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Selection of Contactless-Power-Supply Housing Material Considering Eddy Current Loss, Thermal Load, and Structure Safety

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This paper deals with the selection of the housing material of the contactless power supplier (CPS) used for the field winding power supply in wound field synchronous machine (WFSM). The housing of the CPS encloses the rotary transformer and the converter of secondary side. The housing prevents the damage of ferrite core in the rotary transformer and the secondary converter due to centrifugal force in the highest speed, 10,000 rpm. Therefore, the housing should have been designed considering not only strengthen, but also lighten. Furthermore, efficiency is also one of important characteristics in power transfer to improve the whole system efficiency. Taking account of aforementioned points, the stainless steel (SUS) and aluminum (Al), which are commonly used as housing materials, were under reviewed as CPS housing. After comparing the characteristic of CPSs according to housing material in term of eddy current loss, thermal characteristic, and mechanical stability, the appropriate housing material is suggested. After that, experimental results deriving from tests are presented to confirm the analysis results.

Keywords : finite element analysis, housing material, magnetic loss, thermal analysis

1. Introduction

The contactless-power-supply (CPS) has received significant studies in the recent years as the brushless technology [1-6]. The contactless solution increases the reliability of the system due to maintenance-free and wear-free, and provides good power conversion efficiency in transmission system. CPS mainly consists of two converters and a rotary transformer, which has an air gap between the primary and secondary sides to enable the rotation of a part of the structure.

In this paper, CPS, as shown in Fig. 1, is used to excite for the rotor of the wound field synchronous machine (WFSM). The 15 kW-grade WFSM has been developed for a propulsion system in electric vehicles and CPS was used for WFSM's field winding power supply. The housing of CPS is required to prevent the damage of ferrite core in the rotary transformer and the secondary converter due to centrifugal force in the highest speed, 10,000 rpm.

This paper focuses on how to select CPS housing material. Taking the mechanical strength, weight, and high efficiency into account, stainless steel (SUS) and aluminum (Al) are considered for housing material. At first, according to the required performance, the specifications of CPS and its housing are defined. Moreover, in order to find the appropriate housing dimensions as well as housing material for CPS, three consecutive analyses including electromagnetic, thermal, and mechanical analyses are performed. After comparing output characteristics of the CPS depending on the housing material, the proper

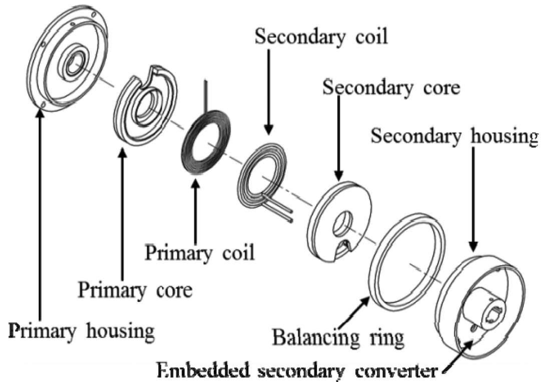

Fig. 1. Configuration of CPS except primary converter.

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Table 1. Specifications of CPS

Parameters		Value	Unit
Frequency		30	kHz
Output power		100-500	W
Material	Core	Mn-Zn soft ferrite	
	Coil	Copper	
	Housing	**SUS304** Permeability: 1.0 Conductivity: 1.1×10^6 Density: 8.0	 S/m g/cm^3
		Al6061 Permeability: 1.0 Conductivity: 23.2×10^6 Density: 2.7	 S/m g/cm^3
Main dimensions of housing		Inner dia. = 24 Outer dia. = 106 Height = 15 Thickness = 3	mm
No. of turns		Primary = 26	Turns
		Secondary = 6	

material for housing part is suggested. Finally, for each housing material, the designed prototype is fabricated and the experiment is conducted to verify the simulation results.

2. Specifications and Computation Methods

2.1. Specifications of CPS and its housing

The specifications of the CPS and its housing are summarized in Table 1. They are considered as meeting the requirements of the CPS system as well as the own performances of the WFSM. The main requirements of the housing are light, low loss, high durability, and low price. Taking account into the mechanical strength and the high efficiency, SUS304 and Al6061 are considered for housing material. After considering the mechanical and loss characteristics, the dimensions of the housing are decided with 3 mm for thickness. It will be checked by mechanical analysis to estimate the structural strength of the CPS housing.

For high frequency inductor or transformer applications, Mn-Zn ferrites are most popular types of material used for magnetic core, and PM11 is chosen among Mn-Zn ferrites series because of high relative magnetic permeability value to improve the power transfer capability over the air gap. To reduce the skin effect and proximity effect losses in coils, Litz wire composed of 100 and 500 conductors of diameter 0.1 mm is used for primary and secondary windings, respectively. Suppose that the natural cooling method is used for cooling on both sides, so the maximum current density is 6 A/mm^2. The number of turns is limited by the current density and the power requirement.

2.2. Electromagnetic analysis

In term of electromagnetic, the eddy current loss distributed on the housing part are calculated and compared between SUS304 housing and Al6061 housing. Moreover, since losses are very important in determining heating, temperature rise, rating and efficiency of the rotary transformer, thus Joule loss in the winding, and core loss in the ferrite core are also mainly considered in this paper for electromagnetic analysis. To simplify the 3-D problem, 2-D axisymmetric model is used for electromagnetic simulation. The cross-sectional of analysis model is shown in Fig. 2.

The eddy current loss in the housing, E_loss, is calculated by the following equation:

$$E\_loss = \frac{1}{\sigma}\int_S J^2 dS \tag{1}$$

where σ is conductivity of housing material, S is the area over which the current flow is computed, J is the induced current density due to time-varying magnetic fields and expresses as follows:

$$J = -j\omega\sigma A \tag{2}$$

where A is the magnetic vector potential.

In axisymmetric model (rZ), the area S in the equation (1) is found by revolving the current flow line you've drawn in the rZ-plane 360 degrees around the Z-axis, forming a 3D surface. The eddy current flow computed is the total current that passes through this surface [7].

The Joule loss in the winding can be calculated by

$$P_{Joule\_loss} = \sum_{i=1}^{2} I_i^2 R_i \tag{3}$$

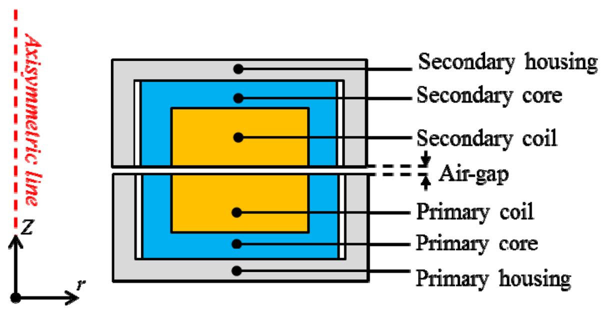


Fig. 2. (Color online) Cross section of analysis model.

with i = 1, 2 denote primary and secondary winding, respectively; I is the RMS phase current; R is winding resistance.

The core loss in the ferrite core W_c is generally varied with the frequency f and the peak flux-density B_{pk}, and determined by C.P. Steinmetz:

$$W_c = C_h f B_{pk}^n + C_e f^2 B_{pk}^2 \tag{4}$$

With coefficient C_h and C_e can be derived from the curve fitting of the measured loss data at several frequencies; f and B_{pk} are the frequency and flux density, respectively; the exponent n depends on the type of materials and typically falls in the range of 1.6-2.2.

2.3. Thermal analysis

The thermal performance is strongly dependent upon the housing material characteristics of CPS. A temperature rise in CPS is obviously undesirable because it is relevant to the optimal working temperature with minimal power losses in the core material and the current density limitation in the winding. The temperature rise in CPS is therefore important criteria in choosing the appropriate material for CPS housing. To estimate the temperature of the CPS, commercial program Flux was used.

The following three contents are mentioned to make clearly understand about thermal analysis presented in this paper:

– Firstly, the three heat transfer mechanisms including conduction, air convection and radiation are all considered for thermal analysis.
– Secondly, to determine the convection coefficient between outer surface and surrounding air, natural cooling is considered for both the primary and secondary outer housing surface as stationary part. Since the air gap between the primary and secondary is only 1.0 mm, the convection will be neglected in the air gap to assume a worth-case thermal situation.
– Thirdly, Joule loss in the winding, core loss in the ferrite core, and eddy current loss in the housing, which are calculated from electromagnetic analysis, are considered as the thermal sources.

The accuracy of thermal prediction problem is dependent upon several parameters and the external convection is one of the most important parameter which needs to pay attention. In order to determine the convection coefficient, CPS can be divided into three places of natural free convection depends on the position and the shape of outer surface: horizontal plates with bottom surface (h_1) and with top surface (h_3), and four vertical cylinder (four lateral surfaces) (h_2), as shown in Fig. 3. For horizontal plates, there is the different behavior of

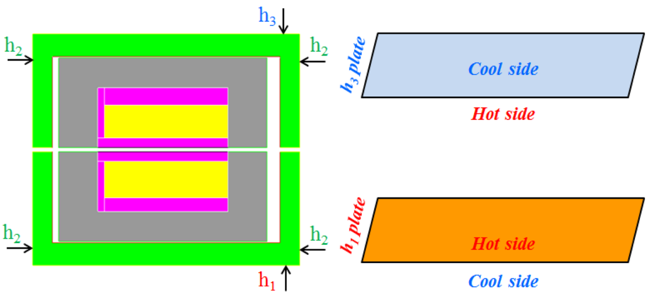


Fig. 3. (Color online) The thermal analyzed model configuration.

thermal exchange for a hot surface facing upward or downward [8]. The two planes in the right side of Fig. 3 show that the top surface of the CPS corresponds to hot surface facing upward and the bottom surface of the CPS corresponds to hot surface facing downward. Therefore, the natural free convection for horizontal bottom surface and top surface is different, which are h_1 and h_3, respectively. The convection determination bases on the estimation of convection coefficient with the empirical correlations. The related theories and the main equations are presented in [8].

2.4. Structure analysis

Under the maximum rotation speed of 10,000 rpm of rotor of WFSM, the secondary core and housing have the possibility to be broken or deformation from the original shape by stress. Therefore, it is necessary to check the mechanical stability of CPS housing and core in dynamic condition with the maximum rotation speed of 10,000 rpm.

The structural stability is evaluated in term of the von Mises stress or equivalent stress by using FEA. The von Mises stress is considered to predict yielding of material under any loading condition. And a material starts yield-

Table 2. Material properties for structural analysis and coefficients for thermal analysis

Item	Housing		Core
	SUS304	Al6061	Ferrite
Density (kg/m^3)	8000	2700	4800
Elastic Modulus (GPa)	193	68.9	166.5
Yield Strength (MPa)	215	276	-
Tensile/Compressive Strength (MPa)	505	310	48
Poisson's ratio	0.29	0.33	0.225
Convection Coefficient (W/m^2.^{0}C)			
h1	4.00		
h2	5.31		
h3	7.15		

ing when its von Mises stress reaches a critical value known as the yield strength [9]. The equivalent stress, σ_e, is related to the principal stresses (σ_1, σ_2, σ_3) and computed by the equation [9, 10]:

$$\sigma_e = \left[\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_2)^2}{2}\right]^{1/2} \quad (5)$$

All the necessary constants for structural analysis are listed in Table 2 with the convection coefficient for thermal analysis.

3. Analysis Model and Results

3.1. Electromagnetic analysis

The magnetic characteristic of Al6061 housing and SUS304 housing are analyzed at 1 mm of air gap and load power range from 100 W to 500W. Figure 4 shows the eddy current loss distribution in the SUS304 housing and Al6061 housing. Figure 5 shows the eddy current and eddy current loss in housing depending upon the load power variation. As we can see from the simulation results, even though Al6061 housing has higher eddy current but the eddy current loss is smaller than that of SUS304 housing.

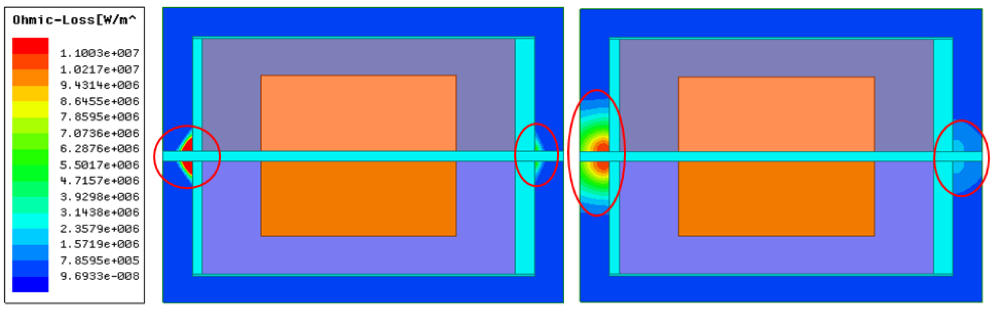
To understand the behavior of eddy currents on the housing part, we need consider the ratio between housing thickness and its skin-depth (δ),

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$

At 30 kHz frequency, the skin-depth values for SUS304 housing is 0.6 mm and for Al6061 housing is 2.7 mm. With 3 mm for housing thickness, the ratio between housing thickness and its skin-depth is over than 1, so the eddy current in this case is called as inductance-limited [11]. This means the eddy current loss will increase if the conductivity of the housing part decreases. Therefore, Al6061 housing has less eddy current loss than SUS304 housing and the simulation results are consistent with the presented theory.

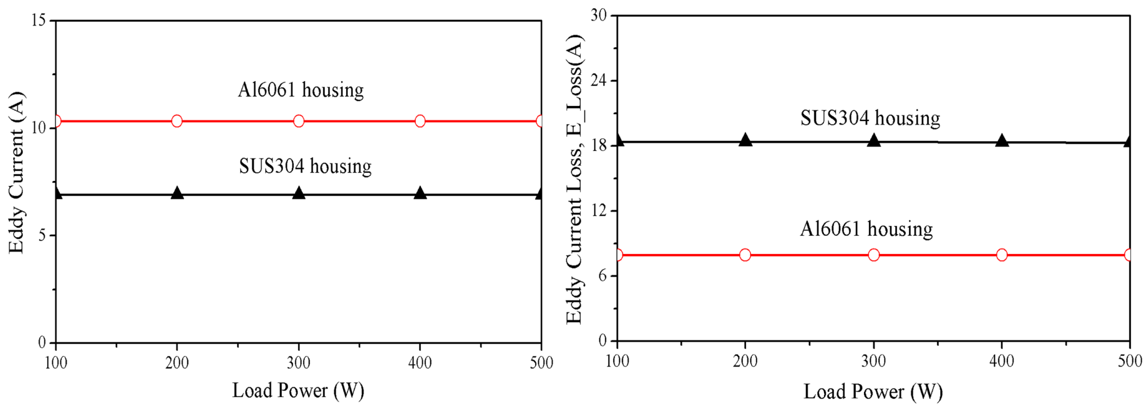
3.2. Thermal analysis results

Thermal analysis is performed when the output power of CPS is 150W. The heat sources including Joule loss in the winding, core loss in ferrite core, and eddy current loss in the housing are calculated from electromagnetic



(a) Al6061 housing (b) SUS304 housing

Fig. 4. (Color online) Eddy current loss distribution in the housing part at 1 mm of air gap.

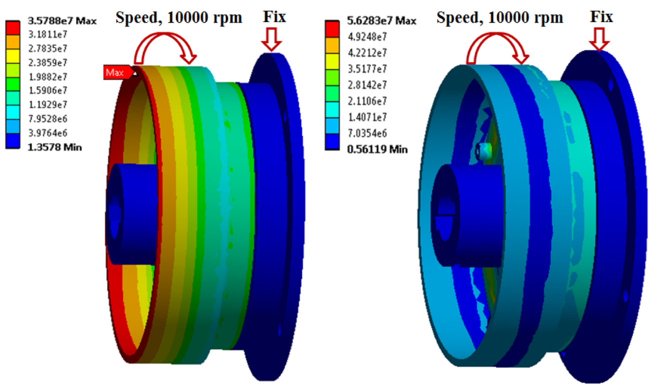


(a) Eddy current (b) Eddy current loss

Fig. 5. (Color online) Comparison of eddy current and eddy current loss distributed in the housing part.

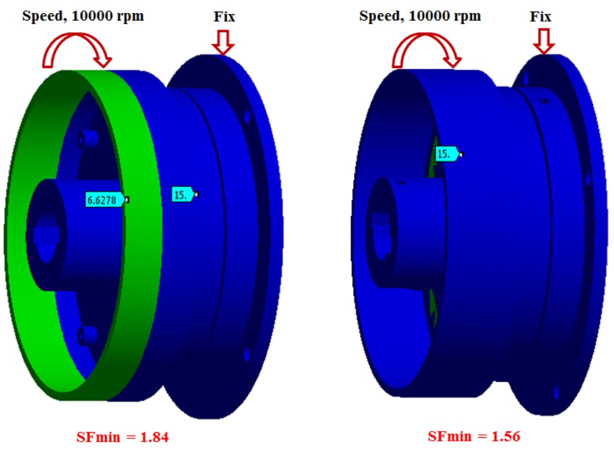
Table 3. Heat sources and thermal analysis results.

Regions		Power Losses (W)		Temperature (^{0}C)	
		SUS304	Al6061	SUS304	Al6061
Primary	Coil	0.458	0.458	43.56	32.64
	Core	0.373	0.366	43.56	33.30
	Housing	2.350	1.020	42.35	32.67
Secondary	Coil	0.081	0.081	41.90	32.2
	Core	0.373	0.366	41.93	31.92
	Housing	2.350	1.020	40.99	31.22



(a) SUS304 housing (b) Al6061 housing

Fig. 6. (Color online) Equivalent stress analysis results.



(a) SUS304 housing (b) Al6061 housing

Fig. 7. (Color online) Safety factor (SFmin: minimum safety factor).

analysis, and the results are shown in Table 3. The estimated average temperatures for CPS in steady state are also presented in Table 3. The temperature distributed in CPS with Al6061 housing is smaller than that of using SUS304 housing because of lower eddy current loss in housing.

Fig. 8. (Color online) Fabricated coil, ferrite core, SUS304 housing, and Al6061 housing.

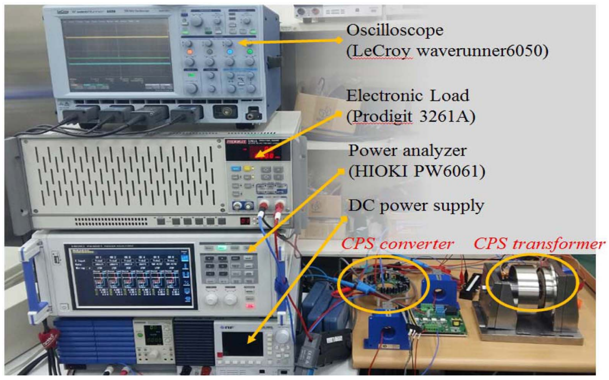


Fig. 9. (Color online) The experimental set up.

3.3. Structural analysis results

In the structural analysis, Al6061 housing and SUS304 housing with ferrite core are checked under maximum rotation speed of 10,000 rpm in the secondary side. Figure 6 shows the equivalent stresses on core and housing parts of CPS. The maximum equivalent stresses of Al6061 and SUS304 housing with ferrite core, which are 35.8 MPa and 12.0 MPa respectively, are smaller than the yield point of the material Al6061 and SUS304. Factor of safety, as the ratio of the maximum allowable stress to the actual stress, is also calculated and shown in Fig. 7. In both cases, the minimum values of safety factor (SFmin) fall to the CPS's core position and are greater than 1. Thus, the mechanical structure of CPS for both cases is stable under the maximum rotation speed.

4. Experiment Validation

Figure 8 shows the manufactured components including coil, ferrite core, Al6061 housing, and SUS304 housing. Figure 9 shows the experimental set up including the CPS and the series-series resonant converter, which built based

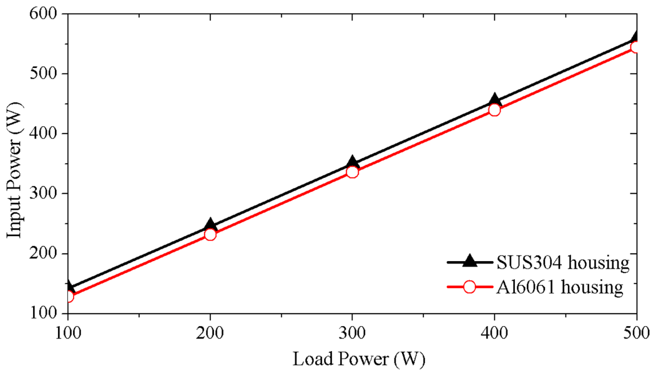


Fig. 10. (Color online) Input power curve according to load power variation and housing material at air gap = 1.0 mm.

on the design specifications in the section 2.1.

Comparison of the input power-load power curve of CPS with different housing material is shown in Fig. 10. To get the same value of output power, CPS using SUS304 housing require more input power than that of using Al6061 housing. That means the smaller losses are obtained in the transformer using Al6061 housing. As the efficiency of CPS is the ratio of load power to input power, the experimental results has the same conclusion with analysis results, revealing that Al6061 housing gives better efficiency in power transfer than that of SUS304 housing because of smaller losses.

The thermal test is also conducted to confirm the

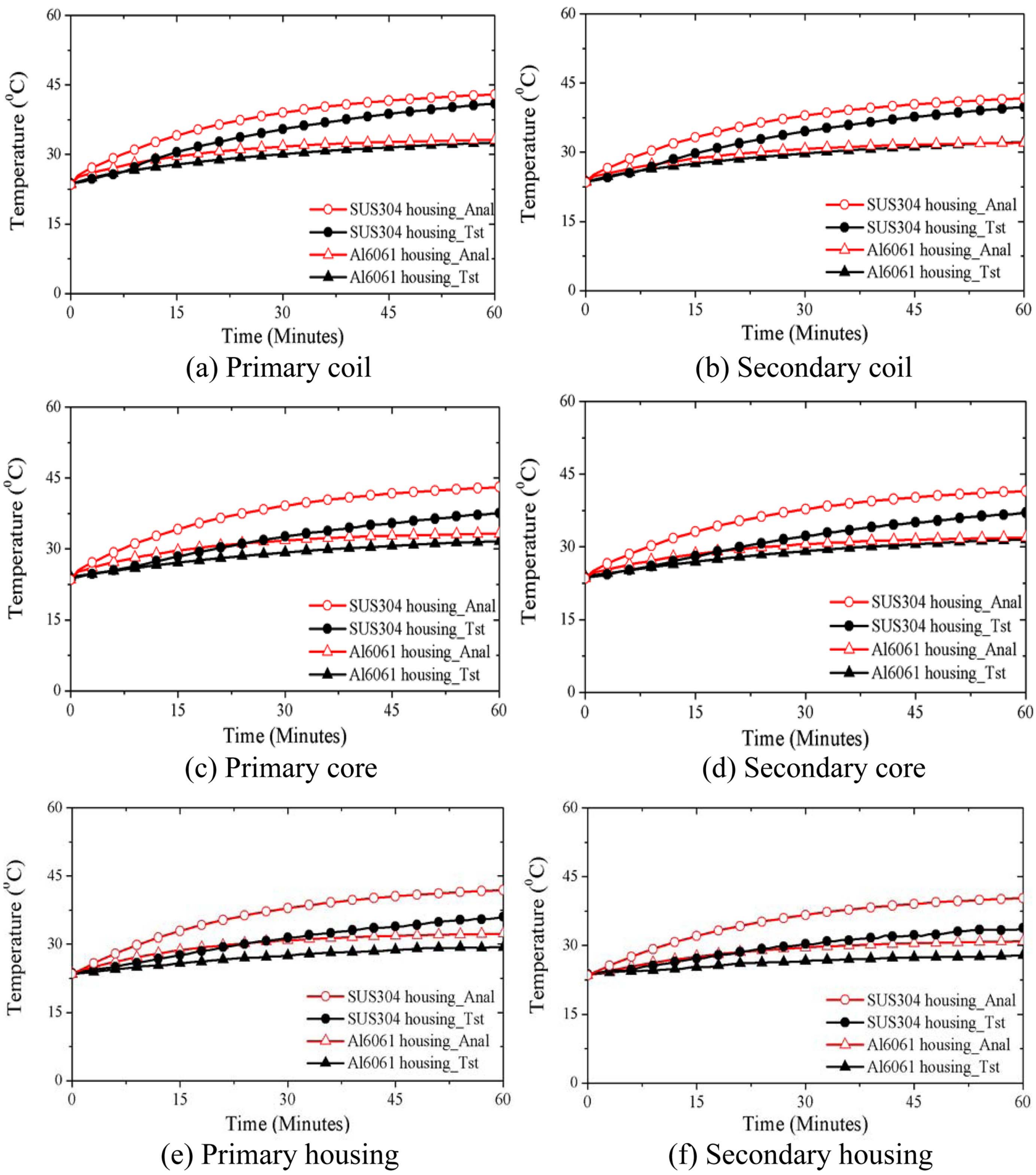


Fig. 11. (Color online) Temperature comparison between CPS with Al6061 housing and SUS304 housing by analytically and experimentally (Anal: analysis result, Tst: Test result).

analysis results under the same condition. The temperature of each part are measured under load condition by using the thermo-coupler within 1 hour. The distribution temperature of CPS are shown by both analytical and experimental in Fig. 11. As mentioned above, the eddy current loss has large influence in the thermal behavior of CPS with different housing material. Because of lower eddy current loss, temperature distribution in each part of CPS using Al6061 housing in both analytical and experimental is smaller than that of using SUS housing. The analysis values are higher than the measured values because in the analysis the convection in the air gap side is neglected. And also, the accuracy of a CPS thermal performance prediction is dependent on many parameters which require reliable data released exactly by the manufacturer, for example, the thermal conductivity of the important materials used in CPS [12]. Therefore, the amount of temperature difference between analysis and test results in this paper is trivial and it can be acceptable in the thermal problem.

5. Conclusion

This paper has proposed a process to select the housing material of the CPS under high speed rotation. Al6061 housing and SUS304 housing were carefully compared in term of eddy current loss, thermal load, and mechanical stability. Because the eddy current is inductance-limited, CPS with Al6061 housing has less eddy current loss than CPS with SUS304 housing even Al6061 has higher conductivity. As the eddy current loss is one of the main thermal source, it is reasonable that the temperature distribution in each part of CPS with Al6061 housing has smaller values than that of SUS304 housing. In addition to critical parameters such as the thermal conductivity of important material, the natural convection coefficient also played an important role for accurately calculating the temperature distribution of CPS using FEA method. Besides, through the mechanical analysis, the structure of Al6061 housing with ferrite core also turned out to be stable for the rotation speed of 10,000 rpm. The calculation results obtained by FEA were experimentally verified with a good agreement, revealing that Al6061 is favorable for housing material of CPS because of lower eddy current loss and smaller temperature in comparison with SUS304 housing.

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