



RESEARCH ARTICLE

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DESIGN OPTIMIZATION AND PERFORMANCE EVALUATION OF VENTURI DUCT-INTEGRATED COOLING SYSTEMS FOR PERMANENT MAGNET SYNCHRONOUS MOTORS IN ELECTRIC TWO-WHEELERS APPLICATIONS

D Roshan¹, C Dineshkumar*², N S Shafeer Ahmed³, Mohamed Jaheen⁴, Mohammed Rizwan⁵

^{1,2,4,5}Department of Automobile Engineering, B S Abdur Rahman Crescent Institute of Science and Technology, Chennai, Tamil Nadu, India.

³Department of Civil Engineering, B S Abdur Rahman Crescent Institute of Science and Technology, Chennai, Tamil Nadu, India.

¹<https://orcid.org/0009-0002-0839-422X>, ²<https://orcid.org/0000-0002-2393-5293>, ³<https://orcid.org/0000-0001-6910-9985>,

⁴<https://orcid.org/0009-0005-6935-7272>, ⁵<https://orcid.org/0009-0003-7371-1997>

Email: roshanindia@gmail.com, *contactdinesh90@gmail.com, shaffircrescent@gmail.com, jaheenmohamed6@gmail.com, mohriz3116@gmail.com.

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ABSTRACT

Effective thermal management is very important for making Permanent Magnet Synchronous Motors (PMSMs) more efficient, reliable, and lasting, especially in electric two-wheelers. This study examines the design of a cooling system that uses a Venturi duct to remove heat from a 5 kW PMSM motor more effectively. The Venturi duct was specially designed to increase airflow and improve the removal of heat from the motor housing. The study used Computational Fluid Dynamics (CFD) simulations under normal operating conditions, which included an inlet airflow speed of 3 m/s and an ambient temperature of 30 °C. It looked at how air moves, the temperature of the motor's surface, and how heat is transferred. The results showed that the Venturi duct creates more even airflow and lowers the motor's surface temperatures far more than without the duct. The study also shows how the shape of the duct affects cooling performance, proving that adding a Venturi duct is a cost-effective, small, and dependable way to manage heat in PMSMs used in electric two-wheelers. These findings help in creating better ways to control temperature, which in turn improves the motor's life and performance in future electric vehicles.



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I. INTRODUCTION

Effective thermal management is important for improving the performance and lifespan of electric vehicle motors. Computational Fluid Dynamics (CFD) simulations have given useful information about how heat is created and removed in Permanent Magnet Synchronous Motors (PMSMs). By improving cooling airflow paths and using better materials, these motors can work at much lower temperatures, which makes them more efficient. Different cooling methods, like forced air and liquid cooling, are important for keeping motors reliable in tough conditions. This research shows that it's important to balance how complicated a cooling system is with how well it works to create practical and efficient solutions [1]. CFD studies on brushless DC (BLDC) motors have found important hotspots and shown that changing airflow patterns can lower peak temperatures, which improves motor reliability and efficiency [2]. Also, simulations of PMSM cooling strategies show that redesigning coolant channels helps reduce operating temperatures, allowing motors to perform better in harsh environments [3]. This highlights the need for cooling designs that are made specifically for each motor setup. Moreover, detailed thermal models confirm that increasing airflow speed improves heat removal, and experimental data back up the accuracy of these simulations [4]. Building on this, the paper also looks at how cooling channel design affects the thermal behaviour of BLDC motors in electric vehicles, using CFD to optimize channel sizes for the best heat dissipation.

The optimized channels help reduce motor temperature and thermal stress. This improves overall motor reliability and efficiency. The study underscores how geometric changes can enhance cooling effectiveness [5]. This research compares various cooling techniques for PMSM motors in EVs using CFD analysis. Liquid cooling is shown to better control temperatures compared to air cooling. Effective cooling directly influences motor efficiency and helps prevent overheating. The study highlights the need for advanced cooling solutions in high-performance motors. It recommends liquid cooling for sustained motor operation [6]. The study evaluates how rising motor temperatures reduce efficiency due to increased electrical resistance. It proposes cooling methods to mitigate thermal losses and sustain performance. Simulations reveal that managing temperature is key to maximizing energy efficiency. Better thermal control can extend battery life and vehicle range. This emphasizes the link between temperature regulation and motor efficiency [7]. This paper models heat transfer within EV motors under various load scenarios to improve design understanding. Results indicate that accurate thermal modelling is critical for predicting motor behaviour.

Implementing cooling improvements based on these insights enhances durability. The study integrates thermal and electrical factors for comprehensive motor analysis. It suggests a holistic design approach for improved performance [8]. The authors examine design modifications for BLDC motors to improve thermal management. CFD results highlight areas where traditional designs fail to cool effectively. Introducing new cooling paths reduces hotspot formation and thermal stress. The improved design leads to better reliability and higher power output. This study provides actionable improvements for motor design in electric vehicles [9]. This research validates CFD-based thermal analysis with experimental testing on EV motors. The results confirm that simulation accurately predicts temperature patterns and cooling efficiency. Different cooling configurations are assessed to find the most effective solutions. The study stresses the importance of real-world testing to support simulation results. This combined approach helps optimize thermal management in EV motors [10].

The use of advanced materials optimized through ANSYS significantly improved suspension durability, strength, and riding comfort in two-wheelers, contributing to better safety and performance [11]. A good method to compare various cooling techniques for PMSMs shows that improved cooling designs can greatly reduce motor temperatures [12]. It looks at the main cooling methods used for PMSMs and how well they work in real situations, giving clear information on which ones offer better efficiency and fit well with more advanced uses [13]. A new intake manifold design improved airflow and combustion efficiency. Trials with alternative fuels showed lower emissions and better performance in diesel engines [14]. Studies on review different air-cooling strategies for PMSMs by comparing analytical and experimental results [15]. In machining, using metal bases with rubber layers helped reduce tool vibrations, which improved process stability and tool life [16]. 3D model that shows both fluid flow and heat movement for an in-wheel PMSM.

They run simulations for different cooling methods, and show which cooling setups work best to keep temperatures from rising too much when the EV is under varies load [17]. Crash tests on five-point seat belts showed better protection during front collisions, lowering injury risks [18]. Using IoT in the auto industry has pushed digital changes, making vehicles more automated, connected, and efficient [19]. Recent studies on simple car models with side vortex generators showed a decrease in aerodynamic drag and better vehicle stability, which together help improve driving performance [20]. At the same time, a lot of research has been done to create good cooling solutions for Permanent Magnet Synchronous Motors (PMSMs), to keep their performance and reliability high even when they are working hard. Different cooling duct setups, like parametric designs and water-jacket systems, have been looked into to make heat removal more efficient and stop parts from getting too hot. Also, detailed reviews of air-cooling and hybrid cooling methods highlight how important they are for keeping motor temperatures steady.

All these findings show that well-designed cooling systems are key to making motors more efficient, lasting longer, and working reliably in tough situations. Moreover, the practice of variable geometry micro channel heat exchangers improves the effectiveness of automotive air conditioning systems. These improvements lead to better general vehicle performance and comfort [21-24]. The research found that a real-time vehicle monitoring system model had designed and analysis, the design can find problems early and stop unexpected mechanical issues, and it also helps drivers react faster with timely warnings, which makes driving safer [25]. The research showed that aloe vera and hemp mixed fibers make bio-composites stiffer without adding much weight, and their ability to handle heat and movement makes them good for lightweight vehicle parts [26].

The work showed that using both rivets and glue in GRP joints makes them stronger and spreads the force better, which lowers the risk of the joints breaking compared to using just one method [27]. The analysis showed that the shape of a vehicle chassis affects how stress is spread and how much weight it can handle, and using different composite materials can cut weight while keeping the structure strong [28]. The test results proved that a system that watches a driver's condition can accurately spot when they're tired or not paying attention, and the warnings from the system help reduce the chance of accidents in vehicle [29]. The survey showed that riding a motorcycle for long periods causes both physical tiredness and mental exhaustion, and making the bike more comfortable along with taking planned breaks can greatly reduce how tired riders feel, the design used for the setup was analysed and valudated in real time for measuring the accurate results [30].

II. MATERIALS AND METHODS

The methodology to design, improve, and study the cooling system that uses a venturi duct for a 5 kW PMSM motor in electric two-wheelers is explained below:

III MOTOR AND COOLING REQUIREMENT ANALYSIS

- A 5-kilowatt permanent magnet synchronous motor, which is often used in electric two-wheelers, was chosen as the test case.
- The motor's rated operating conditions, thermal limits, and critical components were analyzed to determine heat dissipation requirements.
- Ambient conditions were considered at 30 °C, representing typical urban operating scenarios.

IV. VENTURI DUCT DESIGN

- A venturi duct geometry was designed to accelerate airflow and enhance convective heat transfer around the motor housing.
- Key design parameters included the inlet diameter, throat diameter, duct length, and expansion angle.
- The design ensured a balance between airflow acceleration and compact integration with the two-wheeler motor casing.

V. COMPUTATIONAL MODELLING

- The PMSM motor and venturi duct assembly were modelled in a CAD environment.
- Surface and fluid domains were created to define air flow passages around the motor.
- Boundary conditions were set to simulate a steady airflow of 3 m/s entering the venturi duct, with ambient temperature maintained at 30 °C.

VI. CFD SIMULATION SETUP

- CFD simulations were performed using appropriate software (e.g., ANSYS Fluent).
- The air was treated as an incompressible fluid with constant properties at ambient conditions.
- Turbulence was modelled using the k- ϵ model to capture airflow behaviour in the duct.
- Heat generation from the motor was applied based on rated power loss calculations.

VII. ANALYSIS AND PERFORMANCE EVALUATION

- Simulations provided airflow velocity distribution, temperature contours, and heat flux across the motor surface.
- Key performance metrics included motor surface temperature reduction, heat transfer coefficient, and airflow uniformity.
- Comparative analysis was performed with a baseline case (motor without venturi duct) to quantify improvement.

VII. OPTIMIZATION CONSIDERATIONS

- Parametric variations of duct geometry (throat diameter, inlet/outlet angles, and duct length) were analyzed to identify the configuration with maximum cooling effectiveness.
- Optimized design ensured minimal pressure drop while achieving significant thermal performance enhancement.

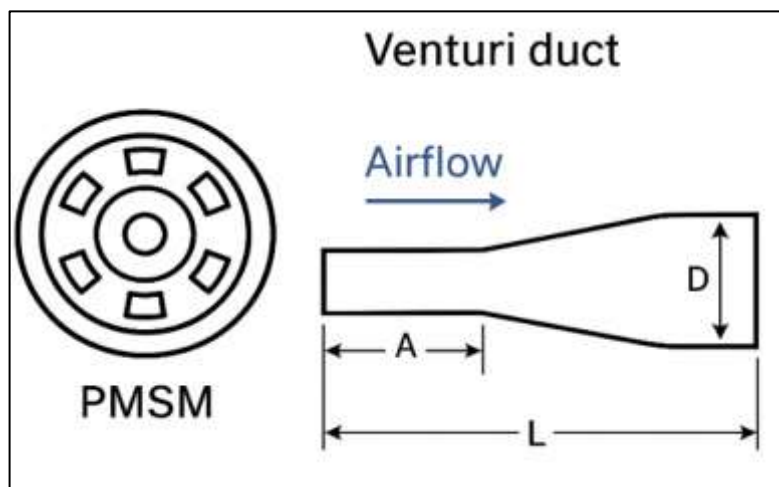


Figure 1: Simple schematic layout of venturi duct of PMSM.

Source: Authors, (2025).

The schematic shows a Venturi duct designed for a PMSM (Permanent Magnet Synchronous Motor) cooling system. The duct tapers from a smaller inlet (A) to a larger outlet (D), creating an accelerated airflow across the motor. The air enters from the left, passes over the motor, and exits through the expanded section, enhancing forced convection and improving thermal management. The total length of the duct is called L, with A showing the width at the beginning and D showing the width at the end. This setup helps guide and boost the airflow around the motor, which keeps the motor running at the right temperature. Table 1 lists the material properties of the permanent magnet synchronous motor.

IX. DATA AND MOTOR DESIGN

Motor Type: Surface-mounted PMSM.

➤ **Key Dimensions:**

Stator outer diameter: 120 mm

Rotor diameter: 100 mm

Axial length: 60 mm

Air gap: 0.5 mm.

➤ **Cooling Ducts:**

Number: 1(Design)

Cross-sectional area: 20, 25, 30mm² each

Positioned evenly around the stator circumference.

➤ **Operating Conditions:**

Rotational speed: 2000-3000 rpm

Heat generation (losses): 120 W (distributed in stator windings and rotor magnets)

Air inlet velocity: 3 m/s and Ambient temperature: 30°C.

Table 1: Material Properties of Permanent Magnet Synchronous Motor (PMSM).

Solid Properties					
Part Name	Material Name	Density (kg/m ³)	Specific Heat (J/kgK)	Thermal Conductivity (W/mK)	
Stator Iron	M36	7872	448	28	
Stator Winding	Enamelled Copper	8933	385	349	
Rotor Iron	M36	7872	448	28	
Rotor Plate	M36	7872	448	28	
Housing	ADC 12	2820	963	92	
Front & Rear Cover	ADC 12	2820	963	92	
Magnet	NdFeB-N40SH	7500	460	7.6	
Bearing	Stainless Steel Casing	7872	470	46	
Shaft	SAE J403 1045	7872	486	50.9	
PCB	FR4	1450	1050	0.4	
Sensors	Polyamide 66 GF30	0.25	1140	1100	
Stator Paper	Nomex	1380	1200	0.157	
Fasteners	Steel	7872	486	50.9	
Magnetic Sensor	NdFeB-Magnet	7500	460	7.6	
Fluid Properties					
Part Name	Material Name	Density (kg/m ³)	Specific Heat (J/kg·K)	Thermal Conductivity (W/m·K)	Dynamic Viscosity (kg/m·s)
Enclosure	Air	Air variable	Air variable	Air variable	Air variable

Source: Authors, (2025).

X. DESIGN AND ANALYSIS OF PMSM MOTOR

X.1 AXIAL VENTURI DUCT DESIGN ANALYSIS WITH PMSM

From Figure 2 and 3, the CFD analysis of the axial Venturi duct shows how the airflow helps cool the motor parts. The duct has a wide part at the front and a narrower section in the middle, which makes the air move faster as it goes toward the motor. This faster-moving air helps remove heat more effectively from the magnets and bearings. The results show that the magnet temperature is around 58°C in the hottest area and slowly goes down as the air moves through, proving that the duct is good at cooling. For the bearings, the airflow helps keep the temperature in important areas low, keeping them within a safe range of about 51-58°C. Overall, the Venturi duct helps provide even cooling and stops the motor parts from getting too hot.

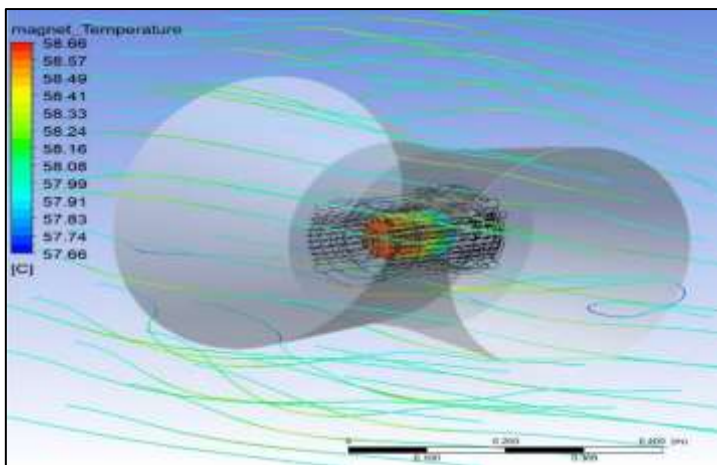


Figure 2: Temperature variation of Magnet.
Source: Authors, (2025).

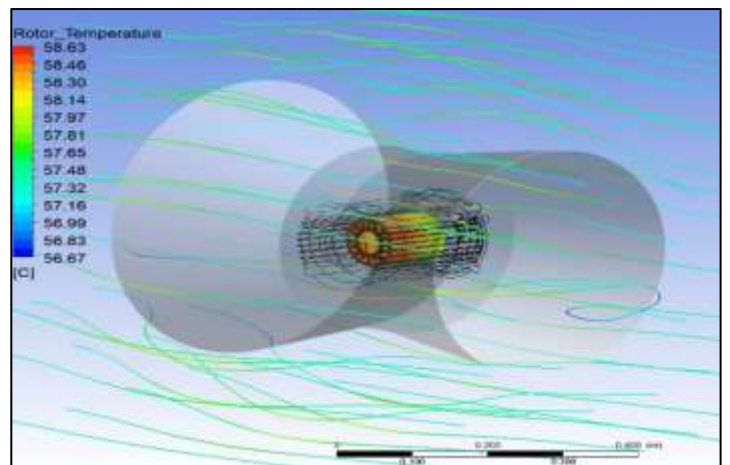


Figure 4: Temperature variation of Rotor
Source: Authors, (2025).

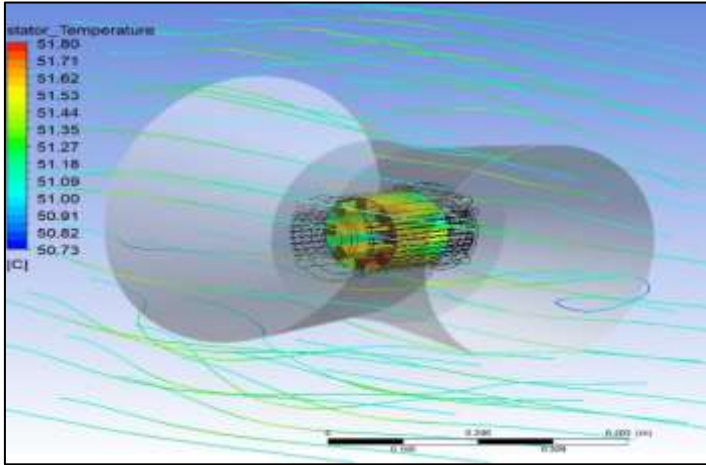


Figure 3: Temperature variation of Bearing.
Source: Authors, (2025).

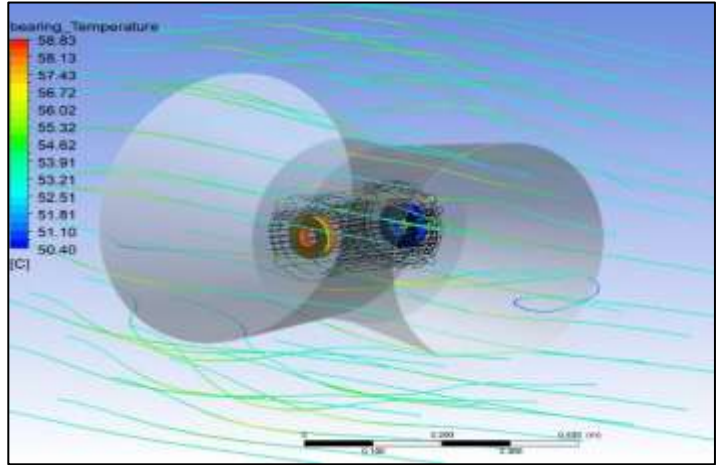


Figure 5: Temperature variation of stator.
Source: Authors, (2025).

Figure 4 and 5, shows the CFD analysis of the axial Venturi duct, and it also shows how temperature is distributed across the rotor and stator surfaces. On the rotor side, the highest temperature is about 58.6 °C in the center area. The airflow inside the Venturi duct helps take away heat, which makes the temperature go down as the air flows through the system. This cooling keeps the rotor at a steady temperature, even in parts where more heat is produced. On the stator side, the temperatures are lower and more consistent, ranging from 50.7 °C to 51.8 °C. The faster airflow through the Venturi duct helps cool the stator slots evenly, stopping the formation of hot spots in specific areas. These results show that the duct design keeps both the rotor and stator at safe temperatures, which improves the motor's thermal stability and overall performance. From Figure 6, the CFD analysis of the winding shows that the temperature stays safely low because of the axial Venturi duct. The highest temperature is about 51.8°C, found in the middle part of the winding where heat is produced more. As air flows through the duct, the faster-moving air helps cool the winding, causing the temperature to decrease gradually along its surface. This even cooling shows that the duct design works well to control temperatures, stop hot spots from forming, and improve the motor's overall heat management. Keeping the winding at this temperature level helps the insulation last longer and lowers the chance of heat damage during ongoing use.

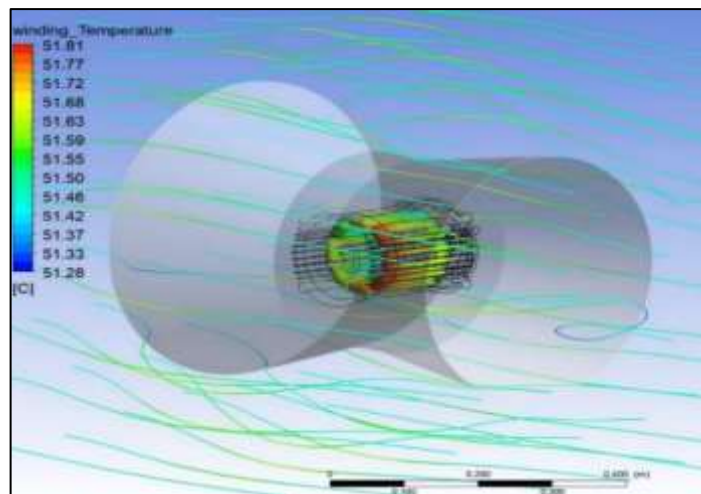


Figure 6: Winding temperature.
Source: Authors, (2025).

XI. RESULTS AND DISCUSSIONS

A comparative thermal analysis was performed for different motor cooling configurations to assess the effectiveness of Venturi duct designs in managing heat dissipation in a 5 kW PMSM motor for electric two-wheelers. The table 2 shows that the baseline configuration without any ducting exhibited the highest maximum temperature of 115 °C, relying solely on natural convection. Introducing Venturi ducts with a cross-sectional area of 25 mm² reduced the maximum temperature to 95 °C, accompanied by a modest pressure drop of 18 Pa, indicating a significant enhancement in convective cooling. Increasing the duct area to 30 mm² resulted in further thermal improvement, reducing the peak temperature to 88 °C with a slightly higher-pressure drop of 22 Pa. Interestingly, a second configuration with 25 mm² ducts showed a marginally better temperature performance at 90 °C, although at the cost of a higher-pressure drop of 25 Pa, possibly due to geometric or flow distribution changes. These results underscore the trade-off between cooling effectiveness and aerodynamic resistance. Overall, the use of Venturi ducts notably improved thermal regulation compared to the baseline, with the 30 mm² variant offering the best overall performance in terms of temperature reduction while maintaining an acceptable pressure drop, making it a promising solution for enhancing motor reliability and efficiency in electric vehicle applications.

Table 2: Venturi Design Optimization.

Design Variant	Max Temp (°C)	Pressure Drop (Pa)	Notes
Baseline (No ducts)	115	0	Natural convection only
Venturi ducts, 25 mm ²	95	18	Significant cooling
Venturi ducts, 30 mm ²	88	22	Further improved cooling
Venturi ducts, 25 mm ²	90	25	Slightly better cooling

Source: Authors, (2025).

From figure 7, the temperature plot defines the thermal response of key components within the 5 kW PMSM motor, cooled using a Venturi duct system, and was evaluated over a continuous 60-minute operation. The rotor exhibited the highest temperature, reaching approximately 57 °C, followed by the magnet and rear bearing, which peaked at around 55 °C and 53 °C, respectively. In contrast, the stator winding, tooth, and front bearing maintained lower temperatures, stabilizing near 48 °C. This temperature distribution reflects the effectiveness of the Venturi duct in enhancing convective cooling, particularly for externally accessible parts such as the stator and front bearing. The observed thermal gradients suggest that the airflow generated by the duct is more effective in regions directly exposed to the airstream, while internal components like the rotor and magnets, being less accessible, retain more heat. Furthermore, the slight temperature difference between the front and rear bearings may indicate non-uniform airflow along the motor axis, potentially influenced by duct geometry or motor orientation. Overall, the results demonstrate that the Venturi duct provides significant thermal management benefits, especially for stator components, and can enhance the operational reliability of PMSM motors in electric two-wheeler applications.

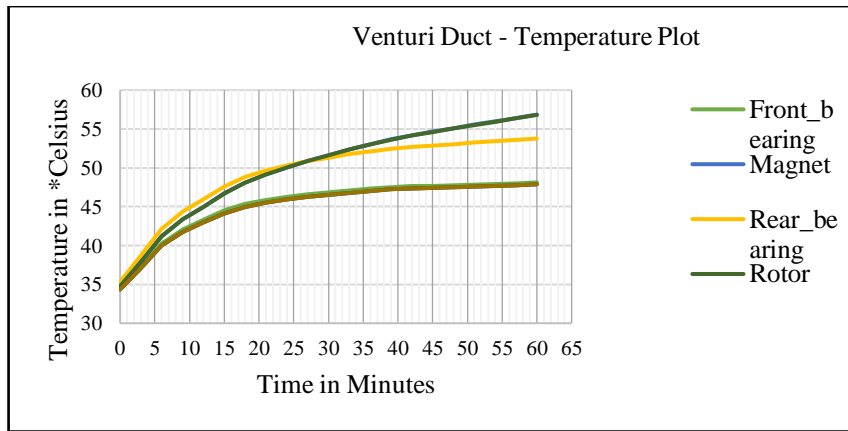


Figure 7: Temperature plot for venturi duct of PMSM. Source: Authors, (2025).

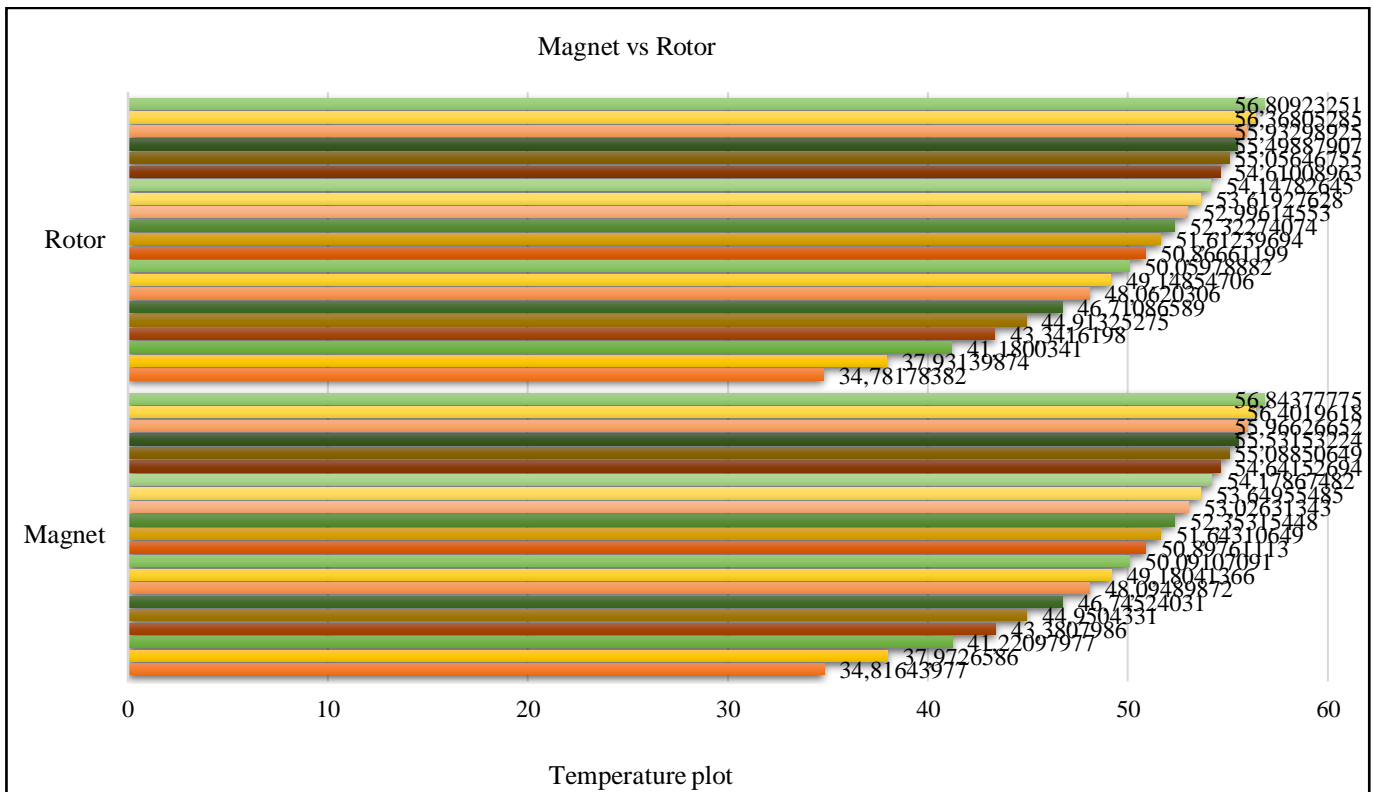


Figure 8: Temperature plot for motor and magnet of PMSM. Source: Authors, (2025).

From figure 8, the rotor and magnet temperature difference is shown below. The rotor temperature raises from 34 degree Celsius to 56-degree Celsius which makes rapid increase of temperature in the rotor and for the magnet temperature raises from 34 degree Celsius to 56-degree Celsius rapid temperature variation. Both the rotor and magnet had similar temperature. The integration of cooling ducts effectively reduces hotspot temperatures in the PMSM motor, improving thermal management and expected operational reliability. The parametric study highlights a trade-off between duct size (and number) and airflow resistance. Optimizing duct geometry balances temperature reduction with pressure drop, informing design choices for Phase 2 experimental validation.

V. CONCLUSION

This study presents a comprehensive thermal analysis of a 5 kW Permanent Magnet Synchronous Motor (PMSM) for electric two-wheelers, focusing on the integration of an axial Venturi duct cooling system. CFD simulations revealed that the Venturi duct's geometry effectively accelerates airflow around critical motor components, enhancing convective heat transfer and significantly reducing temperatures compared to baseline conditions without ducting. The highest temperatures measured were around 58°C at the magnets and rotor core, with the bearing temperatures staying safely between 51-58°C. Throughout the analysis, the stator and winding temperatures stayed below 52°C. The higher airflow speed in the Venturi duct helps cool the motor evenly, stopping hot spots and improving how well the motor handles heat. Keeping the temperatures low is important to protect the motor's insulation and make it last longer. Different Venturi duct dimension shows a balance between how well they cool and how much resistance they create for airflow. The 30 mm² design works best at keeping temperatures under control while also reducing pressure loss. In short, using a Venturi duct cooling system is a small, affordable, and efficient way to boost the thermal performance of PMSM motors in electric vehicles. This helps make the motors more reliable and better for the environment. Future studies should check how well this cooling method works in real driving situations in dynamic and under different loads to improve the design for real use.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: C Dineshkumar, D Roshan.

Methodology: C Dineshkumar, D Roshan.

Investigation: C Dineshkumar, Mohammed Jaheen,

Discussion of results: D Roshan, C Dineshkumar, N S Shafeer Ahmed.

Writing – Original Draft: C Dineshkumar, Mohammed Jaheen, Mohammed Rizwan.

Writing – Review and Editing: Mohammed Jaheen, Mohammed Rizwan, N S Shafeer Ahmed.

Resources: C Dineshkumar, D Roshan, Mohammed Rizwan.

Supervision: C Dineshkumar, D Roshan.

Approval of the final text: C Dineshkumar, D Roshan.

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