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Research Article

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Design and simulation of needle-free syringe device driven by reluctance

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ABSTRACT

Needle-free syringe sprays liquid into the body tissues directly by ultra-fine, high-speed, high-pressure liquid flow. There are many kinds of needle-free injectors in the market currently, but most of them are very complicated and expensive. We designed the new kind of needle-free syringe driven by reluctance to improve the performance of existing electromagnetic needle-free syringes. This paper expressed how it works and established the mathematical model to analyze the relationship between force and displacement. Moreover, ANSYS was be used to simulate the distributions of magnetic induction lines. The simulation reveals that the core would stress a positive force before the middle point of the coil and the method to choose where to be served as the starting point of the iron core.

Key words: Electromagnetic energy; Needle-free injection; Innovative Design; Simulation Analysis

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INTRODUCTION

The traditional injections often cause local skin damage, bleeding, psychological stress, and the risk of infection at the injection site, especially for children. In addition, injection can easily cause the subcutaneous in a long time, nerve and vascular injury. Therefore, World Health Organization (WHO) has been urged to develop needle free injection technology which has application value.

Compared with traditional injection, not only does the needle-free infection solve a series of problems such as pain, bleeding, infection and tissue injury, but also the sprayed medicine is more easily absorbed [1].

In addition, needle-free syringe decreases the risk of subcutaneous hardenings caused by long-term injection because the sprayed drug is more diffused under the body tissue. The needle free syringe based on the technology of instantaneous firing by electromagnetic energy storage were successfully designed in this paper with high initial acceleration, small volume, light weight, and low manufacturing cost, which has bright and broad application prospects, especially suitable for vaccination of children and patients with diabetes mellitus.

As a new kind of injector, the syringe driven by reluctance has features of painless injection, high rate of drug absorption, low risk, convenience and so forth [2]-[5]. The automated device observes medicine fully and leaves no damage after the injection. Since birth, needle-free injections have gradually developed into many forms, they are mainly operated by mechanical, high-pressure gas [6], ammunition, electromagnetic force and so on [7].The former two technologies are already mature, however, they cannot control the thrust force accurately [8]. Syringe driven by electromagnetic has factors of high reliability and high safety. But its complex structure and high cost set restrictions to its application and popularization [9].

The needle-free syringe in this research is based on the above technology. We use an iron core as driving device. At the same time, high-energy capacitance and fixed device such as pawl mechanism are used to store energy. Therefore, this needle-free syringe is successfully designed with high initial acceleration, light weight, small size, and low cost [10]. In addition, the driving power uses safe voltage DC (direct current) to protect the safety of users.

With the development of science and clinical applications, problems on needle-less injectors will be solved in the future. Needle-free injection system will be widely used in the vaccine,injection of insulin, immune of animal. And they will play an important role in the battlefield, ranch and other occasions. Therefore, the research and development of needle-free injection is booming.

WORKING PRINCIPLE

The characteristics of needle-free syringe determine the composition structure syringes of the various types of syringes to be basically same. The composition structure includes: drives, devices to storage energy, delivery systems, transmissions, putt and ampule.The biggest difference between them is the drive and energy storage device. The external structure of this type of injector is shown inFig.1.

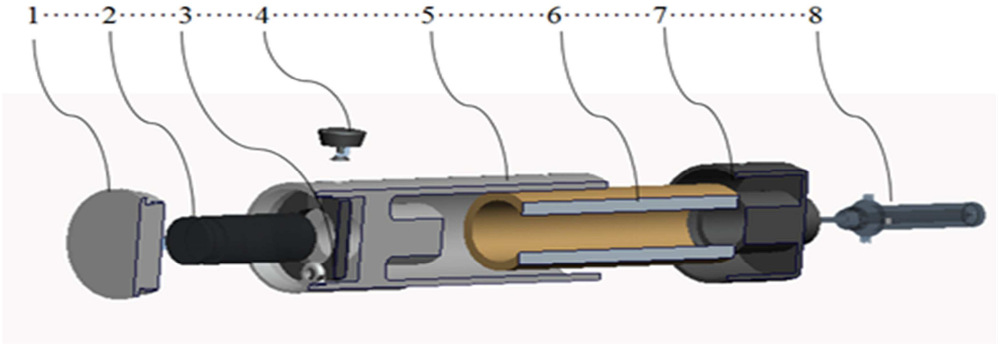

Fig.1:The profile of needle-free syringe

1: Rear cover 2:Iron core 3:Chuck 4: Press-button 5: Shell 6:Magnetic coil 7:The front cover 8:Ampule

A core was used as a living block, which driven by the coil made of copper wire and powered by safe DC asshown in Fig.2. [11].

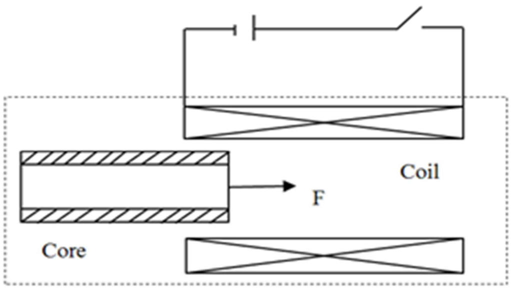

Fig.2:The simplified diagram of the structure

Reluctance means that a type of resistance prevents the establishment of a magnetic flux around the coil.

According to the principle of induction, when a current is passing through the coil, it will first generate an induced magnetic field. Then the magnetic will magnetize the core as shown in Fig.3. Two different magnetic polarities are opposite. So no matter which side the core is placed in, it will be subjected to a tensile force. When the iron core nears the mid-point of the coil, it will be under no tension. If it continues to move forward, the core would be pulled back.

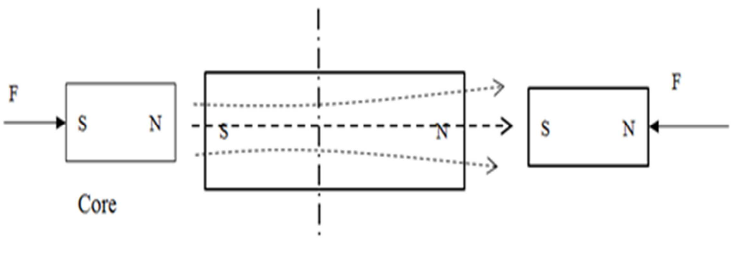

Fig.3:The simplified model of the needle-free syringe

ANALYSIS OF ELECTROMAGNETIC FORCE

According to the analysis, we can draw the equivalent circuit of the needle-free injectors as shown in Fig.4.

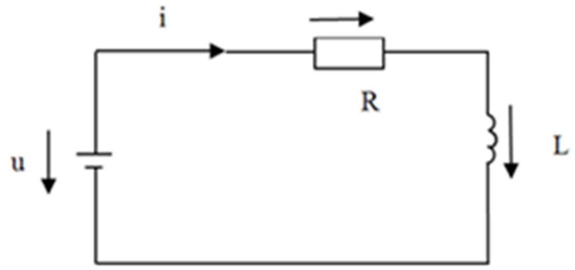

Fig.4:The equivalent circuit of this needle-freeinjector

Where, *u*—Capacitance-voltage; *i*—current; *R*—Resistance; *L*— Circuit inductance of the coil

The magnetic field *H* can be considered to try to magnetize all substances in its space, and the flux-density*B* is the result of action.The magnetic induction*B* is proportional to the magnetic field*H.*

$$B = \mu H = \mu_0 \mu_r H \quad (1)$$

Where, μ_0 —Permeability of vacuum; μ_r —Permeability of the iron core
μ —relativity of the magnetic permeability
If: *l*—Length of the coil; *d*—Diameter of the coil; *i*—The current, according to the theory of electromagnetism, The component of the magnetic flux density*B* in the axial and radial directions are:

Axial component is:

$$B_x = \frac{1}{2} N \mu_0 i (l - \frac{2x}{d}) \quad (2)$$

Radial component is：

$$B_Y = \frac{\mu_0 Ni}{2d} y \quad (3)$$

Where, *X*—The coordinate on axial direction; *Y*—The distance from the axis of the coil.

If the distance between the core and middle of coil is *x(x<l)*, according to the ampere circuital theorem, at *x* the magnetic induction*H* is:

$$H = \frac{Ni}{x+l} \quad (4)$$

Magnetic flux through the section of the coil is:

$$\phi = \mu_0 HA = \frac{\mu_0 ANli}{x+l} \quad (5)$$

When the current goes through the coil, themagnetic energy will be stored in the magnetic field around the coil, the magnetic force is: *F=Ni*

And the magnetic flux is:

$$F_m = Ni = \phi R_m \quad (6)$$

The magnetic energy W_m is:

$$W_m = \int_0^{\phi} Nid\phi = \frac{1}{2}\phi^2 R_m \quad (7)$$

According to Ohm's law, the resistance is:

$$R_m = \frac{l_m}{\mu_0 \mu_r A_m} \quad (8)$$

Where, R_m —The magneticresistance

l_m —The length of the path

A_m —Area of the magnetic circuit

Slice the *x*, we can get the force on core which produced from the punch armature:

$$F = \frac{dW_m}{dx} = \frac{d(\frac{1}{2}\phi^2 R_m)}{dx} = \frac{1}{2} Ni \frac{d\phi}{dx} \quad (9)$$

Where, N—Number of coil turns; i— The current through the coil; $\frac{d\phi}{dx}$ — The rate of change of flux and displacement.

So the energy is:

$$W_m^{'}(x,i) = \int dW_m^{'}(x,i) = \int d[\psi(x,i)i] \quad (10)$$

$\psi(x,i)$ — the magnetic flux

The electromagnetic force with the change of the core is：

$$F(x,i) = \frac{\partial W_m^{'}(x,i)}{\partial x} = \frac{\partial[\psi(x,i)i]}{\partial x} \quad (11)$$

We can get a conclusion for the above: the current is constant, so the force changes along with the magnetic flux. The electric power need to change greatly to meet the requirement of syringe and it determines the iron core only to be pulled instead of being progressed. The change of the current and the magnetic flux can affect the force of the core.

ANALYSIS OFJET-FLOW

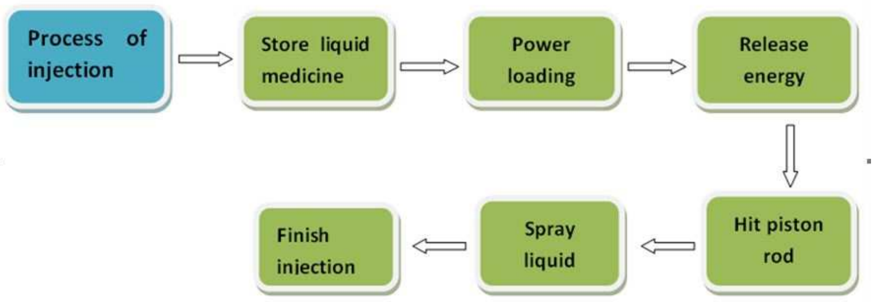

Fig.5:The process of injection

Fig.5 shows the process of injector ,which is divided in six steps: storing medicine, power loading, releasing energy, hitting piston rod, spraying liquid and finishing injection.so there are close links between the electromagnetic force and the jet-flow.

We realize that if we want to establish kinematics equations,the key of the point is to find out that how many components the accelerating force and the resistance are made up of and then we can set up the equations using the theorem of kinetic energy.The elementary resistance is composed of mechanical resistance and air resistance which block the movement of the projectile.We can use computational formula (11) to figure out the accelerating force.In addition,there is also a friction between the projectile and the coil.In general condition,the friction is directly proportional to the gravity of the projectile,so we can set up friction coefficient to figure it out. There is an air resistance as well.According to Knowledge of aerodynamics, the faster the projectile is,the larger the resistance will become.

Take full consideration on the force which iron core stress in the launching systems. And through the formula substitution, we can establish the movement and the energy equation about electromagnetic launch system.

$$\begin{cases} \frac{dp}{dt} = \frac{(p+B)\frac{dx_p}{dt} + \frac{BA_0}{A_p}\sqrt{\frac{2p}{\rho_0}}}{(l-x_p)} \\ \frac{dx_p}{dt^2} = \sqrt{\frac{E_0 - A_p p\cdot(x_p - s) - F_f\cdot(x_p - s)}{m_p}} \end{cases} \quad (12)$$

Where, A_p —area of piston; ρ —liquid density; x_p —Displacement of piston; A_0 —area of the micropore; p—pressure of liquid; B—bulk modulus; F_f —The frictional resistance; s—space left between the piston and core; E_0 —The initial kinetic energy

From this equation group can be seen, the initial jet stagnation pressure has something to do with the impact energy of storage, the weight of iron core, speed, the area of piston rod of ampule and other relevant factors. Ignoring the affection of friction force does not have impacts on the correctness. The friction can be divided into twotypes, one type is the pressure when the sealing ring stop the liquid fluid, the other is the friction between the ampule wall and the sealing ring.

INNOVATIVE DESIGN

1. An electromagnet core is placed in the shell and its energy comes from the external capacitor. According to the phenomenon of electromagnetic induction, the coil provided with current will produces a magnetic field, which will magnetize the core and bring a mutually exclusive force to accelerate the core. The speed of the core will meet the injecting requirement in a short distance. Iron core is a kind of soft magnet, so it is easy to be magnetized and demagnetized. We can adjust the current to control the force. After the injection, we can pass the same current through the coil. Iron core will be subject to tension and began to return, which prepares for the next injection. With this design, the force which moves the coil back and forth becomes controllable.

2. The needle-free injector driven by reluctance is facing a problem about improving the initial velocity: to reach a higher speed, the injector needs a long track and demands larger volume. The needle-free syringe discussed in this article is equipped with a high-energy capacitor as power supply, and the voltage capacitor powered must be safe. Pressing the button when the current reaches to the maximum, then the kinetic energy of liquid will reach the peak and meet the requirement of pressure about 15MPa to penetrate human skin tissue [12].

3. Our design uses two curved discs which are mounted on the carriage with a pin, and uses a spring to connect two discs. When we want to inject, just pressing the button at the top. Then the two discs plates will be pushed away from each other.

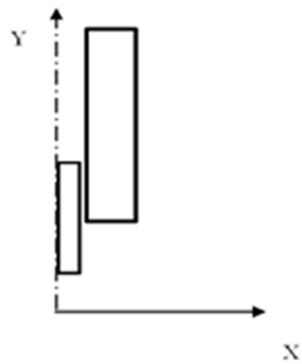

Fig.6:The coil launching model

SIMULATION

The electromagnetic transmission system composed of coil and iron core is an axial symmetric system. In order to analyze easily, three-dimensional structure can be simplified as two-dimensional model. So this paper establishes a coil launching model as shown in Fig.6. And the coil's geometric dimensions as follows:

The axial length: l=20mm; Outer radius: R_0 =10mm; Inner radius: R_1 =5mm; The number of turns: N=200; Cylinder length of the iron core: l=20mm; Diameter:d=9mm [13].

As a whole, the transmitting coil is a tightly wound solenoid.The effect of wire insulation is ignored,and the density current in the coil cross-section can be uniform distributed.Due to the presence of a magnetic field, value of the current in the calculationshould be practically consistent with the coil.

When iron core is located in some random position, we can load current for the coil and get the magnetic field linesfrom ANSYS as shown in Fig.7.

Fig.7. magnetic field lines of the coil (image from ANSYS)

The electromagnetic force becomes strong where the lines of magnetic force areintensive, and weak in loose place. The closer between iron core and coil, the stronger electromagnetic force will be.Once the iron core is inserted fully, both ends of which will stress the same great force in the opposite direction. So they cancel each other out, the resultant force on the iron core will be zero. Through simulation, we can get the curve to describe the inductance as shown in Fig.8

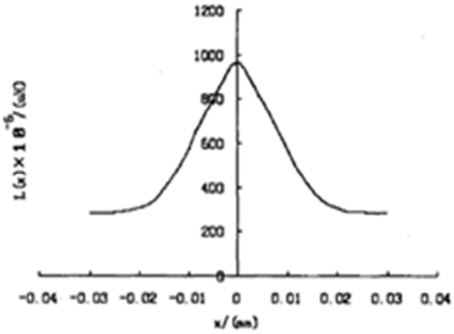

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Fig.8. the curve to describe the inductance

In order to get the characteristic curve, a series of discrete points which are equably distributed along the axis of coil are selected. The electromagnetic force iron core stressed at different positions can also be solved. Then we can synthesize the static to get a visual chart as shown in Fig.9.

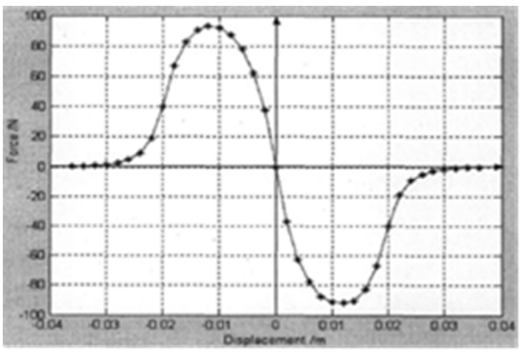

Fig.9. visual chart of the relation between force and displacement

The axis of abscissa represents the value of the displacement between the middle point of coil and iron core, the vertical coordinate is plotted as value of electromagnetic force. The result of curve can show the distributions of the force of iron core approximately. As shown in the figure, when entering the coil, the core would stress positive force, and it will get the most positive force at about -0.012m in the core. When the core is in the middle of the coil, the electromagnetic force will become to zero. If the core continues to move forward, the resistance will prevent the core moving. And the punch armature can get the maximum speed when it arrives at the middle of the coil. The curve of simulation through theoretical analysis is fit for the former conclusion.

In summary, this chapter takes advantage of the software — ANSYS to simulating and establishing a two-dimensional plane model of the coil and solves the problem of distribution of space electromagnetic field in model system.

CONCLUSION

The existing electromagnetic needle-free injectors have features of controllable, stable and secure which other products cannot match. However, Due to the big volume and other issues, the process of application in the market is very slow. To solve this problem, this paper makes the following improvements [14]:

(1)Use iron core as the impact of armature to increase reliability;

(2)Store energy in a high-energy capacitor to reduce restrictions when the capacitor in use [15]

In addition, this paper analyses the principle, establishes mathematical model, simulate and make improvements for this design.

From the present state, we still have a long way to improve needle-free injectors. They are expected to play an increasingly important role in the markets of drug delivery technologies in the future [16]. This paper can provide a good reference for engineers who are engaged in researching needle-free injector technology. And it will have a positive impact on development of needle-free injectors.

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