The fast-response solenoid actuator of the common rail diesel fuel system in high operating temperatures conditions

J Zhao¹ and L Grekhov²

¹College of Power and Energy Engineering, Harbin Engineering University, 145, Nantong Street, Harbin, 150001, The People's Republic of China
²Piston Engine Department, Bauman Moscow State Technical University, 5, Baumanskaia Street, Moscow, 105005, Russian Federation

²E-mail: lgrekhov@mail.ru

Abstract. In this article, the requirements for the materials of the fast-response electromagnetic actuators are formulated. One of the most important requirements for them is temperature stability. The influence of the temperature in the range of 16…150 °C on the magnetic properties of the selected material (the DT4C steel) was determined experimentally. The experiment result shows that the temperature significantly affects the magnetic properties of the DT4C material. With the increase of the temperature, the saturation magnetic flux density, the residual magnetic flux density, and the coercive force are reduced differently. The temperature increase reduces the magnetization of the DT4C material but accelerates demagnetization. The influence of the temperature on magnetic permeability is multi-directional for different values of magnetic flux. The strong temperature dependence of the materials of the electromagnetic actuator leads to disruption of the normal operation of the fuel systems of engines with electronic control.

1. Introduction

Ecological requirements for various transport engines are constantly developing. This leads to the use of electronically controlled fuel systems. These systems are equipped with the fast-response electromagnetic actuators with the time of full operation less than 70 μs. Today, the duration of the electromagnetic actuator cycle in diesel engines with a multiple injection of fuel is 0.1 ms. In this case, the time of their action is limited not only by the mechanical inertia of the parts, but also by the reactance of the coil in the electrical circuit and by the resistance to magnetization in the fast process.

The significance and the level of parameters of diesel fuel systems are growing rapidly [1]. Electromagnetic actuators can now occupy the volume of 5 ml and provide the force of 200 N. Their capabilities are close to the theoretical limit. On the other hand, the injector of the popular Common Rail fuel system is located in the hot cylinder head, and its nozzle has an outlet into the combustion chamber. Besides that, the injector has other sources of heating: from the control current and from the control flow of the heated fuel surrounding the electromagnetic actuator. The elevated temperature of magnetic materials reduces the magnetic flux density and the force of the electromagnetic drive [2]. The saturation magnetic flux density of some magnetic materials can be reduced by 2–3 times when heated at 100 °C [3].

The change in the electromagnetic actuator’s behavior leads to the change in the fuel injection characteristics [4]. This increases harmful emissions into the atmosphere as well as the fuel consumption of the engine. Unfortunately, when calculating the fuel supply in engines, the change in processes in
electromagnetic actuators at elevated injector temperatures is not taken into account [5].

For a successful design of diesel engine fuel systems with high-speed electromagnetic actuators, materials with a number of important properties are necessary. Such properties at elevated temperatures are maximum saturation magnetic flux density, resistance to eddy currents and minimum coercive force, residual induction, and magnetic viscosity. This article deals with the choice, research, and calculation of the properties of the materials for the electromagnetic actuator at high temperature. High-temperature properties of the materials are also relevant for other technical applications, for example, engines for electric vehicles and loaded brake systems [6].

The magnetic material database of the electromagnetic business software also provides \( B-H \) curves at normal temperature for the optimum design of an electromagnetic actuator. It is difficult for magnetic material manufacturers to provide the magnetic properties of DT4C at high temperature.

Therefore, a change in the magnetic properties of the DT4C alloy at high temperature cannot ensure the reliable calculation of all processes in the injector and the quality of its design. In this paper, an experimental study of the influence of temperature on the magnetization of DT4C is described.

2. The thermal condition of working of the diesel fuel systems electromagnetic actuator
The determination of actual operating temperatures of the electromagnetic actuator for the Common Rail injectors and for the control valves of high-pressure pumps is a separate study subject. The authors are carrying out such a research, but only integral estimates are given in this article.

The electromagnetic actuator is warmed up by the control current. The time-averaged power can be estimated as 0.125 \( W \) per kg of fuel injected into the cylinder. However, another flow of fuel (the control flow) flows past the electromagnetic actuator. It can be 25...250 % of the fuel flow into the cylinder. In any case, heat release in the actuator can lead to the fuel heating by 2...6 \(^\circ\)C. However, this source of fuel heating is not the primary one.

Heating the fuel from adiabatic compression can be calculated simply [7, 8]. At high pressure levels of modern fuel systems, such heating is 50...100 \(^\circ\)C (figure 1). The degree of the diesel fuel heating with throttling with high pressures, as a fluid with its individual thermodynamic parameters, is not a well-known fact. The experiments carried out at the BMSTU showed that when the fuel flows through a high-pressure choke, it is heated to a considerable extent. Thus, at the pressure of 180...200 \( MPa \), the heating from the throttling can amount to 30...70 \(^\circ\)C [8]. The initial temperature of the fuel can reach 40...70 \(^\circ\)C, and the nozzle body temperature exceeds 100 \(^\circ\)C. Then, with the current engine parameters, the temperature of the fuel that is washed by the actuator can be 125...200 \(^\circ\)C.

3. Materials selection for electromagnetic actuators of diesel fuel systems
At present, magnetic materials with favorable temperature dependences, suitable for a fuel systems electromagnetic actuator, are created [9]. The designers of these devices are solving the problem of selecting or creating new materials with the complex of important magnetic and other properties. The material for such an electromagnetic actuator should have sufficient strength and low brittleness, high
saturation induction, but small values of coercive force, residual induction, coefficients characterizing the magnetization resistance from the side of magnetic viscosity and eddy currents, low temperature dependence up to 200 °C. For a high-pressure fuel pumps actuator, it is possible to use bonded magnetic cores assembled from thin plates.

The constructors of actuators are forced to choose a compromise solution. The DT4C alloy has a set of good indicators for use in the actuators of engines fuel systems.

The carbon content of the electrical iron DT4C is less than 0.04 %. Thus, it has good magnetic properties such as high saturation magnetic flux density, low coercive force and affordability, which make it the main soft magnetic material core in the electromagnetic actuator.

It is difficult for magnetic material manufacturers to provide the magnetic properties of DT4C at high temperature. A special experimental study of the magnetic properties of the DT4C alloy was carried out to determine the temperature influence on magnetic properties.

4. The method of investigation, samples and experimental data
The measurement principle is based on the analysis of the operation of the transformer device [3, 10]. The MATS-2010SD soft magnetic hysteresis measurement instrument produced by China Hunan Linkjoin Technology Co., Ltd. was employed in this study. This instrument adopts the impact simulation method and the magnetic field scanning method to measure the $B-H$ magnetization curve. These two methods can ensure high measurement accuracy and good repeatability. Figure 2 shows the test principle of the MATS-2010SD. The size of the test ring specimen is consistent with Chinese standard GB/T 13012-2008 and International standard IEC 60404-4. The ring sample DT4C has an external diameter of 23.95 mm, internal diameter of 20 mm, and thickness of 4.8 mm. Figure 3 shows the DT4C measuring device for magnetic properties at high temperature.

The temperature control cabinet can realize temperature ranging from 16 °C to 150 °C precisely. During the magnetic properties test performed at high temperature, the test sample was placed in the temperature control cabinet, and the desired temperature was set. When the temperature reached the set value on the control panel, a waiting period of 20~30 min was observed till the temperature of the temperature control cabinet reached a deviation less than 5 °C. Subsequently, the magnetization curves and hysteresis loops were measured. The measurements were repeated 5–10 times and averaged.

5. Results and discussion
A. The influence of temperature on magnetization characteristics
As shown in figure 4, the variation of the magnetic flux density $B$ with the magnetic field intensity $H$ is similar at different temperatures. With the increase of $H$, $B$ increases rapidly, and when $H>640$ A/m, $B$ increases slowly. As shown in figure 5, the saturation magnetic flux density $B_s$ decreases almost linearly
with the increase of the temperature. The $B_s$ decrease is a disadvantage for the application of the DT4C soft magnetic materials as an electromagnetic actuator to obtain higher electromagnetic force or better dynamic response.

When DT4C undergoes high magnetic flux density, the permeability decreases with the increase in temperature. This indicates that the magnetization of the material is deteriorated by the high temperature in the later stage of magnetization. When the saturation magnetic flux density increases further and begins to transfer to magnetic saturation, the temperature influence on permeability is not apparent. Further, the permeability curves at different temperatures almost coincide and fall slowly with the increase of $B$.

Figure 4. The $B$-$H$ curve at different high temperatures.

Figure 5. The dependence of the saturation induction on the DT4C alloy temperature.

**B. The influence of temperature on the magnetic hysteresis loop**

The influence of temperature on the DT4C hysteresis loop is more apparent than that on the $B$-$H$ curve. In the magnetization process of the hysteresis loop, with the increase of temperature, the increasing rate of $B$ becomes slow with the increase of $H$. When the material is at high magnetic field intensity, the influence of temperature on $B$ in the magnetization process becomes weaker. For the repetitive electromagnetic actuator, the worsening of the magnetic characteristics of the magnetization process reduces the dynamic response of the electromagnetic actuator at the beginning of the operation. The temperature increase hastens the demagnetization of the magnetic material in the demagnetization process, which is beneficial to the quick stopping of the electromagnetic actuator after the external excitation current is cut off, and shortens the closing response time of the high-speed solenoid valve in the common-rail injector for a diesel engine.

Figure 6. The dependency of the residual magnetic flux density on the DT4C alloy temperature.

Figure 7. The dependency of the coercive force on the DT4C alloy temperature.

As shown in figure 6, the residual saturation magnetic flux density $B_r$ decreases quickly with the increase of temperature. $B_r$ is conducive for the reduction of the static hysteresis loss of DT4C and
improvement of the demagnetization characteristics of soft magnetic materials. In figure 7, the change of the coercive force $H_c$ with temperature is similar to that of $Br$. $H_c$ decreases as the temperature increases, but the rate of decrease becomes slow gradually.

C. The influence of the magnetic material properties on the work of the diesel engine fuel system electromagnetic actuator

To illustrate the value of the temperature stability of the electromagnetic actuator operation, the results of a numerical experiment carried out using the INJECT program (http://fuel-bmstu.ru/en/inject-software/) are given below [11]. The operation of the Common Rail diesel fuel system of a 98 kW 4L passenger car with $D/S$=87/94 mm is analyzed (figure 8). The different levels of the saturation induction reflect the values of the temperature instability of the magnetic material. The decrease in the saturation magnetic flux density $B_s$ below 1.15 T due to the heating of the actuator leads to the decrease in the cycle fuel mass, which is approximately proportional to the engine power. The cycle fuel mass feed is stored up to 1.15 T due to the compensation of the engine control system. Thus, to maintain the given cyclic feed, it increases the fuel delivery time. With $B_s$ less than 0.75 T, it becomes impossible, and the whole system becomes completely inoperative.

Figure 8. The influence of the saturation induction on the fuel system performance: a – cyclic feed; b – maximum injection pressure; c – average injection pressure.

However, the failure of the normal operation of the actuator, the control valve which the actuator sets in motion, and the entire engine starts much earlier. Thus, with $B_s$ less than 1.4 T, the duration of the fuel injection increases, and the injection pressure drops. This removes the working process of the diesel engine from the carefully tuned optimal combination of the most important parameters of fuel atomization and combustion. At the same time, the fuel consumption and the emission of harmful substances into the atmosphere certainly grow.

The fluctuations in the performance of the actuator in figure 8 is one more factor in the instability of the engine control. This happens due to the fuzzy operation of the control valve with the actuator. The normal operation of the valve is considered to be its quick exit to the stop and its remaining on the stop during the whole time of the process. The decrease in the magnetic flux density due to heating further reduces the electromagnetic force, and the valve begins to oscillate between the extreme positions.

Thus, the actuator heating of a number of magnetic materials dramatically reduces the quality of the diesel engine. The tested material DT4C changes the saturation magnetic flux density $B_s$ only by 0.066 % at temperatures up to 150 °C, i.e. practically does not change the operation of the fuel system and the engine. The electrical iron DT4C is fully suitable for the use in the engines electromagnetic actuators by the criterion of temperature stability.

6. Conclusions

The obtained experimental results can be summarized as follows.

1. For the DT4C pure iron soft magnetic material, the saturation magnetic flux density, residual saturation magnetic flux density, and coercive force decrease with the increase of temperature, but the degree of decrease is different for each of them.

2. The magnetic flux density range of magnetic materials influences the temperature impact on
permeability. When the magnetic material is at low magnetic flux density, the increase in temperature is an advantage for increasing the permeability of DT4C quickly. When it is at high magnetic flux density, the decrease in temperature reduces the permeability.

3. The temperature significantly affects the hysteresis loop of DT4C. On the one hand, the saturation magnetic flux density decreases, which does not contribute to the high dynamic response of the electromagnetic drive at the beginning of the fuel injection process. On the other hand, with increasing temperature, the residual magnetic flux density and the coercive force also decrease, which contributes to an increase in the speed of the electromagnetic drive at the end of the fuel injection.

4. Heating the electromagnetic actuator reduces its energy capabilities, as well as the quality of the fuel system and the diesel engine. The tested material DT4C changes the saturation magnetic flux density by only 0.066% at temperatures up to 150 °C. It ensures the stable operation of the fuel system and the engine in the range of actual temperatures.

References
[1] Kendlbacher C, Mueller P and Bernhaupt M 2010 CIMAC Congress 2010 Bergen 50 11
[2] Coey J M D 2014 Magnetism and Magnetic Materials (New York: Cambridge Univ. Press) p 617
[3] Lu H Y, Zhu J G and Ron S Y 2007 IEEE Transactions on Magnetics 43 3952–60
[4] Bai Y, Fan L Y, Ma X Z, Peng H L and Song E Z 2016 Int. J. of Automotive Technology 17(4) 567–579
[5] Salvador F, Marti-Aldaravi P, Carreres M and Jaramillo D 2014 SAE Technical Paper 2014-01-1089
[6] Meng F, Shi P, Karimi H R and Zhang H 2016 Mech. Syst. Signal Proces. 68-69 491–503
[7] Payri R, Salvador F J, Carreres M and Belmar-Gil M 2018 SAE Technical Paper 2018-01-0275
[8] Grekhov L, Denisov A and Starkov E 2016 Int. J. of Pharmacy and Technology 8(4) 22571–78
[9] Takahashi N, Morishita M and Miyagi D 2011 IEEE Transactions on Magnetics 47 4352–55
[10] Zhang Y, Alatawneh N, Cheng M C and Pillay P 2009 Magnetic core losses measurement instrumentations and a dynamic hysteresis loss model IEEE Electrical Power & Energy Conf. (EPEC) (Montreal) 1–5
[11] Grekhov L, Mahkamov K and Kuleshov A 2015 SAE Technical Paper 2015-01-1859