Thermal Analysis of Permanent Magnet Motor with Water-Jacket Cooling for Electric Vehicles

Meng Hu[1], Ben Q. Li[2,3] and Changhong Liu[1]
1. Department of Electric Engineering, Shanghai Jiao Tong University,
800 Dongchuan Rd., Shanghai 200240, China
2. Department of Mechanical Engineering, University of Michigan-Dearborn
4901 Evergreen Rd., Dearborn, MI 48128, U.S.
3. Department of Mechanical Engineering Xi'an Jiaotong University
28 West Xianning Rd., Shaanxi 710049, China
Email: liuch@sjtu.edu.cn

***Abstract*—As a key part of new energy automobile, the performance and reliability of a driving motor determine the quality of vehicle directly. A modeling study is presented for the losses and temperature distribution of a permanent magnet synchronous motor (PMSM) with water-jacket cooling used in electric vehicles (EV). The numerical models capable of coupled analysis of electromagnetic field, flow field and temperature field are developed. An effective approach to speed-up the calculation of multi-field coupling is proposed. The models are verified by experiments measurements taken on a prototype of PMSM. The work is useful for motor design and thermal analysis of high power density PMSM.**

***Index Terms*— electric vehicle, permanent magnet motor, losses, temperature, multi-field coupling**

I. INTRODUCTION

Water-jacket cooling is generally used for small or medium motors in which overall compact size and high efficiency cooling are desired. Thermal performance of a motor with water-jacket cooling requires a coupled analysis of magnetic field, flow field and temperature field. While a coupled simulation model can be built with current commercial software, the demand for computing resource and the computational intensity make most of users frustrated. In this paper, an equivalent multi-field coupling method with high accuracy and less time is developed. The iron losses and eddy current loss caused by the tooth harmonics in surface mounted permanent magnet are first calculated. Then, coupled flow-thermal field numerical model was built and studied to obtain the temperature of a 30kW high power density PMSM.

II. MATHEMATICAL MODEL

A. Losses calculation

Accurate prediction of losses, i.e. heat source, is a pre-requisite for analyzing temperature rise in motors. Here the iron loss and eddy current loss are considered, with other losses, e.g. winding copper loss and friction loss etc. are out of scope of this paper.

1) Stator iron loss

Iron loss constitutes a big proportion in the total losses of a motor, especially for high-speed condition. Based on an equivalent elliptical loop, a time domain dynamic hysteresis model, with minor loops taken into account, is employed in this paper. The required parameters in the model are extracted from the pre-known loss curves under sinusoidal excitation, and are the same as those required in the frequency domain approaches such as Steinmetz equation.

2) Eddy current loss of rotor

In a PMSM, the stator slot opening causes flux variation in rotor magnet, which leads to induced voltage and eddy current loss even in no-load condition. With load increasing, the harmonic field component produced by sinusoidal stator current excitation make such losses even bigger. A 2-D time-stepping finite element method is used to solve Maxwell Equation, and the effect of time step and minimum element size are discussed.

The eddy current density expressed by vector potential ***A*** is:

$$J_e = -\sigma \frac{\partial A}{\partial t} \tag{1}$$

and the eddy current lossesof rotor:

$$P_{eddy}(t) = \int_V \frac{\left|\bar{J}_e\right|^2}{\sigma} dV = L\int_S \frac{\left|\bar{J}_e\right|^2}{\sigma} dS \tag{2}$$

where S is the eddy current cross-sectional area, and L is the axial length of the component.

B. Efficient heat and fluid flow analysis

The flow field in water jacket and the temperature field of the motor are directly coupled. In principle, an integrated model which includes both motor body and cooling jacket should be built. However, such an integrated calculation can be computationally intensive. Here, a more efficient procedure is proposed, which allows accomplishing the same objective of coupled electromagnetic-thermal analysis. The procedure entails the following steps:

1) Build 3-D water-jacket geometry model;
2) Apply all the losses of motor to the inner most surface of water-jacket and assume all the losses taken away by cooling liquid;
3) Solve the couple flow-thermal field of the water jacket;
4) Obtainthe surface heat transfer coefficient of every wall element of the spiral water hole and find average;
5) Build simplified motor geometry model;
6) Set stator outer surface convection heat transfer boundary condition with parameters from 4);
7) Solving steady state temperature field of motor.

In the above, the cooling fluid in water jacket is incompressible and obeys the laws of mass conservation, the momentum conservation and the energy conservation. The effect of buoyancy and gravity is ignored.

III. RESULTS AND DISCUSSION

Experiment of a 30kW prototype with load is carried out to verify the presented model.

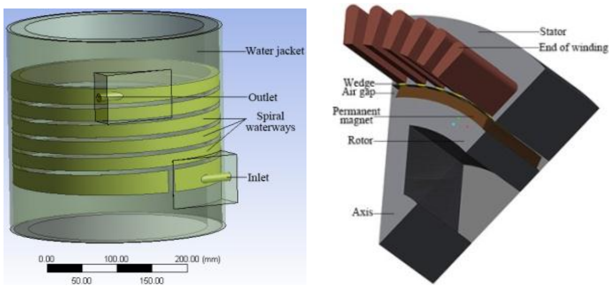
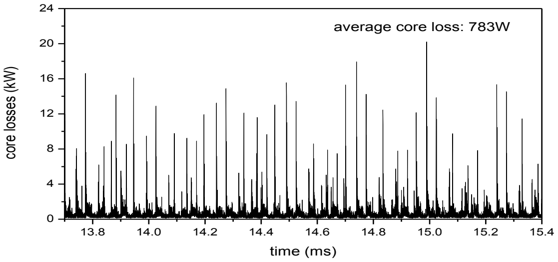


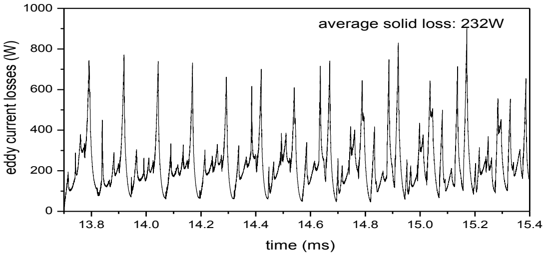
Fig.1. Diagram of water-jacket model and motor model

A. Losses results

The calculation results of iron losses and eddy current losses are shown in Fig. 2. The dramatic oscillation is believed caused by the harmonic current due to an inferior PWM supply (shown in Fig. 3).



(a) Stator iron losses vs. time



(b) Eddy current losses vs. time

Fig.2. Calculation iron losses and eddy current losses in rotor magnet

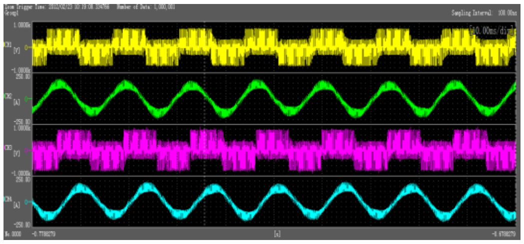


Fig. 3 Measured current and voltage waveform

The sum of calculation iron losses and eddy current losses:

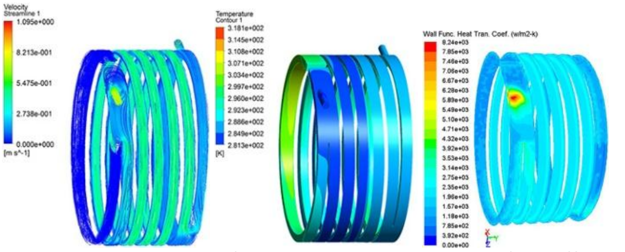
$$Calculation: p_{fe} + p_{e2} = 783 + 232 = 1015\ \mathrm{W}$$

$$Experiment: p_{fe} + p_{e2} = 1121\ \mathrm{W}$$

$$Difference: -9.45\%$$

B. Flow-thermal field results

Figure 4 shows the numerical calculation results of the fluid flow and temperature fields of the prototype water jacket. A dead zone is observed, which leads to higher fluid temperature. In general, the flow rate, temperature, and heat transfer coefficient of cooling fluid are basically uniform. According to the analysis procedure presented before, the applied equivalent heat transfer coefficient of stator outer surface is $1280\ \mathrm{W/m^2 \cdot {}^\circ C}$.



(a) Fluid velocity(b) fluid temperature (c) heat transfer coefficient

Fig. 4.Calculation results of water-jacket

C. Steady-state temperature rise of motor

The comparison of the calculated temperature rise and the experimental ones is shown as Tab.1. Thermal sensors Pt100 were used to measure stator yoke and winding, and surface thermo indicating strip were used for both magnet and stator inner surface.

TABLE I
COMPARISON OF THE CALCULATED TEMPERATURES AND THE MEASURED ONES

Position	Average Calculation Temperature (℃)	Measured Temperature (℃)	Difference (%)
Stator yoke	45.2	43	+5.11
stator Inner surface	56.3	none	none
Air gap*	84.4	88	-4.09
End winding	53.3	51.75	+2.4
Magnet	129.4	130	-0.46

*The air gap temperature is that of 0.5mm away from stator inner surface. Since the thermo-strip attached to the stator inner surface is 0.5mm thickness, the reading should be the temperature of air gap side.

In general, the calculated temperature rise from the numerical model matches well with the experimentally measured data. This suggests that the presented numerical model, equivalent method, as well as the property parameters, are valid and can be applied with a reasonable accuracy for a thermal analysis of PMSM with water-jacket cooling.

REFERENCES

[1] MI Chris, Masrur Abul, and GAO Wen-zhong, *Hybrid electric vehicles: principles and applications with practical perspectives*,John Wiley & Sons, 2011.

[2] Liwei Song, Zijian Li, Jingyi Gao, Qingchu Zeng, Fuping Wang, “3D thermal analysis of water cooling induction motor used for HEV,” *Electrical Machines and Systems, 2008. ICEMS 2008. International Conference on*, pp.534-537, 17-20 Oct. 2008.

[3] Yunkai Huang, Jianning Dong, Jianguo Zhu,Youguang Guo, “Core loss modeling for permanent-magnet motor based on flux variation locus and finite-element method,” *Magnetics, IEEE Transactions on*, vol.48, no.2, pp.1023-1026, Feb. 2012.

[4] YuJiao Zhang, Jiangjun Ruan, Tao Huang, Xiaoping Yang, Houquan Zhu, and Gao Yang, “Calculation of temperature rise in air-cooled induction motors through 3-D coupled electromagnetic fluid-dynamical and thermal finite-element analysis,” *Magnetics, IEEE Transactions on*, vol.48, no.2, pp.1047-1050, Feb. 2012.

[5] Cuiping Li, Yulong Pei, Ronggang Ni, and Shukang Cheng, “Analysis of 3D static temperature field of water cooling induction motor in mini electric vehicle,”*Electrical Machines and Systems (ICEMS), 2011 International Conference on*, pp.1-5, 20-23 Aug. 2011.