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Research Paper

# Effect of air-gap fans on cooling of windings in a large-capacity, high-speed induction motor

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## HIGHLIGHTS

- A 3D numerical analysis was performed to analyze the effects of air-gap fan.
- A novel mapping method considering time and rotation period was introduced.
- Total winding cooling performance was improved by 55% with both side air-gap fans.
- For single fan performance, a rear-side fan was more effective than a front-side fan.

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## ABSTRACT

A 3D computational electromagnetic-thermal coupled analysis was performed to analyze the effects of auxiliary cooling fans, called air-gap fans, on winding cooling in a large-capacity, high-speed induction motor. A novel non-uniform iron loss distribution mapping method considering time and rotation period was introduced to provide more accurate thermal modeling. Winding cooling performance in the motor was calculated and evaluated by considering the variation in thermal-fluid characteristics and thermal flow resulting from the air-gap fans. Results showed that flow rate distributed to the air gap was increased as the stagnant flow disappeared near the air gap because of the air-gap fans. The convective heat transfer coefficient on the winding surface was enhanced by the increased velocity of the internal flow. The heat transfer coefficients at the winding surface and air gap were increased up to 31% and 90%, respectively, due to the increased flow rate. Total winding cooling performance was improved, on average, by 55% with front- and rear-side air-gap fans. For single fan performance, a rear-side air-gap fan was more effective than a front-side air-gap fan.



## 1. Introduction

An induction motor generates mechanical power through the interaction of magnetic fields generated by a winding in a stator and cage bar in a rotor. This non-permanent magnet motor is promising because a shortage of rare-earth metals has become an international issue. However, induction motors also have a thermal problem, like other motor types, with lifespan and efficiency, as they are temperature dependent. The importance of this problem increases steadily as the motor becomes larger and faster. Thus, much research on the thermal characteristics and cooling systems of induction motors has been conducted [1–9].

The design of an appropriate cooling system can be achieved through a heat source analysis of a motor. In an induction motor, heat is generated in the windings, cage bars, stator, and rotor. These heat sources must be controlled to prevent excessive increases in the motor temperature, which will cause a reduction in the lifespan and efficiency of the motor. The insulating sheath for the winding, the most thermally sensitive part of the motor, generally determines the lifespan of the entire motor. Based on the Arrhenius equation, the lifespan is reduced by about half each time the operating temperature of the insulation is increased by 10 °C [1]. Additionally, a lack of cooling performance also has a negative effect on the efficiency of the induction motor, as in a permanent-magnet motor [2]. Thus, it is important to design appropriate cooling systems to improve the lifespan and efficiency of the motor. Air-cooling systems have not been used extensively for motors with high capacities, i.e., over 100 kW, because of their typically insufficient cooling capacity. There have been attempts to use air-cooled cooling systems for large-capacity motors by installing auxiliary internal cooling fans inside the motor to solve the insufficient cooling capacity problem. However, there have been a few studies related to internal cooling fans [9].

The thermal analysis methods for motors are classified as thermal network methods, which are based on thermal resistance, and computational fluid dynamics analysis. The thermal network method

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is more convenient for modeling and has lower computational costs. For this reason, most existing studies on large-capacity induction motors were performed using thermal network analysis methods. Lee et al. [3] performed a thermal analysis of an induction motor having a cooling channel in both the rotor and stator. Malumbres et al. [4] developed the thermal circuit modeling of an induction motor with open self-ventilated cooling system. However, these thermal resistance-based studies assumed the internal flow characteristics of the motor based on experimental or theoretical approaches, without direct analysis. Thus, their methods are not appropriate for a motor with an auxiliary internal cooling fan that causes complex internal flow. Little research has been conducted using computational methods due to the difficulty of the analysis. Trigeol et al. [5] compared the thermal network analysis and CFD analysis results for an induction motor. Komeza et al. [6] developed 3D transient temperature analysis model for a three-phase induction motor. Xie et al. [7] studied 3D temperature estimation for a totally enclosed fan-cooled induction motor with a normal cage bar and a faulty cage bar. However, these studies did not focus on a motor with auxiliary internal cooling fans. Additionally, because these studies considered a motor with low speeds, under 10,000 rpm, and small capacities, less than 100 kW, the results have limited applicability to a large-capacity, high-speed induction motor.

It is important to perform an electromagnetic-thermal coupled analysis to determine the heat generation because heat is generated by electromagnetic phenomena. To improve thermal accuracy, several studies with electromagnetic-thermal coupled analyses used not only the magnitude of the total heat generation but also the distribution information for non-uniform iron loss. Lefik [8] developed an electromagnetic-thermal coupled analysis model in a one-phase induction motor. Fasquelle et al. [9] developed an electromagnetic-thermal coupled analysis model for an induction motor with a cooling fan inside the rotor. However, these studies did not consider the effect of the time period and the physical rotation on the distribution of iron loss.

In this study, a three-dimensional computational electromagnetic-thermal coupled modeling was performed to study the effect of air-gap fans on the winding cooling performance in an induction motor with a large capacity, over 100 kW, and high speed, over 10,000 rpm. A non-uniform iron loss distribution mapping method, considering time and rotation period, was introduced to improve the accuracy of the model. We analyzed the variation in the thermal-flow characteristics of the auxiliary internal cooling fans, called air-gap fans, and quantified the improvement in the winding cooling performance using the air-gap fans.

## 2. Problem formulation of an induction motor

### 2.1. Problem description

Fig. 1 shows the geometry of a large-capacity, high-speed, open-type, air-cooled induction motor with air-gap fans. There are rotor-shaft integrated structures at the center of the motor. The rotor has an inner diameter of 80.80 mm, including 16 copper cage bars, all connected by end rings. Inner and outer diameters of the stator are 83.56 mm and 190.00 mm, respectively. There is an air gap of 1.38 mm between the rotor and the stator. The stator contains 24 slots for the windings (see Fig. 2); each of the slots is filled with insulating paper and winding. As shown in Fig. 1, the stator is surrounded by 30 fins and a fin base for cooling the stator. Finally, the motor is enclosed by the outermost frame structure.

The cooling structure of the induction motor is open-type air cooling. Cooling air enters the induction motor through six inlets on the frame's left side at a constant flow rate of 0.2 $m^3/s$ due to an external fan. This air passes through the gap between the stator/rotor and the duct (cooling channel) consisting of fins and a frame.

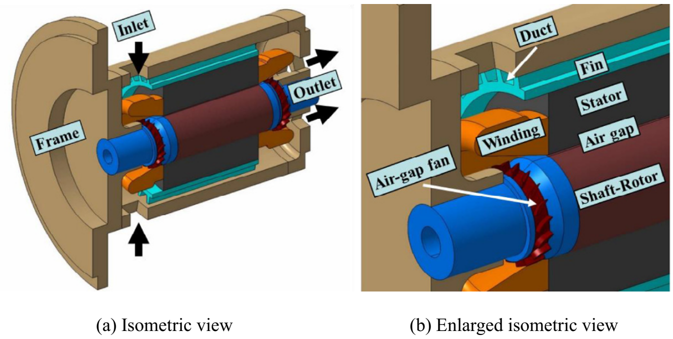


**Fig. 1.** Schematic diagram of an induction motor.

It is discharged through six outlets on the right side of the frame. To supplement the cooling performance of the air-cooled system, an air-gap fan is fixed on the rotary shaft at both ends of the air gap. Each air-gap fan has 18 airfoil-shaped wings, 5.7 mm in height.

### 2.2. Governing equations

The following assumptions were used for the thermal modeling of the induction motor.

1. 3D steady state, turbulent flow
2. Air is an ideal gas
3. Negligible radiation

For the fluid region, the following equations were used to satisfy the conservation laws for mass, momentum, and energy:

Continuity

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

Momentum

$$\frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[(\mu + \mu_t)\frac{\partial u_i}{\partial x_j}\right] \tag{2}$$

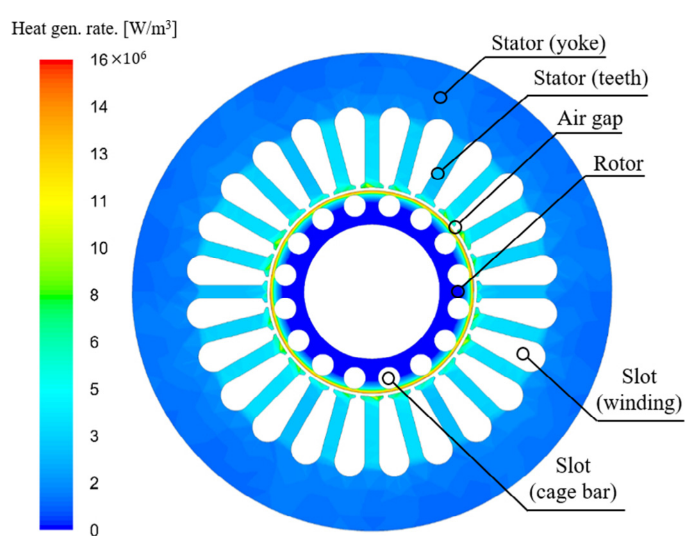


**Fig. 2.** Distribution of volumetric heat generation rate at the stator and rotor.