Design of a Double Paths Magnetic Circuit Structure for High Force Density Hybrid Fuel Injector

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This paper presents a design method of a double layer magnetic circuit structure for hybrid fuel injector. In general, fuel injector models have disadvantages such as significant leakage flux and magnetic saturation; therefore, a finite-element method (FEM) is used to detail the model design and reduce leakage flux from the electromagnet pole to the lead pipe. We put the permanent magnet (PM) in the basic magnetic circuit, forming a double layer magnetic loop other than the coil, effectively increasing the force density of the hybrid fuel injector. Finally, we optimal design the magnetic circuit to maximize the energy density of the PM and consider the demagnetization characteristics in the engine high-temperature environment to ensure the manufacturing possibility of the hybrid fuel injector

***Index Terms*— Hybrid fuel injector, Double paths magnetic circuit, leakage flux, magnetic saturation**

I. INTRODUCTION

A FUEL INJECTOR is an electromagnetic device that produces a magnetic field when current is passed through its coil windings. It also refers to a variety of transducer devices that convert electrical energy into kinetic energy [1]. A basic injector structure consists of an electromagnetically inductive coil wound around a movable armature. The applied force always moves the armature in a direction that increases the coil's inductance. The armature moves into the solenoid when the coil windings are energized, and thus creates linear motion [2]. Fuel injectors are operated at high speed with very short stroke, and therefore, in-depth research about improving the performance and minimizing the response time is required. In light of this, increasing the force density is the most important design objective. However, in the fuel injection system, high fuel pressure and high fuel injection rate make it difficult to achieve this. It is necessary to consider magnetic saturation and reduce flux leakage, and achievers a higher performance [3].

This paper presents a basic fuel injector model first, and analyzed parameters for the pole and lead pipe, while limiting the magnetic saturation and reducing the flux leakage. Then optimization of the PM ring at in the basic magnetic circuit, forming a double layer magnetic loop other than the coil, effectively increasing the force density of the hybrid fuel injector. The optimization of the design is confirmed through demagnetization analysis.

II. BASIC DESIGN PROCESS

The design process related to the minimization of the fuel injection's magnetic saturation and operation of a wide current range is shown in Fig.1.

The design points are obtained from the output characteristic. It determined how much force the armature needed in different positions at static state. And the voltage, limit of current density and fill factor can be determined from the constraints related to the controller, battery and space available for the injector on the engine. The fuel injection basic model consist three modules: actuator module, motion inverter module, and dispensing module, as shown in Fig.2, and its specifications are described in Table I.

To open the injection valve, the voltage is applied to the drive coil. The coil current produces magnetic flux in the fuel injector, which includes the magnetic force at the air gap and armature. Then the injection value is opened and sprays the pressurized fuel into the engine. When the coil current is stopped, the injection valve is closed by the force of the spring.

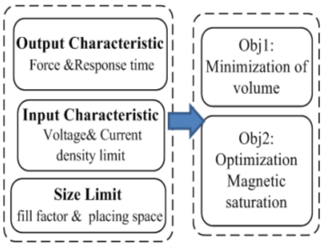


Fig.1.Fuel injector design flow

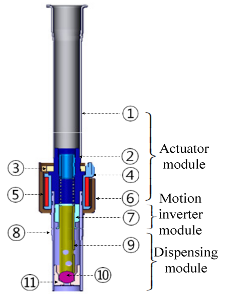


Fig.2. Fuel injector basic model

TABLE I
DESCRIPTION OF LABELLED ITEMS IN FUEL INJECTOR BASIC MODEL

Module	NO.	Description
Actuator module	1	Extension tube
	2	Pole
	3	Cover
	4	Bobbin
	5	Coil
	6	Housing
Motion inverter module	7	Armature
Dispen-sing module	8	Lead pipe
	9	Injection needle
	10	Poppet
	11	Retainer

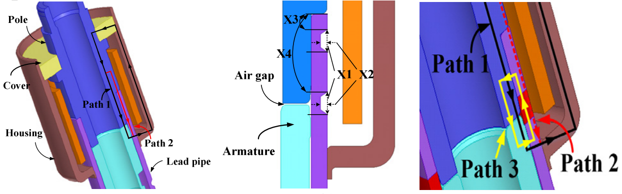
TABLE II
CHARACTERISTICS AND OUTPUT PERFORMANCE OF BASIC MODEL

Item	unit	Basic model
Air gap length	um	60
Turns		377
Coil Resistance	Ω	11.6
Rated current	A	1.17
Magnetic force	N@ 60um	11.94
Armature weight	g	1.65
Eddy current loss	W	3.52

III. ANALYSIS OF VARIABLES FOR WHICH THE OUTPUT CHARACTERISTICS WERE CONSIDERED

A. *Lead pipe optimal design for flux leakage reducing*

The basic model suggested in this study does not satisfy the magnetic force density requirement because leakage flux of the magnetic circuit occurs between the housing and lead pipe area (Fig. 3(a)). The flux path (path 1) occurs from the armature, but the leakage flux path (path 2) occurs without the armature. Therefore, this phenomenon reduces the amount of flux across the armature and air gap, and it makes the plunger response worse at the opening and closing times. Further, the concentrated winding model produces a large eddy current in the magnetic circuit. A maximum eddy current loss of more than 10% occurs, which deteriorates the total efficiency. Therefore, a design process for decreasing the leakage flux is required.



(a) (b) (c)

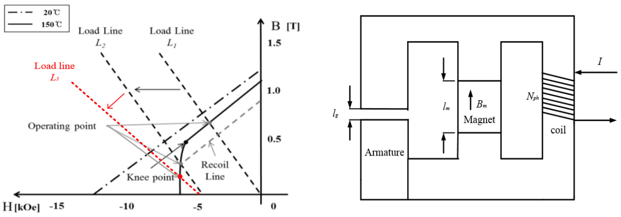
Fig.3.(a) Flux paths of fuel injector(Basic model,Model1) (b) Design variables of fuel injector (added sleeve) (Model2) (c) hybrid fuel injector (Model3)

Fig. 3 (b),(c) shows two ways to reduce the magnetic flux leakage. The method of (b) is to add two sleeves to saturate the path leading to the lead pipe and reduce the magnetic flux leakage.Fig.3 (c) is For the insertion of permanent magnets, not only broken the path2 of magnetic flux leakage, while increasing the new magnetic circuit 3, increasing the force density

B. *Irreversible Demagnetization Analysis and magnetic circuit analysis*

To the next step, irreversible demagnetization analysis is progressed. Irreversible demagnetization analysis considers the B-H curve of the PM with temperature. Fig 4 shows B-H curve of the PM applied in the analysis. The knee point of an Nd-Fe-B magnet is not located in the second quadrant at 20°C, but the knee point moves to the second quadrant at 150°C. In case of the over load condition, load line is changed from *L1* to *L2*. It should be noted that, because the newly generated magnetic circuit path3, through armature and pole between the air-gap, and air-gap changes (0~0.06mm) will make the operating point more down, load line is changed from L_2 to L_3. For this reason, irreversible demagnetization occurs because operating point is lower than knee point. These parts are applied to analysis algorithm of irreversible demagnetization. Analysis process compares the position of operating point and knee-point. If the element in the PM is irreversibly demagnetized, the residual flux density of the element in the PM is renewed, considering the B-H curve of the PM. The renewed or demagnetized residual flux density of the PM is used in the subsequent iteration. The above iterative process is completed when the total time is satisfied. Where (1) is the calculated in the magnetic flux density equation of the PM

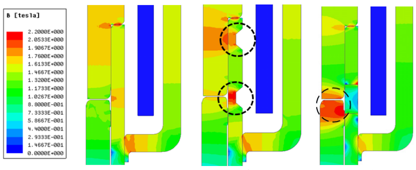
$$B_m = \frac{1}{1+\mu \frac{l_g}{l_m}\frac{A_m}{A_g}\frac{1}{k}}[B_r + \mu_0 \mu_{rm}\frac{N_{ph}I}{l_m}] \qquad (1)$$



(a) (b)

Fig.4.(a) B-H curve of the PM, (b) Simple hybrid fuel injector device with PM

Fig.5 shows the magnetic field distribution of the three models, and Fig. 6 shows the magnetic force with different aip-gap length of the basic model with 3 Models.



(a) (b) (c)

Fig.5. Magnetic field distribution of basic model and parameter model , current 1.17A, air-gap 60um. (a) Model1. (b) Model2 (c) Model 3

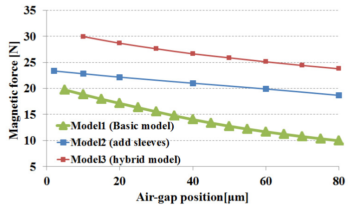
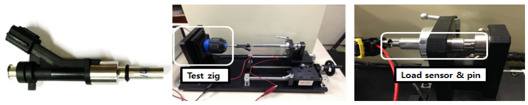


Fig.6. Compare with the result of basic model and optimal design model use FEM analysis

IV. EXPERIMENT AND CONCLUSION

In this study, a PM insert hybrid fuel injector model for force density improves was presented, and the parameter optimal design was carried out to reduce the leakage flux. And Irreversible demagnetization analysis considers the design and manufacture of the possibility. As a FEM design result, the fuel injector force density through permanent magnets has been greatly improved we will design and manufacture in full paper, and use the experiment to prove the accuracy of the design



(a) (b) (c)

Fig.7. Prototype of (a) fuel injector and (b) test zig, and (c) load sensor

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