

Research Article

Optimization of Internal Rotor Cooling Using Variable Fan Configuration and Blade Angles in a Synchronous Reluctance Motor

P. H. Ngo¹
N. Depaiwa¹
T. Pham¹
C. T. Vo²
M. Masomtob³
B. Kerdsup⁴
P. Champa^{4,*}

¹ Department of Mechanical Engineering, School of Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok, 10250, Thailand

² Faculty of Automotive Engineering Technology, Industrial University of Ho Chi Minh City, Ho Chi Minh City, 727900, Viet Nam

³ National Energy and Technology Center (ENTEC), National Science and Technology Development Agency (NSTDA), Pathum Thani, 12120, Thailand

⁴ National Electronics and Computer Technology Center (NECTEC), National Science and Technology Development Agency (NSTDA), Pathum Thani, 12120, Thailand

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Abstract:

This study investigates the cooling efficiency of an internal rotor fan system integrated into a synchronous reluctance motor (SynRM), aiming to optimize key fan configuration parameters. The analysis focuses on the effects of fan blade angle, installation position (front, back, and both), and rotational speed on the motor's thermal behaviour under various operating conditions. The experiment evaluated the cooling efficiency, while the simulation model was used to clarify the effects of air velocity and pressure on cooling performance. The results show that fan blade geometry and positioning influence the heat transfer coefficient. The 60° fan blade configuration, when installed at the rear side, generates the highest cooling airflow through the rotor, reaching 11.31 m³/h at 2000 rpm, it achieves the lowest rotor temperature of 43°C after 10 minutes of cooling. Moreover, increasing the fan's rotational speed from 1000 rpm to 3000 rpm enhances airflow, which improves heat transfer and further lowers rotor temperature. These findings contribute to improved thermal management strategies in SynRM design by demonstrating how integrated fan systems can enhance cooling efficiency through optimized configuration.

Keywords: Internal rotor cooling, Fan blade angle, Fan position, Synchronous reluctance motor (SynRM)

1. Introduction

In recent years, the global shift to electric vehicles (EVs) has accelerated, driven by concerns over climate change, stricter emission regulations, and advances in battery and motor technology. Despite rapid development, there is still room for improvement, with vehicle performance remaining a key research focus [1–4]. Electric machines are central to the powertrain, converting electrical energy into mechanical motion and directly influencing efficiency and driving performance [5]. Among them, the synchronous reluctance motor (SynRM) has attracted interest for its high efficiency, durability, and elimination of rare-earth magnets, which reduces costs and improves supply stability [6]. However, its performance and longevity depend on effective cooling of the rotor and stator. Excessive rotor temperatures can degrade insulation, shorten bearing life, and lower efficiency [7, 8]. Therefore, enhancing rotor cooling is essential to fully exploit the potential of SynRM in EV applications, as it improves efficiency, reliability, and durability under high-load conditions.

* Corresponding author: P. Champa
E-mail address: prasit.champa@nectec.or.th



There are several methods for controlling the temperature of rotor motor. Spray cooling is an effective thermal management technique, particularly for applications requiring high heat dissipation. Garud et al. [9] investigate the thermal management characteristics of electric vehicle driving motors using oil spray cooling, with a focus on spray locations and oil types. The result shows that the lowest temperature of 113.7 °C, maximum torque of 266.72 N.m. In term of liquid cooling method, Alamian et al. [10] reported that internal water flow through a liquid cooled rotor shaft markedly increases heat transfer and lowers rotor temperature compared with conventional designs. Liu and Yan achieved a rotor temperature reduction of about 30 °C using a water cooled external rotor structure [11], while Xu et al. [12] showed that a dual waterway rotor system further reduces rotor temperature and enhances thermal uniformity in high power density machines. Although these methods provide high cooling efficiency, they require additional components such as pumps, tubing, and other auxiliary equipment. These elements contribute to increased system complexity, weight, and energy consumption [13]. In addition, these systems require precise sealing to prevent leaks, which can make them less suitable for applications that need simple and reliable designs.

The coolant does not have to be a liquid; it can also be air, which can still provide remarkable cooling performance. Jaeger et al. [14] developed a fin-assisted air cooling method for a hollow-shaft rotor, reducing magnet temperature by 40 °C at 10,000 rpm. Wu et al. [15] showed that airflow cooling of a hollow-shaft rotor shifted hot spots to the shaft surface and reduced temperature from 80.1 °C to 70.53 °C under the tested heat load. Reinap et al. [16] study direct air cooling of rotor windings using a conjugate heat transfer model and show that increasing internal cooling surfaces and optimizing airflow distribution significantly improves cooling performance and keeps rotor temperatures within safe limits. Yuan et al. [17] investigate the effect of rotor blade angle on stall onset in an axial fan using CFD, showing that blade angle influences flow separation, pressure distribution, and vortex development. Hyeon et al. [18] compared an open EM with no flow guide, a disk-type, and a ring-type flow guide, finding that the ring-type achieved the highest HTC (149.7 W/(m²·K)), followed by the disk-type (147.5 W/(m²·K)), while the case without a flow guide showed much lower performance (120.4 W/(m²·K)). These studies mainly focused on external cooling or motor geometry modifications, with limited research on how internal fan geometry, especially blade angle and fan position, directly affects aerodynamic performance when integrated with a slotted SynRM rotor.

This study aims to address this gap by optimizing internal fan configuration with different blade angles, ranging from 20° to 70°, and fan position installation to enhance rotor cooling without changing the motor structure, offering a simple and practical solution. The cooling performance of each configuration is experimentally evaluated under controlled conditions, and numerical simulations are performed to provide further insight into airflow characteristics and heat transfer behavior. The results are expected to contribute to the development of more efficient rotor cooling solutions for high performance electric machines.

2. Methodology

2.1 Design and Manufacture Cooling Fans

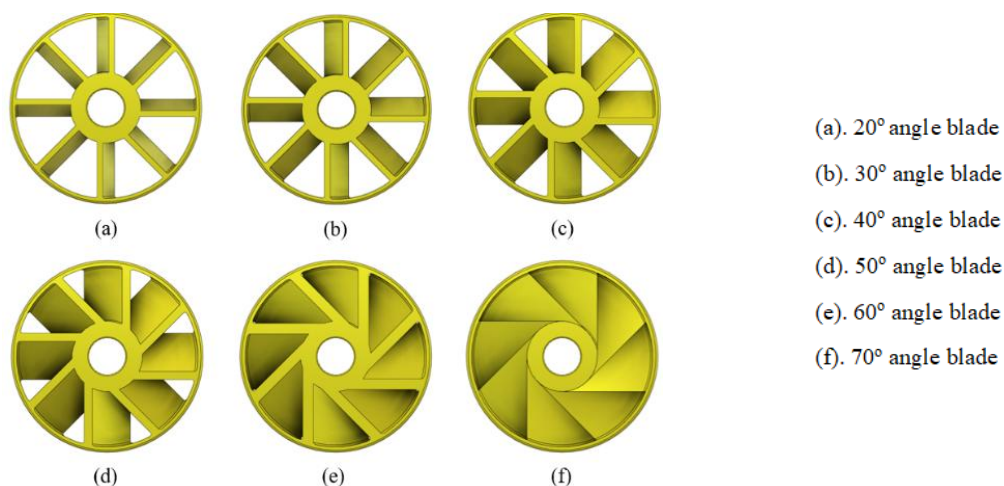


Fig. 1. The fan blades 3D design.

The cooling fan was designed using a 3D computer aided design (CAD) software to optimize airflow within the rotor of a synchronous reluctance motor. A parametric modeling approach was applied, enabling systematic variation of the blade inclination while maintaining the same outer and inner diameters, 82 mm and 17 mm respectively. In this study, six fan configurations were developed with blade angles of 20°, 30°, 40°, 50°, 60°, and 70°, as illustrated in Fig. 1. The blade angle range of 20° - 70° was chosen to cover typical low to high pitch axial fan configurations, allowing evaluation of airflow enhancement and potential aerodynamic losses at excessive pitch angles. The hub diameter was designed to enhance the blade strength, with a thickness of 3 mm, and the number of blades was 8. The blade count (e.g., 5–12 blades) is often selected to balance airflow, pressure rise, mechanical stability, and low noise levels in axial fan designs [19]. These parameters were kept constant to isolate the effect of blade angle as the primary variable.

The fan models with varying blade angles were fabricated using a fused deposition modeling (FDM) 3D printer, as shown in Fig. 2. Polylactic acid (PLA) filament, shown in Table 1, was selected for its high stiffness, ease of processing, and adequate thermal resistance for the intended motor operating conditions. The printed fans had smooth surfaces with minimal layer lines, as shown in Fig. 3. They were printed as solid parts to ensure sufficient strength when rotating at high speeds. Dimensional tolerance was maintained within ± 0.3 mm, ensuring accurate fitting into the rotor slot without additional machining.

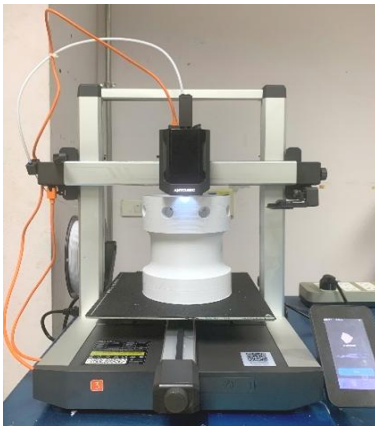


Fig. 2. 3D printer machine.



Fig. 3. The printed fan blade with 60°.

Table 1: Polylactic acid filament properties

Parameters	Value
Density	1240 kg/m ³
Young's Modulus	3.5 GPa
Tensile Strength	70 MPa
Melting Temperature	180 °C
Heat Deflection Temperature	85 °C
Thermal conductivity	0.13 W/m-K

2.2 Experiment Setup and Test Condition

The experimental setup, shown in Fig. 4 and Fig. 5, was designed to evaluate the cooling performance of the rotor under different fan configurations and blade angles. It should be noted that the experimental system evaluates the surface temperature of the rotor. The system consists of a specific synchronous reluctance motor (SynRM) rotor configuration featuring six axial cylindrical ventilation holes equipped with a heating element (cartridge heater 350 W) to heat the rotor up 60 °C then start the driving motor to rotate for 10 minutes. An inverter controls the motor speed, while a tachometer measures the rotational speed with an accuracy ± 2 %. An anemometer is used to measure the air velocity, which is then employed to calculate the Reynolds number using Eq (1).

$$Re = \frac{\rho \cdot V \cdot L}{\mu} \quad (1)$$

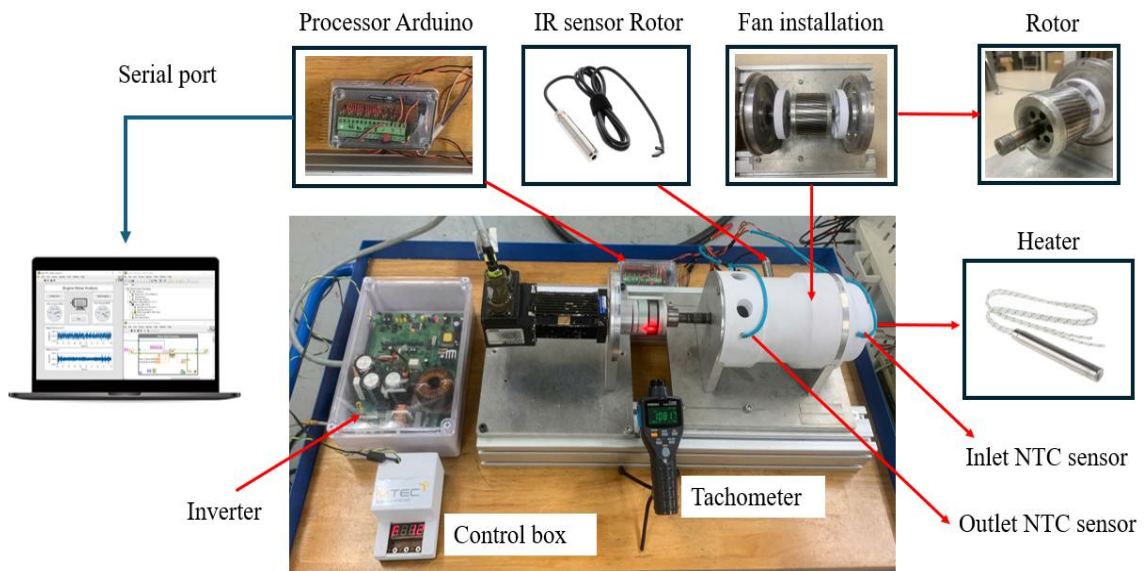


Fig. 4. The experimental setup.

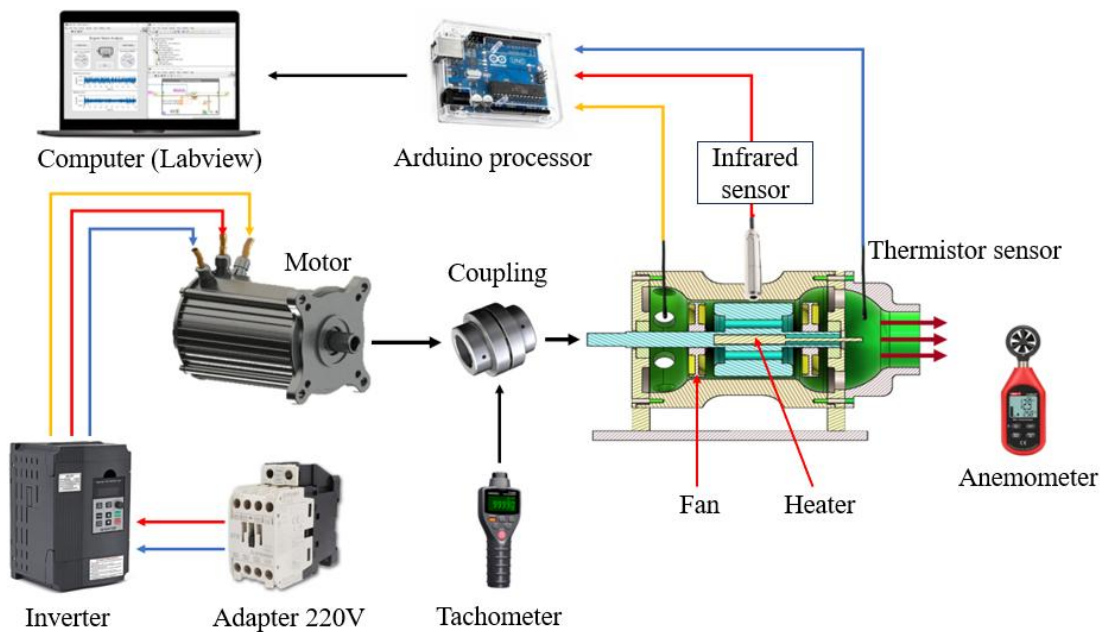


Fig. 5. Schematic of the experimental setup.

Air inlet and outlet temperatures are monitored using thermistor sensors (± 1 °C), and an infrared (± 1 °C) sensor measures the rotor surface temperature without physical contact, all the values collected from the sensors were validated using a UT301+ Series infrared thermometer to verify their accuracy. The entire measurement system was connected to an Arduino-based processor, which collected temperature data via a serial port at a sampling rate of 5 Hz and transferred it to a computer for real-time monitoring and data logging.

A total of 54 test cases were conducted to evaluate the cooling performance of the synchronous reluctance motor under varying fan configurations, as shown in Table 2. Each test case was repeated three times to ensure the consistency of the results. This full factorial design enabled a comprehensive assessment of the individual and combined effects of these factors on rotor cooling efficiency.

Table 2: Condition Test

The angle of fan blade	Fan Position	Speed of Rotor [rpm]
20°	Front	1000
30°	Rear	2000
40°	Both	3000
50°		
60°		
70°		

2.3 Simulation Technology

2.3.1. Meshing

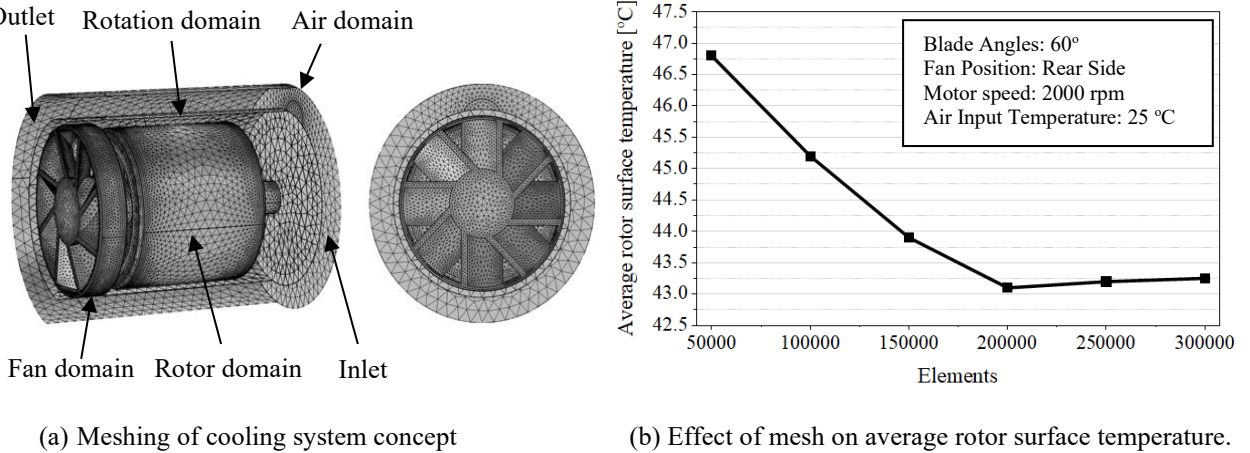


Fig. 6. Meshing of rear side simulation setup.

Fig. 6 illustrates the meshing configuration of the rear-side cooling simulation and the corresponding mesh independence study. As shown in Fig. 6a, the computational domain consists of the fan domain, rotor domain, rotation domain, and surrounding air domain, with clearly defined inlet and outlet boundaries to capture the airflow through the cooling system. An unstructured mesh is applied to accurately resolve the complex geometry of the fan blades and rotor surfaces. Fig. 6b presents the effect of mesh density on the average rotor surface temperature at a blade angle of 60°, a fan positioned on the rear side, a motor speed of 2000 rpm, and an inlet air temperature of 25 °C. The results indicate that the predicted rotor temperature converges as the number of elements exceeds approximately 200,000, confirming that the selected mesh provides a good balance between computational accuracy and efficiency.

2.3.2. Step Simulation Running Techniques

Table 3: Reynolds number calculations

Motor speed [rpm]	Air velocity [m/s]	Reynolds number	Type of flow
1000	1.4	3584	Turbulent flow (>2300)
2000	2.5	6400	Turbulent flow (>2300)
3000	3.25	8320	Turbulent flow (>2300)

As shown in Table 3, all Reynolds numbers exceed 2300; therefore, turbulent flow is assumed in all simulations. Results from the turbulent flow analysis, including the air velocity and pressure fields, were used as the initial conditions for the subsequent heat transfer calculations. This method was applied to reduce computational load and shorten simulation time by avoiding the simultaneous solution of all components. The simulation procedure is conducted following the flowchart shown in Fig. 7.

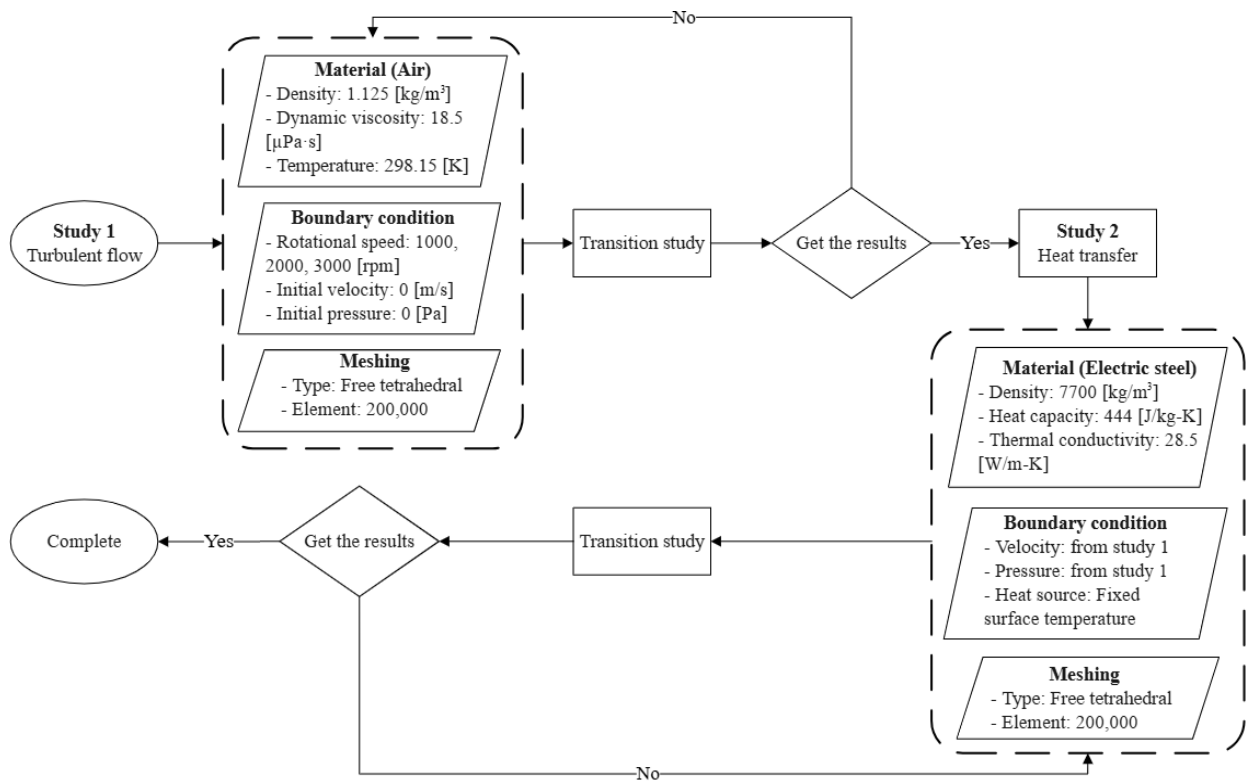


Fig. 7. Step running of simulation process.

3. Result and Analysis

3.1 Simulation Validated via Experiment

To validate the accuracy of the thermal simulation model, experimental data were collected under various cooling conditions and compared with simulation results. Fig. 8a shows the rotor temperature over time for different fan positions at a constant motor speed of 2000 rpm and an air input temperature of 25 °C. In terms of Fig. 8b shows the rotor temperature over time for different motor speeds with the fan fixed at the rear position and an air input temperature of 25 °C. All these cases were used the fan with the blade angles is 60°.

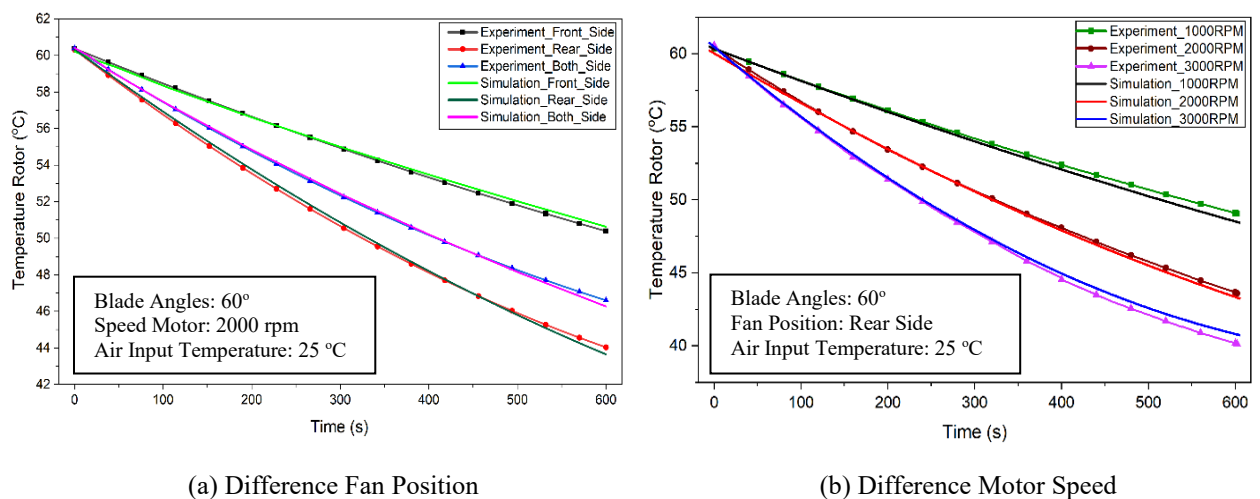


Fig. 8. Rotor temperature comparison between simulation and experiment.

The comparison between simulation and experimental results demonstrates a high level of agreement across various test conditions, including different fan positions and motor speeds. The close alignment in temperature profiles confirms that the simulation model accurately captures the thermal behavior of the rotor under forced convection. This consistency confirms the reliability of the model and supports the model's applicability to explain the influence of air velocity and pressure fields on cooling performance in similar cooling configuration.

3.2 Effect of Fan Position on Rotor Cooling

Fig. 9a presents experimental rotor temperature profiles under different fan configurations at a constant blade angle of 60° and motor speed of 2000 rpm. The air input temperature was maintained at 25 °C throughout the test.

After 600 seconds, the rotor temperature without fan assistance remained at 54.13 °C. When cooling was applied from the front side only, the temperature decreased to 50.66 °C. Rear side cooling resulted in the lowest temperature of 43.20 °C, indicating superior heat dissipation in this configuration. Interestingly, applying fans to both sides led to a final temperature of 45.68 °C, which is higher than the rear side only setup. This suggests that simultaneous front and rear airflow may cause aerodynamic interference, reducing the overall cooling efficiency compared to rear-only cooling. In Fig. 9b, the heat distribution of the rotor is evenly distributed, with no excessive temperature gradients observed within the rotor when fan cooling is applied.

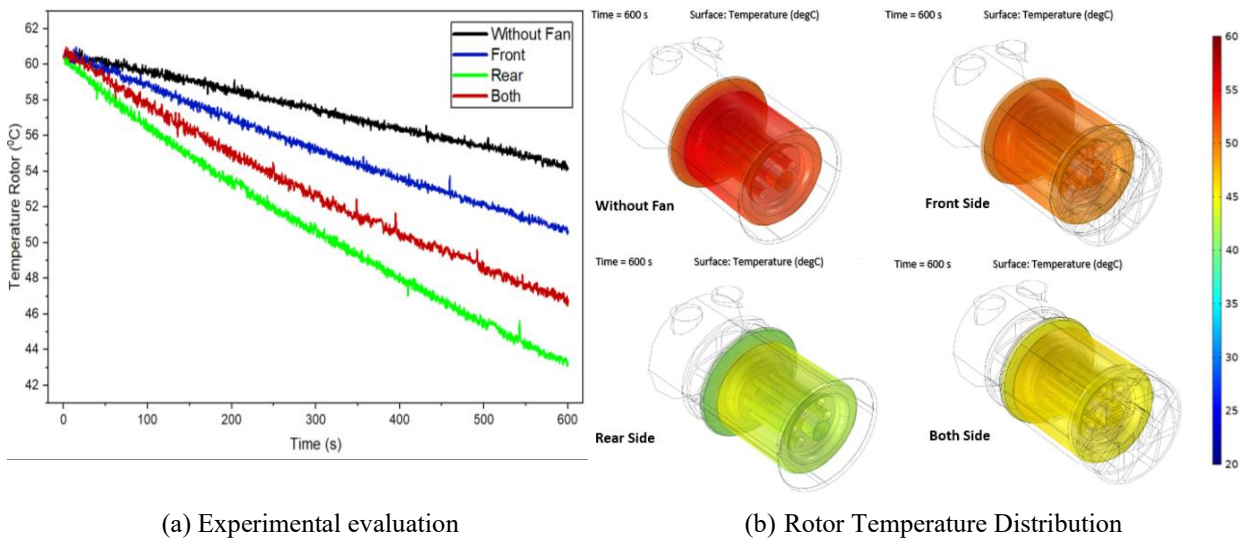


Fig. 9. Effect of Fan Position on Rotor Cooling Performance.

Fig. 10 illustrates the simulated velocity and pressure distributions for three fan configurations: front, rear, and both sides. In the rear-side configuration, the airflow penetrates more deeply into the center rotor region, exhibiting higher velocity magnitudes and a stronger pressure gradient, which enhances forced convection and improves heat removal. In contrast, the front-side configuration generates lower airflow velocities and a weaker pressure field, limiting its cooling performance. The airflow in this setup primarily passes through the air gap between the rotor and stator. This behavior may result from the centrifugal force generated by the front fan blades, which directs the air radially outward and reduces the flow penetration into the rotor's inner region.

Both side configuration increases overall airflow but introduces complex interactions between opposing streams. Although the configuration enhances the amount of air passing through the rotor region, most of the airflow tends to move along the air gap between the rotor and stator rather than penetrating the inner rotor area, which limits its cooling contribution to the core region. These disturbances may reduce the effectiveness of heat transfer despite the higher flow rate. The simulation results are consistent with experimental findings, where rear-side cooling showed the best thermal performance.

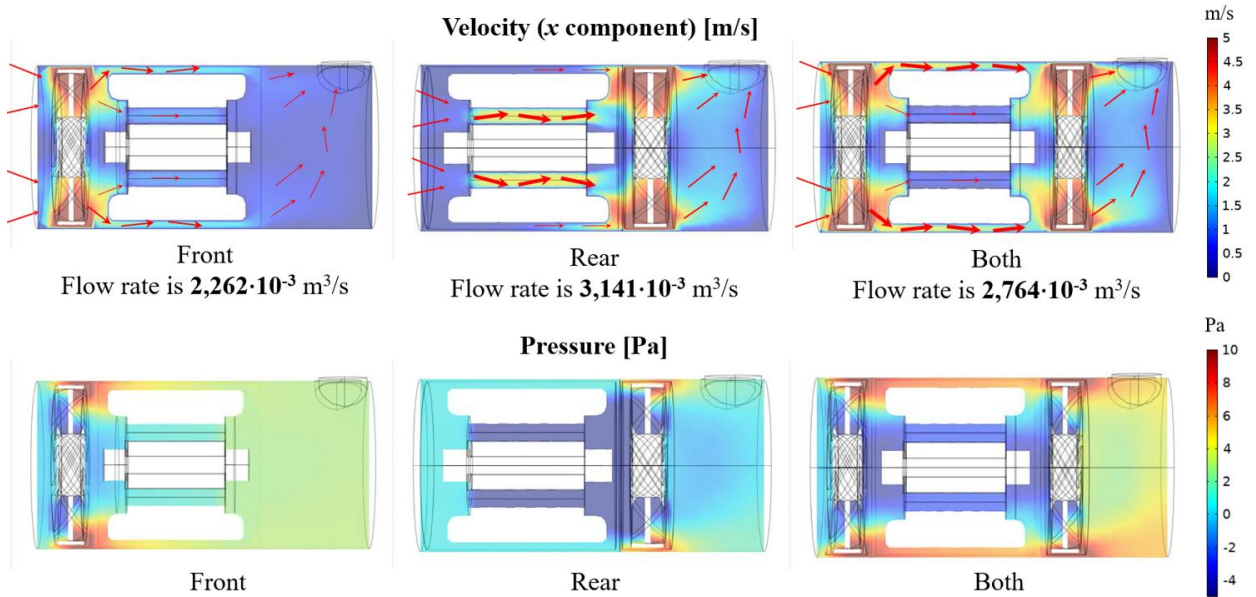


Fig. 10. The simulated velocity and pressure distributions of different fan positions.

3.3 Effect of Blade Angles on Rotor Cooling

Fig. 11 illustrates the effect of blade angle on rotor temperature under forced convection, with the fan positioned at the rear side. All tests were performed at a motor speed of 2000 rpm and an air input temperature of 25 °C. After 600 seconds, the rotor temperature decreases as the blade angle increases from 20° to 60°, reaching a minimum temperature of 43.19 °C at 60°. At smaller angles, the airflow is weaker, resulting in higher final temperatures 48.59 °C at 20° and 47.34 °C at 30°, respectively. Although increasing the angle enhances cooling, a slight temperature rise to 44.02 °C is observed at 70°, the suction force generated by the fan starts to weaken at this angle. These findings suggest that a blade angle of 60° offers optimal cooling performance in the given setup.

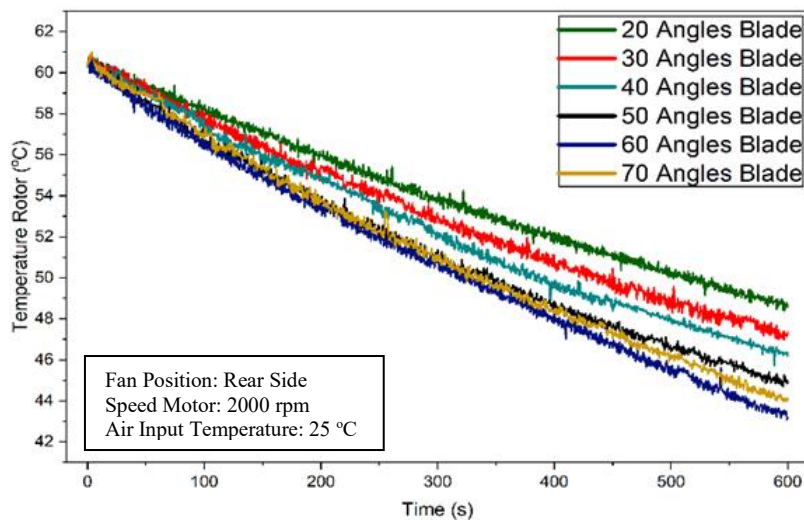


Fig. 11. Experimental Rotor Cooling for Various Blade Angles.

Fig. 12 illustrates the simulated velocity fields for different blade angles ranging from 20° to 70°, under the same operating conditions: rear fan position, motor speed of 2000 rpm, and air input temperature of 25 °C.

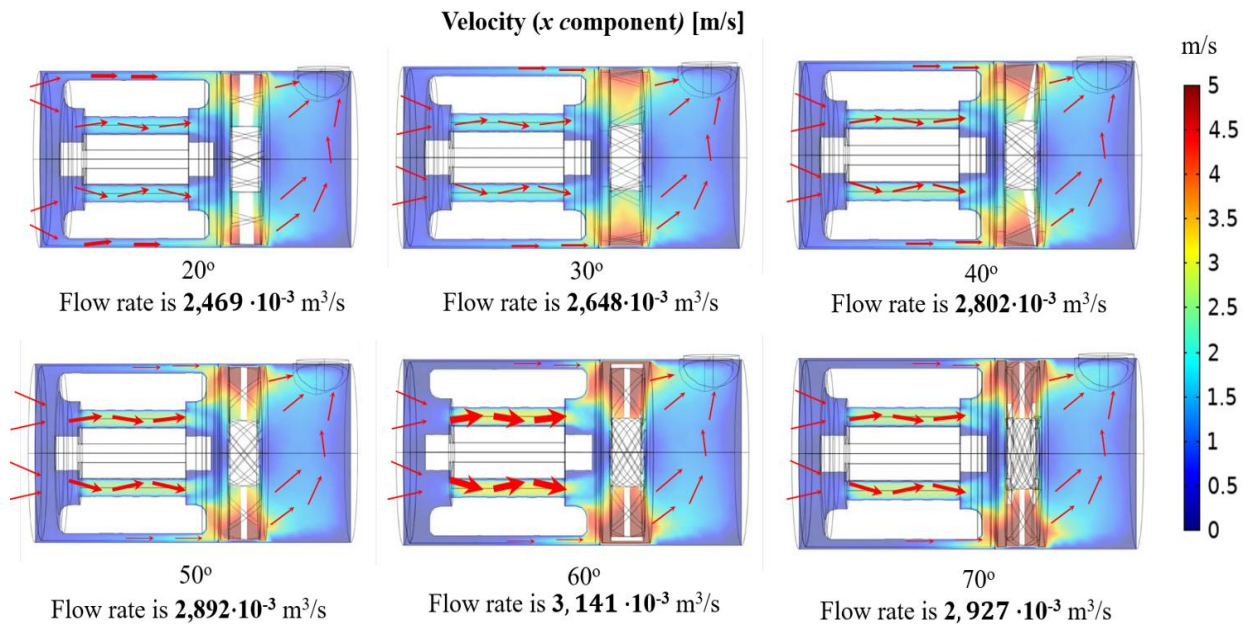


Fig. 12. The simulated velocity field with different angle blades.

In the velocity magnitude plots, at smaller blade angles 20° , the air flow passing through the rotor remains relatively weak, with only a minor portion flowing through the air gap. A small pitch angle produces a limited axial pressure gradient, resulting in weaker suction and reduced through flow. When the blade angle increases to 60° , both the airflow velocity and volumetric flow rate through the rotor significantly improve, especially at the central region, where the high velocity zone becomes more prominent. As the pitch increases, the axial component of the aerodynamic force becomes stronger, thereby enhancing the pressure difference and improving the flow across the rotor. Nevertheless, excessive blade inclination can induce boundary layer separation and flow blockage near the blade surfaces, leading to a drop in flow efficiency at 70° . Therefore, the blade angle of approximately 60° appears to be the optimal configuration for achieving high axial flow velocity and stable airflow through the rotor.

3.4 Effect of Motor Speed on Rotor Cooling

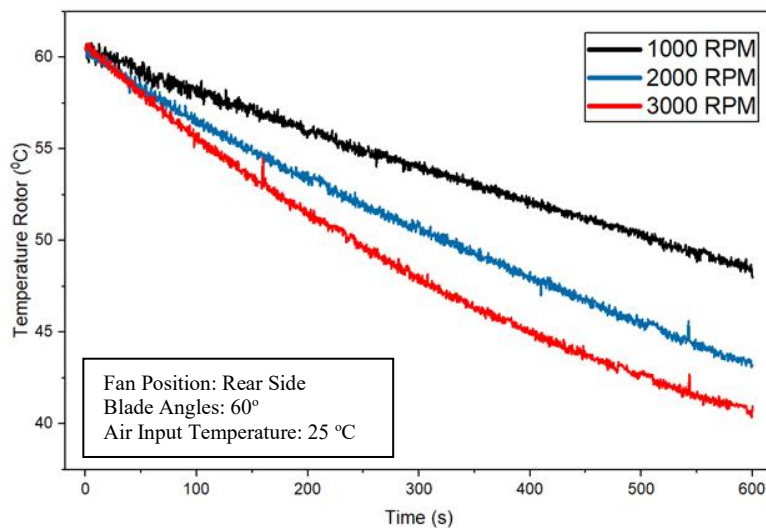


Fig. 13. Experimental Rotor Cooling for Various Motor Speeds.

Fig. 13 illustrates the effect of motor speed on rotor temperature over a 600s cooling period, with the fan positioned at the rear side and an air input temperature of 25 °C. Three motor speeds were tested: 1000 rpm, 2000 rpm, and 3000 rpm. The results show a clear trend: higher motor speeds lead to more effective cooling.

At 1000 rpm, the rotor temperature decreases gradually, remaining above 50 °C for most of the duration. At 2000 rpm, the temperature drops more significantly, indicating improved convective heat transfer. The best performance is observed at 3000 rpm, where the rotor temperature reaches its lowest value by the end of the test. This enhancement in cooling efficiency can be attributed to the increased airflow rate generated by higher fan speeds, which promotes stronger forced convection around the rotor.

4. Conclusion

This study investigated the thermal performance of an internal rotor cooling system in a synchronous reluctance motor by varying fan blade angles, installation positions, and rotor speeds. Experimental results, supported by numerical simulations, demonstrated that fan configuration significantly influences cooling effectiveness. Among all tested setups, the 60° blade angle installed at the rear achieved the lowest rotor temperature, highlighting its superior heat dissipation capability. Increasing the rotor speed further enhanced forced convection, leading to more effective cooling.

This study can serve as a foundation for developing lightweight, air-cooled traction motors with low cost and reliable thermal management solutions for high performance electric machines, particularly in electric vehicle applications. Compared with conventional external air-cooling methods, which primarily dissipate heat from the motor housing and offer limited effectiveness for rotor cooling, the proposed internal fan-based approach directly enhances airflow through the rotor interior. The findings confirm that optimized fan blade geometry and positioning can substantially improve rotor cooling, thereby simplifying complex cooling systems without requiring additional external components. Future work will focus on refining fan structures, investigating long-term durability under real driving conditions, and exploring hybrid cooling approaches that integrate internal airflow management with advanced materials.

Nomenclature

ρ	density of air, kg/m ³
μ	dynamic viscosity of air, N·s/m ²
L	pipe diameter, m
V	air velocity, m/s
<i>SynRM</i>	Synchronous Reluctance Motor
<i>PLA</i>	Polylactic Acid
<i>FDM</i>	Fused deposition modeling

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