International Journal of Heat and Mass Transfer 110 (2017) 746–752

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Numerical investigation of the air-gap flow heating phenomena in large-capacity induction motors

Chiwon Kim, Kwan-Soo Lee *

School of Mechanical Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea

ARTICLE INFO

Article history:
Received 23 November 2016
Received in revised form 21 March 2017
Accepted 21 March 2017
Available online 30 March 2017

Keywords:
Motor
Large-capacity motor
Air gap
Winding
Thermal modeling

ABSTRACT

The thermal characteristics of a large-capacity induction motor were investigated with an air-gap flow temperature that is higher than the stator and winding temperatures. Air-gap flow heating phenomena were defined and classified into three states: under-heating, over-heating, and super-heating. A non-dimensional temperature was suggested to predict the corresponding air-gap flow heating state of a motor. Based on the non-dimensional temperature, the over-heating state is inevitable for a motor with a capacity above 50 kW, and the super-heating state is inevitable for a motor with a capacity above 100 kW. Furthermore, the effects of the over-heating and super-heating states of the air-gap flow on the stator and windings were investigated. Under these two states, the cooling of the stator by the air-gap flow was diminished. Additionally, the winding temperature increased because of the discharged air-gap flow.

1. Introduction

An electric motor is a device that can convert electrical energy into mechanical energy. Recently, demands have increased for motors with capacities greater than 100 kW for transportation, such as electric vehicles and high-speed railroads, and industrial manufacturing. When the motor capacity increases, predicting the thermal characteristics of a motor becomes more important because of increased heat generation.

The thermal management of a motor is important because the thermal characteristics of a motor are strongly related to its lifespan and efficiency [1–3]. And for the thermal management of a motor, it is essential to identify the internal temperature of the motor. Many studies have been conducted to predict the temperature distribution of a motor with various motor types and operating conditions. Most studies have focused on the thermal characteristics of the stator and winding instead of the air-gap flow between the stator and rotor. Li [4] examined the winding temperature variation with a combined rotor-impeller structure in a permanent magnet electric motor. Kim et al. [5] optimized the blade and inlet geometries for a brushless DC motor to minimize the winding temperature. Xie and Wang [6] studied the effects of a damaged rotor component on the thermal characteristics of the stator and winding in an induction motor. Wang et al. [7] improved the cooling performance of the stator of an actuator motor by introducing phase-change materials into the casing structure. However, these solid-region-focused studies cannot be applied to a large-capacity motor, where the air-gap flow temperature may exceed the stator and winding temperatures.

Despite a notably low flow rate through the air gap between the stator and rotor, the air gap provides most of the cooling for the stator and windings [8–11]. Hence, the effects of the air-gap flow on the thermal characteristics of motors have been studied. Most studies on air-gap flow focused on obtaining the heat transfer coefficient. Kuosa et al. [12] studied the relationship between the turbulent characteristics and convective heat transfer of the air-gap flow in a motor. Howey et al. [13] investigated the convective heat transfer of the air-gap flow based on the rotational speed. Fenot et al. [14] analyzed the effects of a non-uniform air-gap shape on the thermal characteristics of a motor. However, there has been limited research on the air-gap flow temperature and effect of the air-gap flow temperature on the thermal characteristics of the stator and winding.

In this study, air-gap flow heating phenomena were defined for a large-capacity induction motor, in which the maximum temperature of the motor was measured in the rotor. A numerical analysis was also conducted to examine the effects of air-gap flow heating on the thermal characteristics of the stator and windings.

* Corresponding author.
E-mail address: ksleehy@hanyang.ac.kr (K.-S. Lee).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.03.075
0017-9310/

Nomenclature

A	area [m^2]
a	curve-fitting constant
b	curve-fitting curvature
C_p	specific heat [J/kg K]
D_h	hydraulic diameter, $2(r_s - r_r)$ [m]
e	error [%]
f	function
h	heat transfer coefficient [W/m^2 K]
k	thermal conductivity [W/m K]
L	length in axial direction [m]
$\dot{m}$	mass flow rate [kg/s]
Nu	Nusselt number
Pr	Prandtl number
p	pressure [Pa]
$\dot{Q}$	heat generation rate [W]
$\dot{Q}^*$	normalized heat generation rate
R	thermal resistance [K/W]
Re	Reynolds number in the air gap, $\rho u_z D_h/\mu$
r	radius [m]
S	volumetric heat source [W/m^3]
T	temperature [K or °C]
ΔT_{ag}	temperature difference in the air gap, $(T_{ag} - T_s)$ [K or °C]
u	velocity [m/s]
W	capacity of the motor [W]
W*	normalized capacity of the motor
x	Cartesian coordinate [m]
z	axial coordinate
z^*	non-dimensional axial coordinate

Greek symbols

α	distribution ratio to air gap
β	temperature-fitting constant
η_r	heat generation ratio of the rotor
η_e	efficiency of the motor
η_w	insulation enhancement ratio
ϕ	angle [rad]
μ	viscosity [kg/m s]
μ_t	turbulent viscosity [kg/m s]
π	Pi
θ	non-dimensional temperature
θ_{NADT}	non-dimensional air-gap discharge temperature
ρ	density [kg/m^3]
τ	shear stress [N/m^2]
ω	rotational speed [rpm]

Subscripts

0	intercept point
(A)	surface (A)
∞	ambient
ag	air gap or air-gap flow
avg	average
d	designed
eff	effective value
i	index, i = 1, 2, 3
j	index, j = 1, 2, 3
r	rotor
s	stator
sh	sheath
w	winding
z	axial

2. Mathematical modeling

2.1. Model description

Fig. 1 presents the schematic diagram of a large-capacity induction motor. The motor has air-cooled system. The inner and outer diameters of the rotor were 12.50 mm and 80.80 mm, respectively. The stator had an inner diameter of 83.56 mm and an outer diameter of 190.00 mm. The size of the air gap between the stator and the rotor was 1.38 mm.

The induction motor had an open-type air cooling system. The stator was cooled by cooling fins, which surrounded the exterior of the stator. Air from an external fan entered the induction motor through six inlets with 0.2 m^3/s. This air was distributed through the stator-rotor air gap and duct, which consisted of its fins, fin base, and frame. These two flows merged after passing through

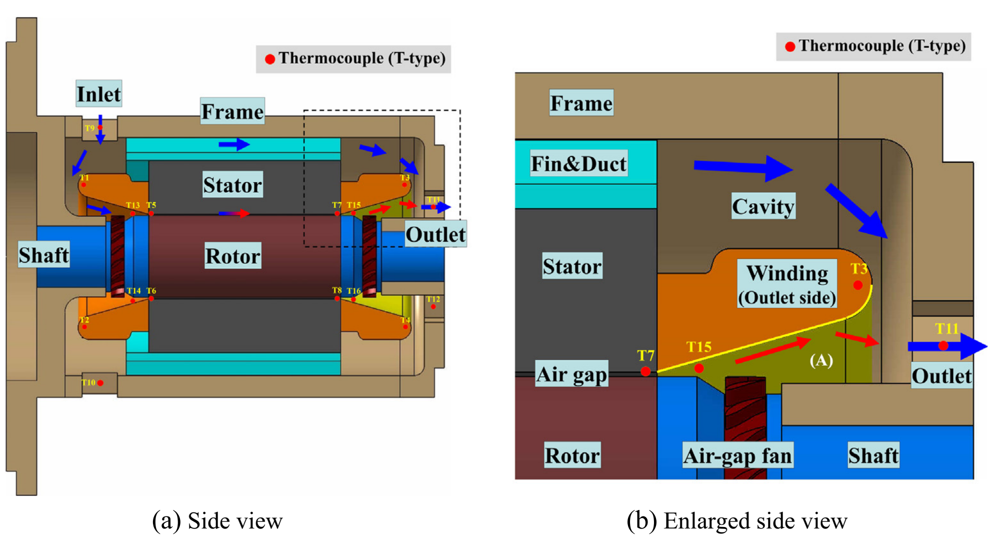

Fig. 1. Induction motor geometry.