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Drivetrain and Powertrain Thermal Analyses of a Tesla Model 3 Electric Vehicle

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In this study, we thermally analyze the drivetrain and powertrain of a Telsa Model 3 electric vehicle. When size and weight limitations are coupled with the need for high power output, the traction motor of a vehicle can cause excessive heat to the insulation of the motor windings, causing them to degrade rapidly. Furthermore, the rotor experiences overheating, leading to a loss of magnetic properties in the permanent magnets within the rotor, which ultimately leads to inefficient performance. Therefore, it is necessary to implement cooling mechanisms for both the internal rotor components and the external stator components. The insulation of motor windings deteriorates rapidly when exposed to overheating. Overheating in interior permanent magnet motors causes the permanent magnets in the rotor to lose their magnetic properties, and that will decrease the operation efficiency of the motor. To maintain optimal performance, it is essential to cool both the stator and rotor ends of the motor and keep the temperature constant. For the motor cooling system to function effectively, it needs to be capable of handling a wide range of dust, humidity, and temperature levels. To accurately analyze the temperature distribution in water-cooling systems, a comprehensive automated meshing approach is employed. This involves creating meshes for gaps, slots, windings, and flow paths, enabling the use of simulated drivetrain and powertrain thermal analyses to assess the motor's thermal performance.

1. Introduction

The thermal management of high-power motors in Tesla electric vehicles (EVs) has become increasingly crucial as these vehicles gain popularity on the road. The general design trend in electric motors is to increase the motor output power while simultaneously reducing the motor's

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volume for easier application. However, this trend results in a rapid increase in heat density, leading to a significant rise in motor temperature, and excessive motor temperature poses several challenges. Firstly, it negatively affects the life and reliability of the motor. High temperatures can cause accelerated wear and degradation of motor components, reducing their lifespan. Additionally, elevated temperatures can impact the motor's electromagnetic performance, potentially leading to decreased efficiency and suboptimal operation. To address these challenges, the thermal management of electric motors with high heat density has become an important issue. The rear and front motors of Tesla EVs employ different cooling technologies for their motor systems. The rear motor, which uses permanent magnet synchronous motors, utilizes liquid cooling technology. Liquid coolant circulates through the motor to dissipate heat efficiently.

As EVs continue to evolve and their motor output power density increases while their volume decreases, managing the heat generated by these high-power motors becomes even more critical. Proper thermal management not only ensures the longevity and reliability of the motor but also preserves its electromagnetic performance, enabling optimal efficiency and overall vehicle performance. Overall, as the popularity of EVs continues to grow, the importance of motor thermal management cannot be overstated. The ongoing efforts to enhance thermal management technologies are aimed at addressing the challenges associated with high heat density in electric motors, ensuring their optimal performance and contributing to the overall advancement of EV technology.(1) Tesla's new EV utilizes a permanent magnet synchronous motor (PMSM) as its main power source. Because the induction motors excel in high-speed scenarios that demand high torque and efficiency, the PMSMs can perform better than a gasoline car at low speeds. PMSMs prioritize efficiency over acceleration, requiring higher torque than a gasoline car. These motors generate torque by utilizing permanent magnets in the rotor, which interact with the stator magnets. When the current flow increases, it enhances efficiency and torque but also generates more heat.(2)

The high-performance motor plays a crucial role in the success of Tesla electric cars in the market. The electric motor is a complex, high-speed rotating machine. It is challenging to experimentally measure and understand the internal heat flow field during operation. To overcome this obstacle, computer simulations are used to calculate fluid dynamics. Computational fluid dynamics (CFD) is an essential tool for analyzing and designing motor thermal management, as it provides detailed physical data on internal phenomena. Optimizing Tesla's high-performance motor is a key factor in its success. This motor is a sophisticated rotating machine that operates at high speeds. To overcome the challenges associated with internal heat flow, Tesla employs computer calculations and fluid dynamics analysis to understand the thermal management system. During operation or charging, both motors and batteries generate heat. Elevated temperatures can decrease battery efficiency and even lead to instability, resulting in reduced performance or shortened battery life. To address this issue, Tesla utilizes a dual-mode coolant loop in their patent to effectively cool the powertrain. This cooling system helps maintain optimal operating conditions for the motor and battery, preventing efficiency losses and potential damage.(3)

However, the structure of the high-efficiency and high-power motors is extremely complex, presenting numerous challenges in numerical simulation analysis. Traditional approaches often involve simplifying intricate geometries, but these simplifications can lead to the loss or distortion of important physical phenomena, potentially leading to erroneous design decisions. Furthermore, the arduous and cumbersome simulation process hinders designers' willingness to utilize CFD. To achieve effective and accurate thermal management in the design of high-power motors, it is crucial to develop the techniques for advanced numerical simulation, particularly fast mesh construction methods, which can tailor the extremely intricate geometries. The complex structure of high-efficiency and high-speed motors poses significant difficulties during numerical simulation analysis. The simplifications of intricate geometries can result in omission or misrepresentation of key physical phenomena, which may lead to flawed design conclusions. The simulation process for CFD is also laborious and challenging. To address these issues and design high-power motors with precise and efficient thermal management, the development of efficient mesh generation techniques becomes paramount, specifically for handling complex geometries. The objective of this study is to investigate the utilization of the CFD calculations of heat transfer and thermal mixing in examining a comprehensive EV powertrain, encompassing electric motors, interconnected output gearboxes, and a SiC-based MOSFET inverter of a Telsa Model 3 EV. The analysis is aimed at retaining the authentic geometry without simplification and assessing the attainable outcomes. Additionally, numerical calculation technology is employed to analyze the powertrain of an EV comprising electric motors and interconnected output gearboxes.

2. Analysis Method

Our study starts with acquiring a 2018 Tesla Model 3 EV and involves importing the rear drive unit, consisting of the inverter, motor, and differential sets shown in Fig. 1.$^{(4–6)}$ The motor

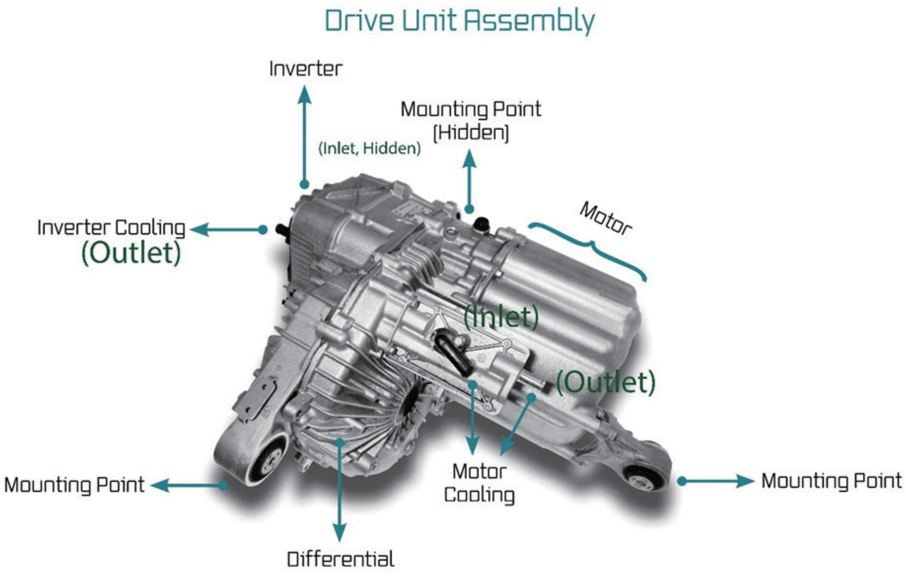


Fig. 1. (Color online) Tesla Model 3 rear drivetrain.

assembly is then disassembled from the rest of the drivetrain system. After removing the casing, the internal structure is broadly categorized into an inverter with a printed circuit board (PCB), the motor body, the differential gear sets, and the water-cooling pipes that cover the inverter and motor externally. Unlike previous Tesla Model S/X products, the Model 3/Y utilizes interior permanent magnet synchronous motors (IPMSMs) to replace the induction motors. Additionally, water cooling has been replaced by oil cooling, which can result in a more efficient and compact electric powertrain. The inverter has been enhanced with a new power module, in which silicon carbide is used to fabricate the metal oxide semiconductor field-effect transistors, increasing its power and decreasing its size. Moreover, the battery pack incorporates a new cell configuration that features unique connection methods and technical characteristics, ensuring high reliability and efficient cooling.(5)

The gear set includes not only the gears but also the shafts and bearings, which will be meshed and analyzed together. Traditionally, owing to limitations in complex geometric processing, this part is often omitted, and only the individual motor is analyzed, which makes it challenging to comprehend the overall thermal management of the entire drivetrain system.

In Tesla's motor, both the stator and rotor are equipped with liquid cooling. Jet oil is used to cool the rotor and the rotor can rotate 90 degrees to the right and left of the central shaft. This rotation can effectively eliminate the uneven torque pulsation. The rotor of the multipole motor contains magnets arranged in a V shape. These magnets are inserted into laminated electromagnetic steel sheets, forming a magnetic core. The rotor shafts consist of multiple hollow parts and holes, which serve as oil passages. Cooling oil can be dispersed through these passages as the rotor rotates, effectively cooling both the stator and rotor cores. The rotor cores are composed of electromagnetic steel plates measuring 70 mm and 150 mm in diameter, with a thickness of 0.25 mm. All the assembly parameters of the Model 3 stator and rotor are shown in Table 1.(6)

Table 1
Tesla's motor stator and rotor assembly parameters.

Number of stator slots	56
Lamination stack length	134 mm
Stator lamination inner diameter	150 mm
Stator lamination outer diameter	250 mm
Lamination stacking factor	0.95 (estimated)
Diameter of the winding	0.8 mm
End winding axial overhang	40 mm
Number of pole pairs	3
Number of turns	2
Parallel paths	3
Number of phases	3
Phase resistance	0.00475 Ω at 20 °C
Rotor lamination inner diameter	70 mm
Rotor lamination outer diameter	150 mm
Rotor lamination thickness	0.25 mm
Magnet dimensions	$33 \times 21.5 \times 6.5$ mm^3

The Model 3/Y features a sophisticated system for heating the battery using exhaust heat generated by the electric powertrain. Furthermore, the Model Y features an advanced heat pump system designed to work seamlessly with a coolant and incorporates a specialized set of valves known as the Octovalve. This Octovalve system provides extensive control over heat distribution, encompassing cabin heating, ventilation, and air conditioning (HVAC) management, and can even be employed to warm the battery by precisely controlling the coolant flow.(3) To ensure efficient cooling of the gearbox, an integrated motor structure is employed, which uses cooling water to cool the oil via a heat exchanger. The motor is supplied with oil through an electric oil pump and an oil filter, ensuring proper lubrication. The stator cores of the motor consist of 56 slots and have an outer diameter of 250 mm and an inner diameter of 150 mm. These stator cores have a unique design that incorporates numerous oil passageways. Moreover, Tesla's powertrain modules contribute to a more streamlined controller and inverter system. The inverter plays a pivotal role in converting the battery's direct current (DC) into alternating current (AC), a vital function for managing the regenerative energy and motor's drive. The primary board of the motor controller is situated atop the inverter, with the driver circuitry sending instructions to the power module positioned at the bottom.

The Model Y shares various components with the Model 3, including its inverter. This inverter is equipped with silicon insulated gate bipolar transistors (IGBTs) for the front-wheel drive and 24 SiC MOSFET modules for the rear-wheel drive, a configuration engineered to reduce conduction and switching losses. Tesla utilizes an inventive cooling system that combines a shaft groove with a traditional cooling jacket. Cooling units for power electronics and the gearbox are interconnected by parallel pipes carrying cooling fluid. Cold fluid, obtained from the heat exchanger, is employed to cool both the rotor and stator. Connecting all parts of the motor cooling system in series would result in higher coolant temperatures inside the rotor shafts compared with the stator shafts. To optimize performance, Tesla developed a dual-mode coolant loop in their powertrain design, enabling effective cooling of the innovative windings, as well as the stator and rotor assemblies. It is important to highlight that motors are meticulously designed for specific drivetrains, and even rear-wheel drive and front-wheel drive vehicles come with unique designs and configurations. Figure 2 offers a glimpse of the overall mesh structure of the powertrain unit, where the intricate geometry of numerous coils traditionally presents the most complex aspect of motor body analysis.

3. Results and Discussion

As an illustration, let us consider the motor in question. It features 96 sets of overlapping coils, as depicted in Fig. 3. Typically, such a complex geometry is simplified, resulting in the integration of independent coils, as shown in Fig. 4. However, this simplification leads to overly optimistic predictions and increased risks in product design owing to the assumption of low and excessively uniform temperatures. To address this, we opted to maintain the original geometry of all 96 sets of coils for mesh construction and heat flow analysis. In Fig. 5, you can observe the enlarged surface mesh of eight coil sets. Each coil has been accurately and correctly meshed individually. This approach breaks away from the traditional oversimplification method,

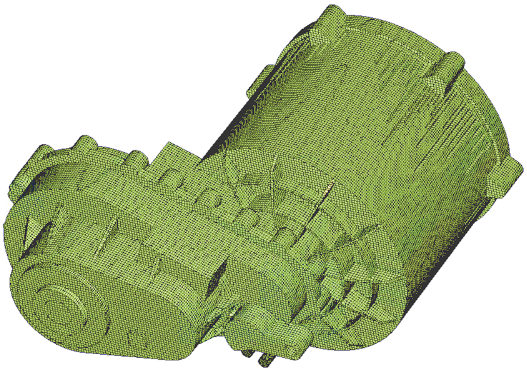


Fig. 2. (Color online) Overall mesh of the powertrain unit.

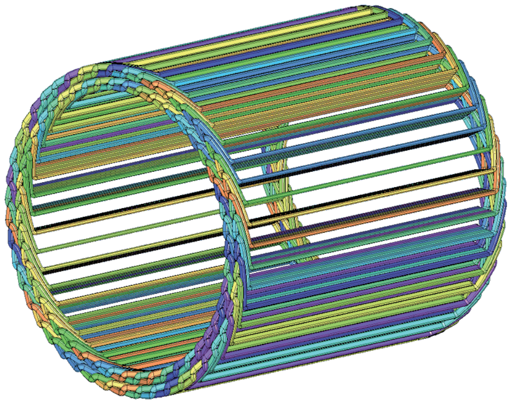


Fig. 3. (Color online) Stator with 96 sets of overlapping coils.

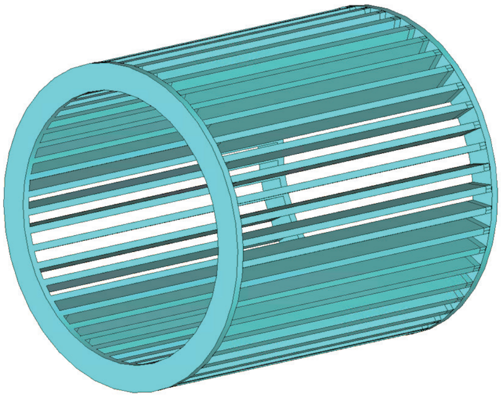


Fig. 4. (Color online) Simplifying the stator with 96 sets of overlapping coils.

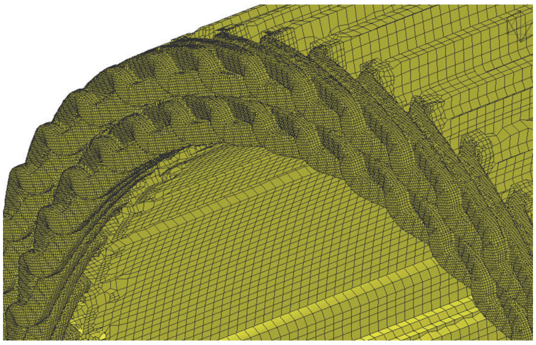


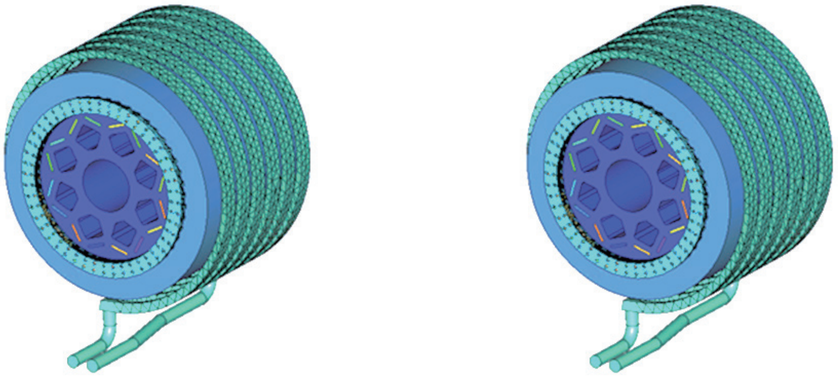
Fig. 5. (Color online) Mesh grid of coil surface.

ensuring the successful and complete meshing of all 96 coil groups. After the grid technology precisely generates the calculation grid, the motor's heat source is examined using electromagnetic analysis software. Subsequently, the heat flow field is analyzed, taking into account factors such as motor speed, relevant material properties, and other boundary conditions. These analyses yield a comprehensive set of information. Besides assessing the internal temperature of the motor, we also scrutinize the temperature distribution in the gears, bearings, and shafting to provide a more in-depth reference.

The Model 3/Y vehicles manufactured by Tesla are equipped with an IPMSM, as opposed to the induction motor used in previous Tesla models such as the S/X. This change offers several advantages, including size reduction and increased efficiency of the electric powertrain. Another significant modification is the transition from a water-cooled system to an oil-cooled system for motor cooling. The rotor shaft of the IPMSM contains numerous hollow portions and holes that function as oil passages. During operation, the cooling oil is distributed through these passages by the rotation of the rotor, effectively cooling both the stator windings and the rotor core. The oil cooling mechanism plays a pivotal role in the stator's design. Tesla's cooling system combines a traditional cooling jacket for the stator with a groundbreaking spiral groove in the shaft. Cooling fluid is simultaneously supplied to both the stator and rotor systems through parallel channels. These cooling pipes are interconnected with the gearbox cooling units and the power electronics. Cold fluid, sourced from the heat exchanger, directly cools both the stator and rotor components. It is worth noting that unlike the Model S/X, where the stator features a cooling jacket, the Model 3/Y's stator is designed with internal cooling using oil. Furthermore, the stator core of the Model 3/Y is designed with 56 slots and a unique shape that accommodates multiple oil passageways. These passageways are integrated into the laminated core to facilitate the flow and dispersion of oil for optimal cooling.

When it comes to motor body analysis, the most challenging aspect traditionally has been dealing with a large number of coils with intricate geometry. Let us take this motor, which consists of a total of 96 sets of overlapping coils, as an example. Typically, such complex geometries are simplified by integrating coils that are independent of each other. However, this simplification often leads to lower and excessively uniform temperature prediction results, resulting in overly optimistic predictions and increased risks in product design. In this study, we aimed to address this issue by preserving the original geometry of all 96 sets of coils for mesh construction and heat flow analysis. Additionally, two different liquid-cooled runner modules were analyzed and compared, as depicted in Fig. 6.(6) The liquid cooling pipeline grid is illustrated in Fig. 7. The grid technology is employed to generate a geometric calculation grid, which is then used in conjunction with electromagnetic analysis software to analyze the motor's heat source. By setting the motor speed, relevant material properties, and boundary conditions, the heat flow field can be analyzed. This allows for a temperature distribution analysis of the gears, bearings, and shafting, enabling us to determine the internal temperature of the motor.

Considering that the highest temperature is reached by the stator coil, the analysis of the rotor results alone is insufficient. The provided figures illustrate the liquid pressure values in the schematic flow channel, while other objects are represented by temperature values. The ambient temperature remains constant at 20 °C for both cases. In the flow channel analysis of design 2,



(a) (b)

Fig. 6. (Color online) (a) Design 1 and (b) design 2 of Tesla Model 3 EV liquid cooling pipelines.

(a) (b)

Fig. 7. (Color online) Temperature analysis of the flow channel: (a) design 1 and (b) design 2 of the Tesla Model 3 EV electric motor.

the pressure changes are minimal, resulting in insignificant pressure loss. However, the corresponding motor temperature is higher. On the other hand, design 1 exhibits significant pressure loss in the flow channel, but the motor temperature is lower in comparison. To study the heat transfer phenomenon between the motor and the gearbox, the motor with the output gear set is coupled. In both designs 1 and 2, the temperatures of the gears are approximately 80 ℃. However, as shown in Fig. 8, the stator within the motor featuring flow channel design 1 can reach a maximum temperature of 380 ℃.

To address these temperature concerns, a coolant is introduced into the motor to circulate independently within the stator. Additionally, the coolant also circulates within the inverter, which houses high-power electronics such as SiC MOSFETs, before exiting the system. The transmission of the reduction gear and differential also receives the necessary cooling, albeit it absorbs some heat through the lubricant oils because of its placement between the warm motor and the controller with the PCB. However, an interposed heat exchanger between these components can elevate the oil temperature within the motor and enhance the overall efficiency of the vehicle.

It is worth noting that the rotor temperature can reach up to 200 ℃, and the temperature of the inverter's electronics, particularly the PCB, should also be taken into consideration, although it is not depicted in the figures provided.

In this study, we focused on the simulation and analysis of the Tesla Model 3 EVs. We aimed to provide a comprehensive understanding of its performance by comparing simulation results with actual motor measurements. To achieve this, the CFD software was utilized to conduct a post-motor analysis, showcasing the high-efficiency outcomes. The key highlight of our approach lies in the utilization of advanced grid generation technology and efficient calculation performance offered by the CFD honeycomb control volume grid. This unique grid generation method allows for the direct generation of grids for solid CAD, eliminating the need for traditional fluid area calculation, manual surface registration, and complex grid generation processes. This capability proved particularly beneficial for dealing with geometrically complex components such as electric motors. In this study, we analyzed the real EV power motor using this innovative technology. Our analysis not only covered the motor body but also included an

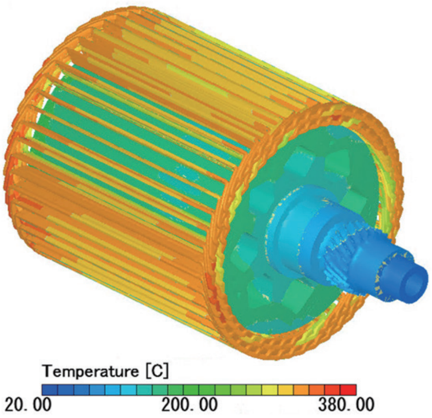


Fig. 8. (Color online) Temperature distribution of stator and rotor for runner design 1.

examination of the gear set connected to the motor's power output. The operating conditions were taken into account, and the temperature of the gearbox set was carefully considered. This consideration helped us evaluate the impact of lubrication conditions and potential thermal deformation on the gear engagement. To achieve a comprehensive analysis, the dynamic rotating discontinuous meshes and multi-fluid analysis techniques were incorporated in addition to the mesh generation methods.

4. Conclusions

In this study, we successfully conducted thermal analyses of the drivetrain and powertrain of a Tesla Model 3 electric vehicle using CFD. Notably, we adopted a novel approach of meticulously meshing each coil individually, departing from the conventional oversimplified methods. This methodology not only guarantees the accuracy and correctness of the meshing but also ensures the comprehensive analysis of all 96 coil groups. This innovative technique significantly advances our understanding of the Model 3's thermal performance. By specifying pertinent material properties, motor speeds, and boundary conditions, we were able to effectively analyze the heat flow field. This meticulous approach allowed us to gain valuable insights into how heat is distributed and managed within the system. Furthermore, the careful selection of these parameters demonstrates the importance of accurate and realistic simulations in engineering analyses, ultimately contributing to a more precise understanding of the thermal behavior in our study. The electric motor, power inverter assembly, and gearbox are interconnected within a common thermal management system. This arrangement ensures efficient heat dissipation and temperature regulation. To effectively analyze the temperature distribution during water cooling, various design challenges associated with modern water-cooled permanent magnet motors need to be addressed. These challenges include the automatic meshing of windings, slots, gaps, and flow paths to accurately simulate and predict the cooling performance.

Acknowledgments

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