Simulation Analysis of Thermal Management of Inductor Applied to PFN Under Continuous Discharge Condition

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INTRODUCTION

As one of the important development directions of new concept launch technology, electromagnetic launch technology has broad application prospects in fields of national defense and aerospace. The capacitive pulse power supply(PPS) is considered as a reliable and useful way to provide energy for electromagnetic launch. As an important component of capacitive PPS, pulse inductors have a decisive impact on the peak value, rise time, pulse width of the discharge current. The high current operation condition of the pulse inductor leads to a large heat generation, and the inductor is generally an epoxy resin packaging structure, which is not conducive to heat dissipation. The continuous discharge will cause the heat to accumulate in the pulse inductor and increase its temperature. On the one hand, it changes the electrical parameters of the inductor, which affects the discharge consistency of the PPS; on the other hand, it weakens the insulation performance of epoxy resin, which increases the probability of electric breakdown, and even causes safety accident. Thus, thermal analysis is one of the key issues in thermal management design of pulsed inductors under continuous discharge condition. Some studies about thermal analysis of pulsed inductors have been done.

The main aim of this paper is to investigate the heat accumulation and diffusion processes over a solenoid pulsed inductor with natural cooling mode and liquid cooling mode under continuous discharge condition. In the following, a 3-D transient coupled heat transfer model of the inductor is developed, then the characteristics of thermal diffusion and temperature distribution are analyzed. Considering the insulation requirements of the pulse power supply, deionized water was selected as the coolant. This paper is expected to provide the basis and experience for the design of thermal management system and temperature monitoring system of the pulsed inductor.

CIRCUIT MODEL OF PFU AND DISCHARGE CURRENT

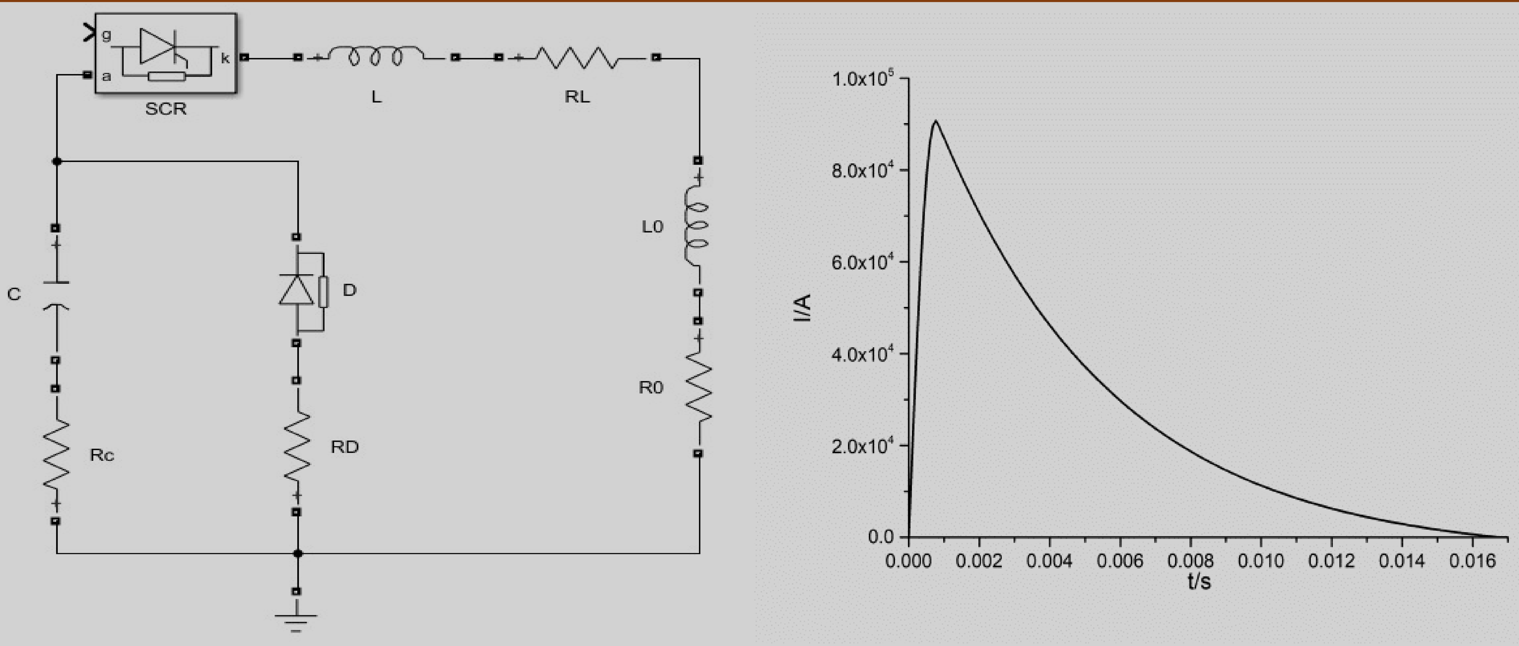

Fig. 1 Circuit Model and Discharge Current Curve of 250kJ PFU

Table. 1 Component parameters of 250kJ PFU

Parameter	Value
Capacitor Capacitance C/mF	10
Capacitor Initial Voltage u_C/kV	10
Inductor Inductance L/μH	25
Equivalent resistance of capacitor branch Rc/mΩ	4
Equivalent resistance of inductance branch RL/mΩ	4
Equivalent resistance of diode branch RD/mΩ	2
Load Inductance L0/μH	0.5
Load ResistanceR0/mΩ	2

MATHEMATICAL MODEL

The mathematical model of inductor thermal analysis is established based on theories of electromagnetics, heat transfer and fluid mechanics. As shown in Fig. 2, the solenoid pulsed inductor is made of copper tube, and its whole body is cast with epoxy resin to achieve the purpose of fixation and insulation. The deionized water is pumped into the copper tube to dissipate heat under continuous discharge condition. In order to investigate the thermal accumulation and heat transfer process in the inductor, following assumptions have been made.

1) The initial temperature of the inductor is uniform, and it is equal to the ambient temperature.

2) The parameters of copper tube and epoxy resin are isotropic and are not affected by temperature.

3) For the discharge time is very short, the heat transfer between coil and deionized water is ignored.

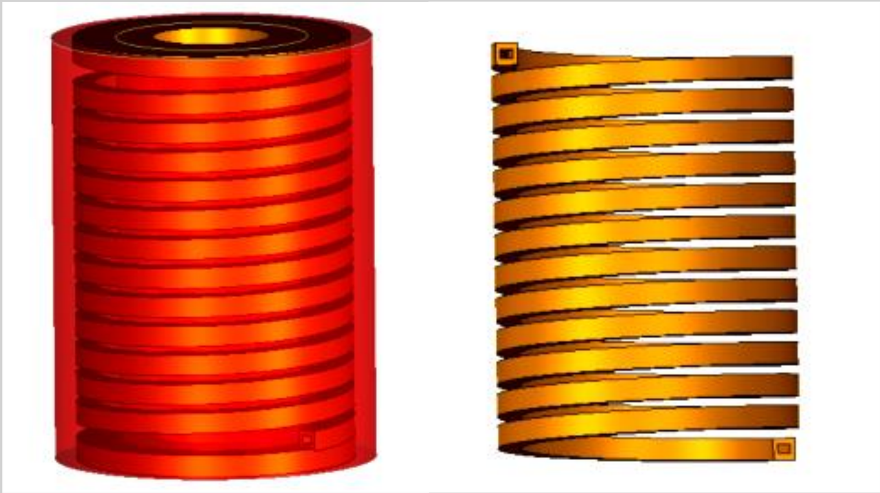

Fig. 2 Structure of the Solenoid Pulsed Inducor

Discharge Stage

The electromagnetic model for the inductor is

$$J = -\sigma\left(\frac{dA}{dt} + \nabla\phi\right)$$

$$\nabla \times \frac{1}{\mu_r}\nabla \times A = \sigma\left(-\frac{dA}{dt} - \nabla\phi\right)$$

$$\nabla \cdot \left[\sigma\left(-\frac{dA}{dt} - \nabla\phi\right)\right] = 0$$

The heat transfer model for the inductor is

$$\rho c\frac{\partial T}{\partial t} = \nabla \cdot \left(\kappa \nabla T\right) + \frac{1}{\sigma}\left|\boldsymbol{J}\right|^2$$

Cooling Stage

The heat transfer model for the inductor is

$$\rho c\frac{\partial T}{\partial t} = \nabla \cdot \left(\kappa \nabla T\right)$$

$$\nabla \cdot \boldsymbol{U}_w = 0$$

$$\frac{\partial(\rho_w \boldsymbol{U}_w)}{\partial t} + \nabla \cdot (\rho_w \boldsymbol{U}_w \otimes \boldsymbol{U}_w) = \nabla \cdot ((\mu_w \nabla \otimes \boldsymbol{U}_w)^T - p_w I)$$

$$\frac{\partial\left(\rho_w c_w T_w\right)}{\partial t} + \nabla \cdot (\rho_w c_w \boldsymbol{U}_w T_w) = \nabla \cdot \left(\kappa_w \nabla T_w\right)$$

NUMERICAL ANALYSIS

The simulation condition is 10 discharges per minute with a discharge interval of 6s, and total analysis time is 1min. During discharge interval, solid coil inductor is naturally, while hollow coil is cooled by cooling water. Cooling water flow is maintained at 2L/min, and the temperature of cooling water is 25℃. The thermal conductivity of the epoxy resin is 0.2 W/(m·K), and the total simulation time is short, so it could be assumed that the outer surface of the inductance coil is adiabatic. The initial temperature of pulse inductor is assumed to be 40℃.

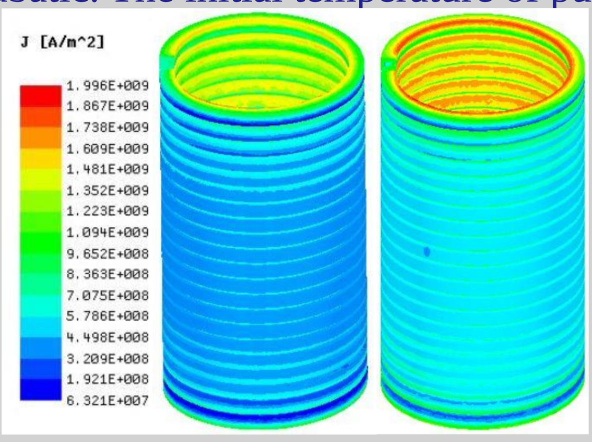

Fig. 3 Current Density Distribution of Solid Coil Inductor (Left) and Hollow Coil Inductor (Right)

Fig. 3 is the current density distribution of pulse inductor at peak current moment. Due to proximity effect, the maximum current density is located at the edge of the inner surface of the inductor; and because the resistance of hollow coil inductor is slightly larger than that of solid coil, the current density of hollow coil inductor is larger than that of solid coil.

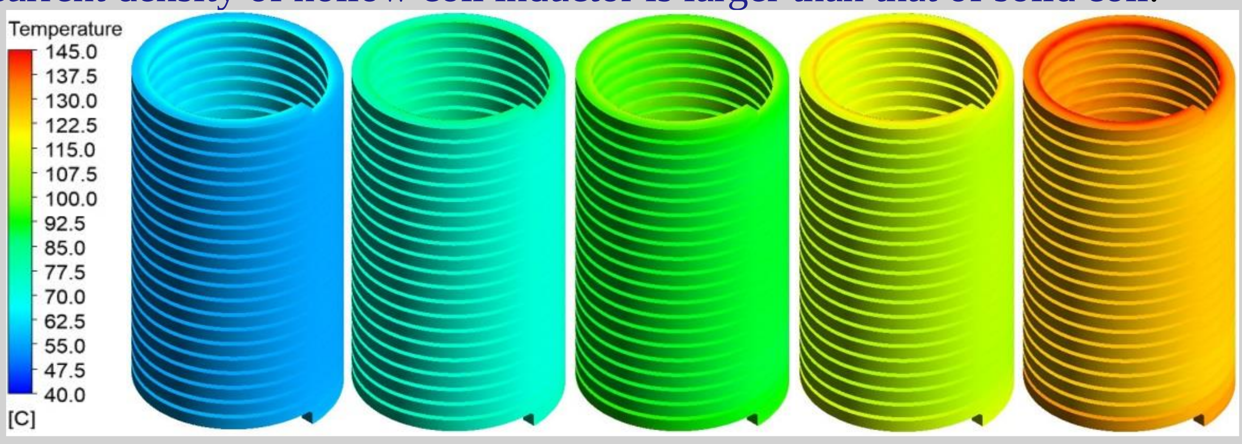

Fig. 4 Temperature Distribution at the End of the 2st, 4th, 6th, 8th and 10th Discharge of Solid Coil Inductor

Fig.4 shows the temperature distribution at the end of the 1st, 4th, 6th, 8th and 10th discharge of solid coil inductor. The temperature of solid coil inductor increases with the increase of discharge times. The peak temperature is close to 145 ℃, which exceeds allowable peak temperature of pulse inductor, indicating that the natural cooling conditions cannot meet the temperature control requirements of continuous discharge of designed PFU.

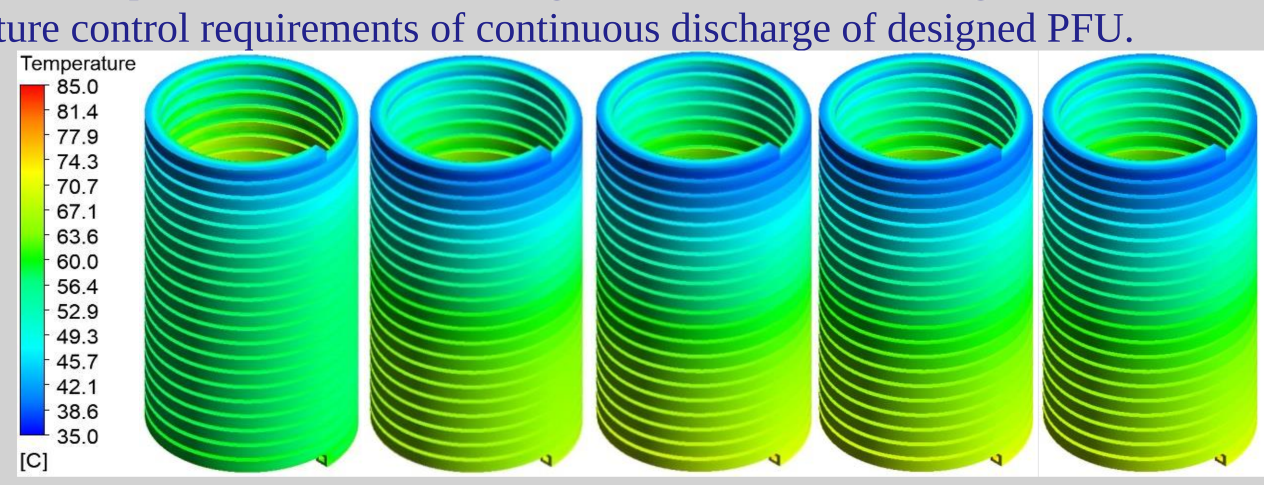

Fig. 5 Temperature Distribution at the End of the 2st, 4th, 6th, 8th and 10th Discharge of Hollow Coil Inductor

Fig.5 shows the temperature distribution at the end of the 1st, 4th, 6th, 8th and 10th discharge of hollow coil inductor. The temperature of hollow coil inductor changes little after the 4th discharge, that is to say, from the fourth discharge, the temperature of inductor tends to be stable. The peak temperature is not more than 85 ℃, indicating that the cooling scheme can meet the temperature control requirements of continuous discharge of designed PFU. Meanwhile, the inner surface temperature is higher than the outer surface temperature, and temperature gradient in the water inlet area is larger, and gradually decreases with the distance from the water inlet.

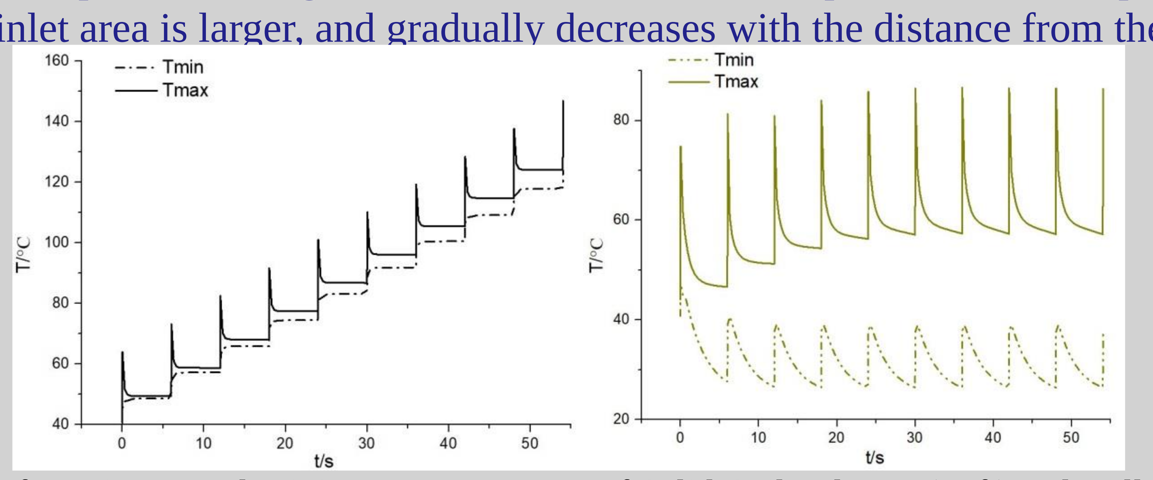

Fig. 6 Curves of Maximum and Minimum Temperature of Solid Coil Inductor (Left) and Hollow Coil Inductor (Right) during Continuous Discharge

Fig.6 shows the curves of maximum and minimum temperature of solid coil inductor and hollow coil inductor with time during continuous discharge. The maximum and minimum temperature of solid coil inductor and their difference rise with the increase of discharge times, and the maximum difference is about 20 ℃. With the increase of discharge times, the maximum temperature of hollow coil inductor rises slowly, while the minimum temperature decreases slowly. Both of them tend to be stable from the 4th discharge, and the maximum difference between them is about 50 ℃.

CONCLUSION

Due to proximity effect, the maximum current density is located at the edge of the inner surface of the inductor; and because the resistance of hollow coil inductor is slightly larger than that of solid coil, the current density and the average Joule thermal power of hollow coil inductor is larger than that of solid coil.

The temperature of solid coil inductor rises with the increase of discharge times. The peak temperature is close to 145℃ at the end of 10th discharge, which exceeds allowable peak temperature of pulse inductor, indicating that the natural cooling conditions cannot meet the temperature control requirements of continuous discharge of designed PFU.

When cooling water flow is maintained at 2L/min, the temperature distribution of hollow coil inductor tends to be stable after 4th discharge, and the peak temperature is not more than 85 ℃, indicating that the cooling scheme can meet the temperature control requirements of continuous discharge of designed PFU. Temperature gradient of inductor near the water inlet is larger, and gradually decreases with the distance from the water inlet. It should be noted that after stabilization, the maximum temperature difference inside the inductor is close to 50℃.

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