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Air-Gap Heat Transfer in Rotating Electrical Machines: A Parametric Study

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Abstract

More than half of all electrical energy is consumed by motors and generators in an industrialized country. About 5-25% of this energy is lost and converted to heat. This heat produced by the losses has adverse effect on the lifetime and performance of a machine. A machine has to be operated at a given temperature to achieve maximum efficiency, therefore heat transfer study of machines is of special interest to rotating machines manufacturers. In this paper we investigate the heat transfer in the air-gap between the rotor and the stator of a simplified induction motor using Computational Fluid Dynamics. We consider three different air-gap widths and rotation speeds to explore the change in air-gap heat transfer when changing the air-gap width and the rotation speed. The simulated average heat transfer coefficients for all the models are in good agreement with the correlations from published literature. The Taylor-Couette vortical flow pattern is observed in the air-gap in our simulation results for the models with large air-gaps. The numerical results show that the presence of Taylor-Couette vortices in the air-gap enhance the heat transfer. The heat transfer coefficient increases with the increase in the rotation speed and decreases with the decrease in the air-gap width.

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Keywords: Air-gap; Rotating electrical machine; CFD simulation; Thermal analysis; Taylor-Couette flow

1. Introduction

Motors and generators are one of the largest energy consumers in the world [1]. Several studies highlighted that the energy consumptions by motors and generators amount to between 60-80% within the European Union (EU) [2], [3]. The use of motors and generators are increasing day by day, thus the demand of energy is also increasing from this sector. To meet the increasing demand, the energy providers often need to use the non-renewable energy resources which increase the greenhouse gas emission [4]. Therefore, energy savings from motors and generators in industrial and commercial sectors became a key focus in many EU countries [5]. An increase in the efficiency of standard motors and generators by 2% will reduce the energy consumption by 25% [6].

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Nomenclature

D_h	$=2g$, Hydraulic diameter (m)	Ta_{cr}	Critical Taylor number
g	$=r_2-r_1$, Gap size (m)	Nu	Nusselt number
k	Thermal conductivity of air (W/m-K)	Nu_{avg}	Average Nusselt number
r_1	Outer radius of the rotor (0.075m)	ν	Kinematic viscosity of air (m^2/s)
r_2	Inner radius of the stator (m)	Ω	Angular velocity of the rotor (rad/s)
r_m	$=\frac{r_1+r_2}{2}$, Mean radius (m)	Ω_{cr}	Critical angular velocity (rad/s)
Ta	Taylor number	Pr	Prandtl number

About 5-25% of total electrical energy consumed is lost during the machine operation [7]. This lost energy is then converted into heat which increases the temperature inside the rotating electrical machine. The rise of temperature has a great impact on the performance and lifetime of a machine. A machine must be operated under a given temperature to achieve a specified efficiency and maintain its lifetime. Therefore, the heat transfer inside the machine is of special interest to the motors and generators manufacturers. To operate rotating machine, variable speed drivers are most often used which control the speed of a machine based on load demand to achieve higher efficiency. The major heat transfer occurs in the air-gap between the rotor and the stator which is mainly driven by the air flow pattern. Therefore, it is crucial to understand the relationship of air-gap width and rotor's rotation speed to the heat transfer to optimize machine design, to reduce the losses, to achieve proper cooling and to operate the machine at an optimal condition. Air-gap heat transfer has been subject to many other numerical and experimental studies both for the enclosed machines and the open machines [8]. The airflow inside an enclosed and an open machine is known as Taylor-Couette flow and Taylor-Couette-Poiseuille flow respectively. In this article we consider an enclosed machine geometry thus we focus only on Taylor-Couette type flow. Use of Computational Fluid Dynamics (CFD) to study the air-gap heat transfer numerically are very few compared to the experimental studies [8]. Romanazzi and Howey [9] and Anderson et al. [10] presented CFD simulation results to analyze the heat transfer and also proposed correlations to calculate heat transfer coefficients. Previous experimental investigations provide correlations to calculate heat transfer coefficients for a broad range of air-gap width and operating conditions [8], [11].

In a preceding investigation [12], we studied the transient heat transfer inside the annulus air-gap of a rotating electrical machine. The main focus in [12] was to investigate the transient behavior of the airflow and its influence on the heat transfer while taking into account the turbulence effect from the rotor wafters. In this paper, we present a parametric study based on air-gap width and rotor's rotation speed for the same model geometry as in [12] resembling a low voltage induction motor. Such numerical parametric studies are rare in the available published literature. In this study, we present the numerical results and discuss the changes in heat transfer behavior while changing the chosen parameters to understand the relationship between each parameter and their overall impact on the heat transfer.

2. Numerical domain and operating conditions

The simplified numerical model presented in Fig. 1a represents a low voltage induction motor which mainly consists of a smooth cylindrical rotor together with wafters and the internal surfaces of the stator and the housing. The air-gap width in general is different for different machines depending on the size and power ratings of the machine. Fig. 1b presents a 2D cross section of the domain with all the dimensions. The model geometry is parametrized to study three different air-gap widths of 1mm, 3mm and 5mm where rest of the dimensions are kept exactly same. The rotation speed of the rotor is also varied to 1500rpm, 5000rpm and 10000rpm for all the three air-gap widths to investigate the impact of air-gap width and rotation speed on the heat transfer. The meshes (Table 1) for all the three models consist only hexahedral structured cells where the cells close to the solid walls are refined to fully resolve the boundary layer (Fig. 1c). In total nine different simulations (Table 2) are performed and the results are compared and validated using available correlations from experimental data. To model the rotating machine efficiently the sliding