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Research Paper

Transient cooling effect analyses for a permanent-magnet synchronous motor with phase-change-material packaging

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HIGHLIGHTS

- A paraffin based casing for the cooling of actuator motor was proposed.
- The working time of the motor can be prolonged with this paraffin-based casing.
- The motor's peak temperature can be decreased during the period working modes.
- Bigger quality and higher melting rate of paraffin lead to better cooling effect.
- The melting point of the paraffin affects the thermal control performance greatly.

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ABSTRACT

Permanent-magnet synchronous motors (PMSMs) are widely involved in more-electric aircrafts and all-electric aircrafts. But the cooling strategy of the PMSM is still a challenge for the designers. This paper proposed a novel thermal management approach with phase change material (PCM) for a PMSM applied in the actuator systems of aircraft. A simplified 3D model of the PMSM with a special casing packaged by paraffin-PCM was built. With the finite element method, the impact of paraffin cavity configurations and the paraffin types on the transient cooling effect of the casings have been simulated and analyzed under conditions of various heat load duty cycles and different ambient temperatures. The results suggest that, by replacing the convectional motor casing with this paraffin-based enclosure, the effective time for the PMSM temperature control could be prolonged by approximate 32.7% when the motor works under a continuous mode, and the peak temperature of the PMSM could be decreased evidently when the PMSM operates under a periodic mode.

1. Introduction

With the development of more electric aircrafts (MEAs) and all electric aircrafts (AEAs), most of the aerospace systems are undergoing a long-term transition from using mechanical, hydraulic, and pneumatic power systems toward globally optimized electrical systems [1]. And the electric motors make the ultimate goal to be achieved by converting electrical power to mechanical work to drive actuators, pumps, compressors and other subsystems at variable speeds [2–4]. Hundreds of electric motors are demanded for a large MEA, and hundreds of kilowatt electric power is required to drive the motors. However, the output power can never equal the input power, for there are always losses. A larger amount of heat will be unavoidably generated inside the motor with an increasing requirement for the output power [5,6]. Most of the motors on aircraft can no longer be kept at a safe temperature level by only natural convection cooling [7], such as the permanent-magnet synchronous motors (PMSMs) in actuator systems [8,9]. There is a contradiction between the large heat generation and the insufficient cooling capacity of the PMSMs during the operating time. Therefore, how to balance the thermal management requirement and the limited heat releasing ability of the motor is an imperative problem to be solved.

There are various approaches to realizing the motor cooling. For instance, the simplest one is self-cooling by natural convection with external fins incorporated in the casing, and the cooling effect could be enhanced by a fan mounted on one end of the shaft

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Nomenclature

g	gravity coefficient
c	specific heat capacity, J/kg K
h	heat convection coefficient, W/m^2 K
k	thermal conductivity, W/m K
l	height of the casing, m
m	mass of paraffin, kg
n	normal direction of surface
n_r	rotational speed of the rotor, r/min
q	heat flux into the boundary, W/m^2
x, y, z	component in a Cartesian coordinate system
C	heat capacity, J/K
Gr	Grashotf number
L	heat latent of the paraffin, J/kg
Nu	Nusselt number
N_i, N_j	interpolation function
P	heat power, W
Pr	Prandtl number
Q	heat, J
Re	Reynolds number
R	heat resistant, K/W
T	temperature, K
ΔT	temperature difference, K
V	volume, m^3

Greek symbols

α	expansion coefficient of air
β	surface roughness factor
δ	length of air gap, m
ε	emissivity factor
ξ	heat storage proportion,%
η	liquid fraction of paraffin
ω	rotor peripheral speed, rad/min
ν	viscosity of air, m^2/s
ρ	density, kg/m^3
σ	Boltzmann constant
τ	operating time of the motor, s
Ω	volume of each element
Γ	boundary surfaces of elements
Ψ	Production power density, W/m^3

Subscript

0	ambient
ave	average value
c	casing
e	partitioned finite element
eff	equivalent value
h	heat convection
i, j	number of node
init	initial time
load	operating state
off	stop state
m1	solidification point of the paraffin
m2	melting point of the paraffin
para	paraffin
r	rotor
s	stator
H_ave	average value during the heating time
L_ave	average value during the interrupt time

[10,11]. This method is suitable to the motors with low power density for its low heat dissipating efficiency. Another kind of motor thermal management tactic is the liquid-cooling. Two working fluids, water [12,13] and oil [14,15], were generally used in the previous research. For the first one, sophisticated design with internal water channels inserted in the casings is a major work. It can provide a long time constant and high thermal overload capacity with high efficient fluidic path arrangement. Moreover, the cooling circle can be shared with other collaborative devices such as inverter and braking resistor. The oil-cooling scheme, including oil bath and oil injection which are usually used for the high-power motors in aircraft, performs better for the higher thermal capacity of oil compared with that of water. These liquid-cooling methods share a common disadvantage that external fluid circle system including pump package, heat dissipation unit, tube system, etc. will increase the whole system's weight and size, and decrease the reliability and efficiency. Therefore, self-cooling or air-cooling is still the major thermal management method for the PMSMs in actuator systems. Meanwhile, in consideration of the intermittent operating mode of the PMSMs, the phase change heat storage could be used to improve the cooling performance of the motors.

The phase change material (PCM) has been widely applied in heat storage and thermal management systems because it provides a high energy storage density. The paraffin-PCM, for an example, absorbs approximately 200 J/kg–290 kJ/kg of heat if it undergoes a melting process [16,17]. High amount of heat absorbed by the paraffin can be released to the surroundings in a cooling process starting at the PCM's crystallization temperature. What is more, the latent heat storage has the capacity to store heat of fusion at an almost constant temperature corresponding to the phase transition temperature of the PCM. The paraffin-PCM with specific characteristics, such as melting temperature range, volume expansibility, and density, can be made to meet various needs by blended different raw materials and accessory materials [18]. However, its low thermal conductivity sharply restricts the efficient charging and discharging process of latent heat energy. To solve this problem, some heat transfer and enhancement techniques can be employed by adding fins, high conductivity metal or graphite particles into the PCMs [19–22].

Many investigators have applied the PCM to the air-conditioning and electronic devices thermal controlling systems. Turnpenny et al. [23] first published their study about the cooling of buildings using heat pipes embedded in PCM ($Na_2SO_4 \cdot 10H_2O$) storage unit in 2000. In the next year, they [24] installed a prototype free cooling system to prevent a typical office building from being overheating in summer. Jankowski et al. [25] had discussed the PCM applications in vehicle component thermal buffering. Tan et al. [26] designed a helmet cooling system with PCM to store the heat produced by the wearer head, and the helmet could provide comfortable cooling for up to 2 h when the PCM was completely melted. They [27] also studied the cooling of mobile electronic devices (heat power from 4 W to 16 W) with a heat storage unit filled with n-eicosane. Kandasamy et al. [28] investigated a PCM-based heat sink experimentally and numerically for the thermal management of electronic devices with the input power ranging from 2 W to 6 W. Several researchers have discussed the temperature control effect of high power devices with PCMs. Lu [29] studied the prospect of high power electronic packages with phase change cooling by numerical method. In addition, Bellettre et al. [30] tried to put paraffin around the windings in the fully-enclosed motor to cool the hot spot in 1997. He gave some nodal type models to simulate the transient phase change cooling performance and a good temperature control result was obtained. But it is hard to hold the liquid paraffin in a fixed position relative to the windings inside the motor, and how to ensure that the paraffin is reusable after its solidification process remains to be solved.