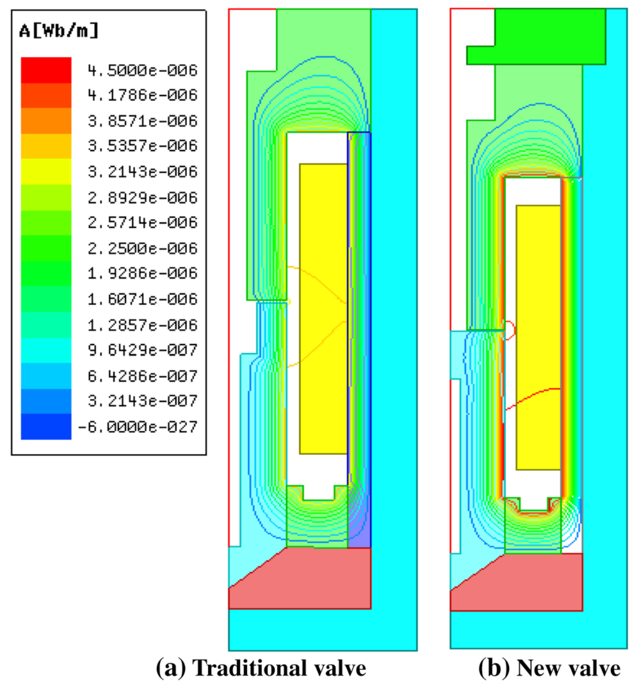


Fig. 15 Distribution of magnetic lines of force

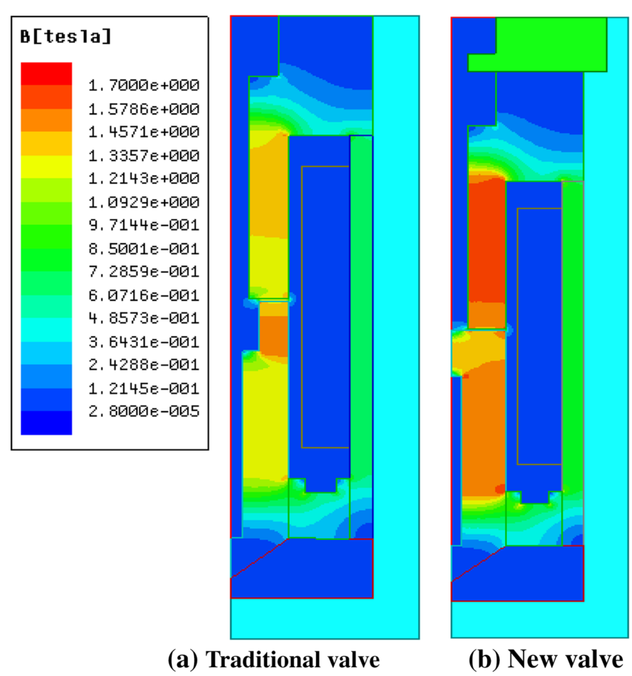
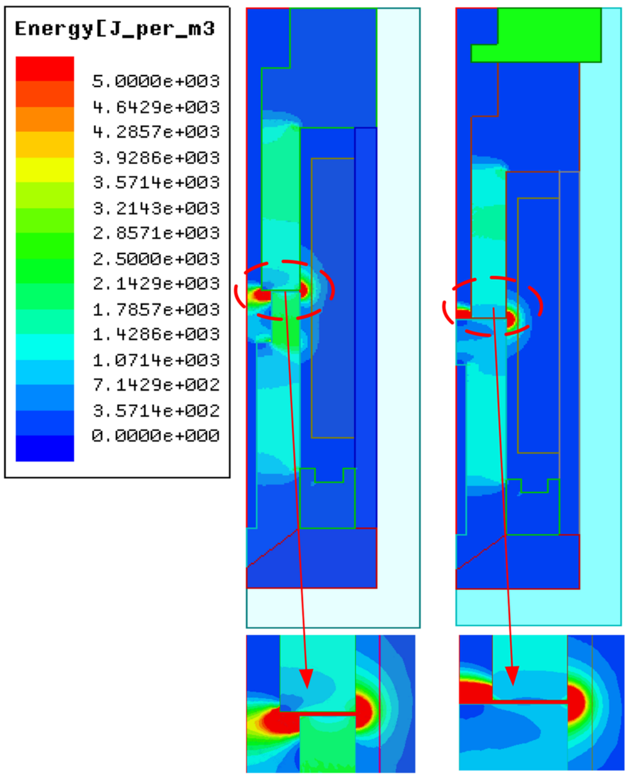


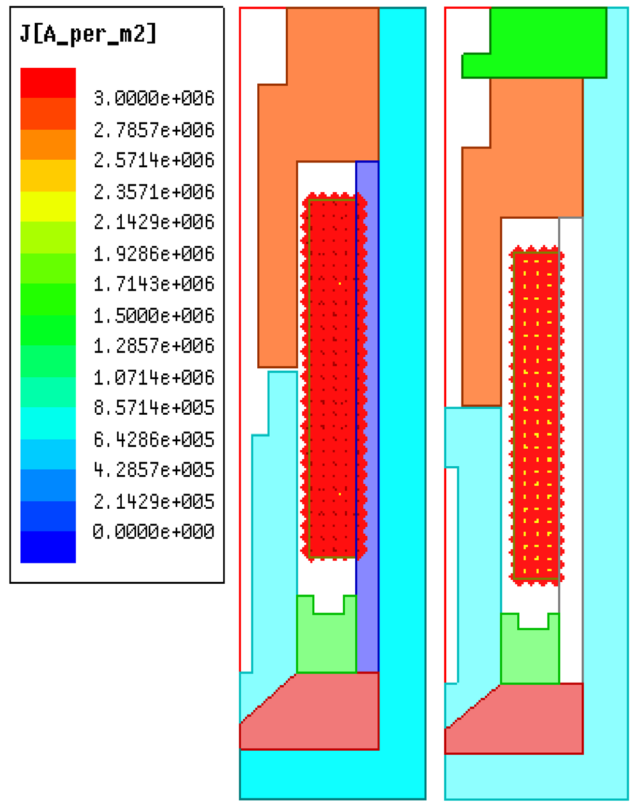
Fig. 16 Magnetic induction intensity

nephogram of shows that the core of the new valve consumes more energy, which means that the electric energy can be converted to magnetic energy to a greater extent at the same voltage. The Joule heat images shown in Fig. 18, the Joule heat of the novel valve is smaller than the traditional valve, which means that the coil of the novel valve



(a) Traditional valve **(b) New valve**

Fig. 17 Energy nephogram



(a) Traditional valve **(b) New valve**

Fig. 18 Joule heat nephogram

has lower thermal consumption. Therefore, the structure of the novel valve is more reasonable than the traditional valve.

4.2 Influence of materials

Selection of the materials for the installation shell directly affects the electromagnetic performance of the valve, and can also be used as the material selection basis of the valve block. In this paper, the novel valve was used as the study object. Two kinds of materials were chose for comparative analysis: non-magnetic material-Al and magnetic material-DT4. As shown in Fig. 19, the distribution of the magnetic lines of the two installation shell. Because of the magnetic isolation effect of Al material, the magnetic lines cannot pass through the installation shell, so that the magnetic lines are concentrated together. The magnetic field distribution of the installation shell of Al material concentrates and gathers in the valve shell. However, due to the redistribution effect of the magnetic field lines, the magnetic field of the installation shell of the DT4 material diffuses to the outside, part of the magnetic lines are introduced to the installation shell, so the magnetic field of the DT4 material is weaker and the electromagnetic force at the valve spool is smaller. Electromagnetic force of two kinds of the two installation shell are as shown in Fig. 20. At 240 A turns, the electromagnetic force of the Al material installation shell is 1.33 times as that of the DT4 material installation shell. Therefore, in the processing of the valve block, Al alloy material should be selected to produce a cluster effect on the magnetic circuit, so that the electromagnetic force reaches the maximum effect.

4.3 Magnetic saturation

When the number of ampere turns increases to a certain value, there is a magnetic saturation phenomenon in the electromagnetic field. At the moment, the magnetic flux of the electromagnet is no longer increase, and electromagnetic force will maintain. The electromagnetic force change trend under different air gap distance and different ampere turns, is as shown in Fig. 21. It can be seen that: (1) in the certain air gap distance, with the increase of the number of ampere turns, the electromagnetic force has an increasing trend. While ampere-turns increases to a certain value, the electromagnetic force tends to be stable, electromagnetic structure reaches to magnetic saturation. If the excitation current is still be increased, which will lead to

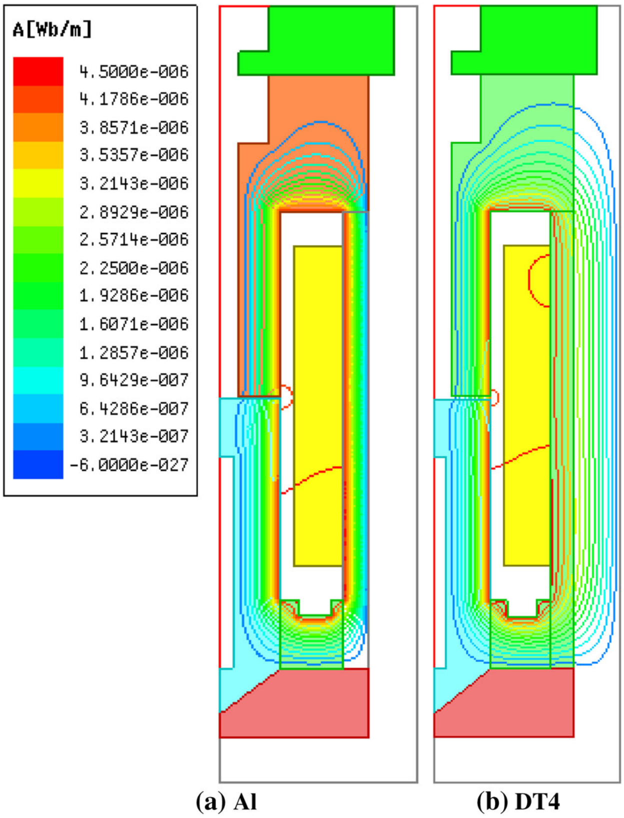


Fig. 19 Distribution of magnetic lines of force of different installation shell

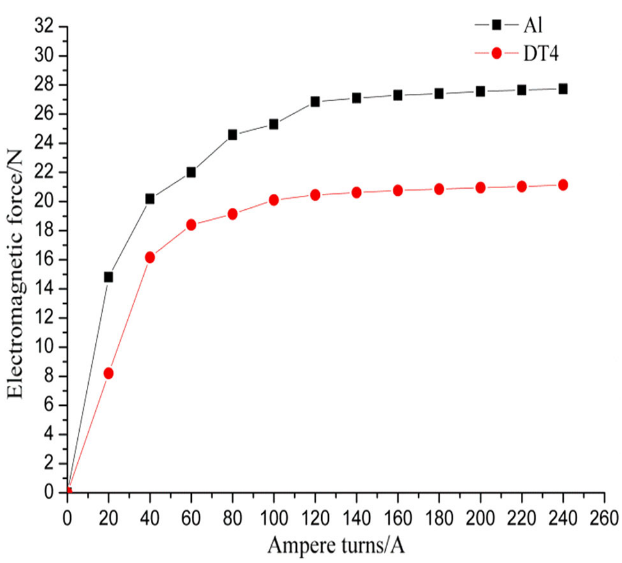


Fig. 20 Electromagnetic force of different installation shell

unnecessary electrical energy is converted to heat. That will results in temperature of coil rise, and electromagnetic coil may be burned. (2) Compared with the large air gap distance, the electromagnetic structure with small gap distance is easier to achieve the magnetic saturation state.

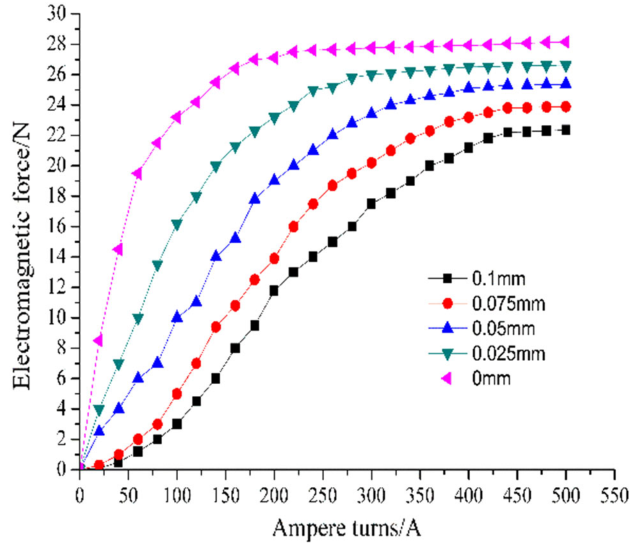


Fig. 21 Electromagnetic force of different Ampere-turns

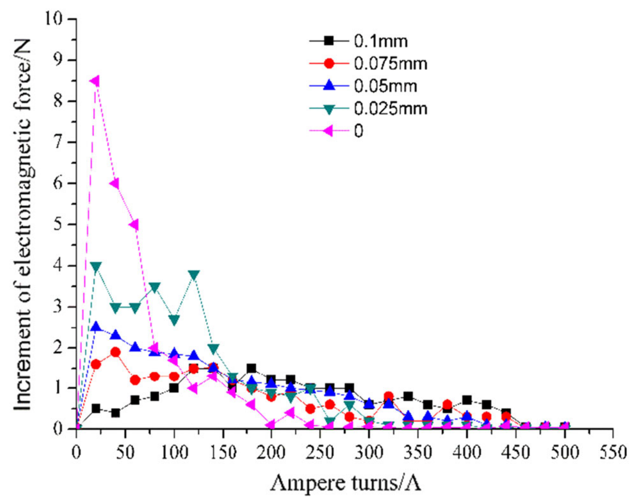


Fig. 22 Increased electromagnetic force of different Ampere-turns Ampere-turns

This is ascribed to the magnetic induction intensity of electromagnet get larger with the air gap distance get smaller under the same number of ampere-turns. As shown in Fig. 22, in 0–100 A-turns, the electromagnetic force increases rapidly with the air gap distance get smaller. In 100–500 A-turns range, the electromagnetic force increases slowly as the air gap distance get smaller.

5 Conclusions

The effect of relevant parameters on the electromagnetic force of the new micro digital valve and the testing method are studied. The contrast tests are done to get some comparison data. The main conclusions are listed in the following:

1. Turn affects the electromagnetic force through changing the magnetic field intensity. Electromagnetic force can be increased by adding the turn of coil. Electromagnetic force and turn vary in proportion, and they have approximate linear relationship.
2. Electromagnetic force and current have approximate linear relationship in a certain range. But when the current exceed one value, magnetic field would reach to the saturated state and electromagnetic force does not increase.
3. The cross-sectional area of air gas is crucial to the electromagnetic force. They have a positive correlation relationship. The cross-sectional area of air gap should be increased to improve the electromagnetic force.
4. Electromagnetic force are nearly uniform between valve seat of the magnetic material and valve seat of the non-magnetic material. Therefore, influence of different materials for valve seat is tiny. However, endurance of Cr12MoV is better than that of 2A12. Therefore, Cr12MoV should be used as the material of the valve seat.
5. Electromagnetic force has a little difference between the two installation shells in the process of demagnetization. Smaller electromagnetic force would be needed in the process of demagnetization. 2A12 should be used as the material of installation shell.
6. Through the research on the installation shell material, it is can be found that the non-magnetic material does not affect the magnetic circuit structure, but magnetic material can affect the magnetic circuit and led to a distributed magnetic field. Therefore, the non-magnetic material should be used as the valve block material, such as aluminum alloy.
7. It is found that the micro digital valve reaches to the saturation state more easily at the smaller air gap. The simulation model can be used to choose a reasonable incentive ampere-turns to avoid overheating and damage of coils.

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