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Electric Vehicle' Powertrain Thermal Analysis

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Abstract: *The purpose of this paper is to discuss the thermal analysis of electric vehicle powertrains. Due to their high-power output requirements, electric vehicles' traction motors generate significant amounts of heat. Motor winding insulation deteriorates rapidly when overheated. Overheating causes permanent magnets in the rotor of interior permanent magnet motors (IPMs) to lose their magnetic properties, resulting in inefficient operation. Both ends of the stator and rotor must be cooled to maintain a constant temperature. For a motor cooling system to function effectively, it must be able to handle a wide range of temperature, humidity, and dust levels. In this paper, we present an automated meshing of windings, slots, gaps, and flow paths that allows us to accurately thermal analyse liquid-cooling temperature fields.*

Keywords: *electric vehicle, powertrain unit, simulation.*

1. Introduction

Motor thermal management is becoming increasingly important as electric vehicles become more popular. Tesla, for example, uses permanent magnet synchronous motors with liquid cooling technology in its rear motor, while its induction motor uses liquid cooling technology and frequency converters in its front motor. To increase performance and efficiency, motor output power density is increasing while its volume is decreasing. Therefore, due to an increase in heat density, the motor temperature increases significantly. The electromagnetic performance of a motor can also be adversely affected by excessive motor temperatures. This has made managing the heat generated by electric motors with a high heat density increasingly important [1].

Tesla's new electric vehicle uses permanent magnet synchronous motors. Induction motors have an advantage at high speeds requiring high efficiency and torque, while permanent magnet motors have an advantage at low speeds. A permanent-magnet synchronous motor prioritizes efficiency over acceleration, which requires more torque. Magnet synchronous motors produce torque using permanent magnets as the rotor as a result of their interaction between stator and rotor magnets. Increasing current flow not only produces more torque and efficiency, but also generates more heat [2].

Tesla's high-performance motor is the first key to its success. A high-performance motor is a rotating machine with a complex structure that rotates at high speeds. The computer measures and understands the internal heat flow field in the running state by calculating the fluid to overcome this obstacle. The use of mechanical CFD (Computational Fluid Dynamics) is essential to the analysis and design of motor thermal management systems since it provides information on internal fine physical phenomena. Motors and batteries generate heat during operation or charging. A battery will lose efficiency and even become unstable at extreme temperatures, reducing performance or causing a shortening. Thus, they use dual mode coolant loops in their patent [3] to cool the powertrain.

The structure of high-speed and high-efficiency motors is complex, and numerical simulation analysis often encounters many difficulties. The simplification of complex geometries results in the loss or error of many physical phenomena, which can mislead design judgments. Simulating CFD is also cumbersome and difficult. Designing high-power motors with accurate and effective thermal management requires the development of advanced numerical simulation techniques, especially fast mesh construction techniques for extremely complex geometries. These problems can be overcome by developing efficient mesh generation techniques. By using numerical calculation technology, we analyze the powertrain of an electric vehicle, including electric motors and connected output gearboxes, retaining the actual geometry without simplifying it.

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2. Analysis

Unlike previous Model S/X products, Tesla's Model 3/Y uses IPMSMs instead of induction motors. Furthermore, oil cooling has replaced water cooling, resulting in a smaller, more efficient electric powertrain. A new power module made from Silicon Carbide Metal Oxide Semiconductor Field Effect Transistor has made the inverter more powerful and smaller. A new cell configuration for the battery has been adopted, and it is characterized by a number of unique connection methods and technical features that make the battery pack highly reliable and cooling [4].

This study begins with a Tesla electric vehicle [5], imports the motor, inverter, and differential gearbox set shown in Figure 1, and disassembles the motor assembly. When the casing is removed, the internal structure can be roughly divided into the inverter with PCB, the differential gear set, the motor body, and the liquid-cooling pipes covering the motor and inverter. The gear set also includes shafts and bearings, which will be analyzed together later. Traditional methods use complex geometric processes and analyze only one motor, making it difficult to understand the thermal management of the whole powertrain.

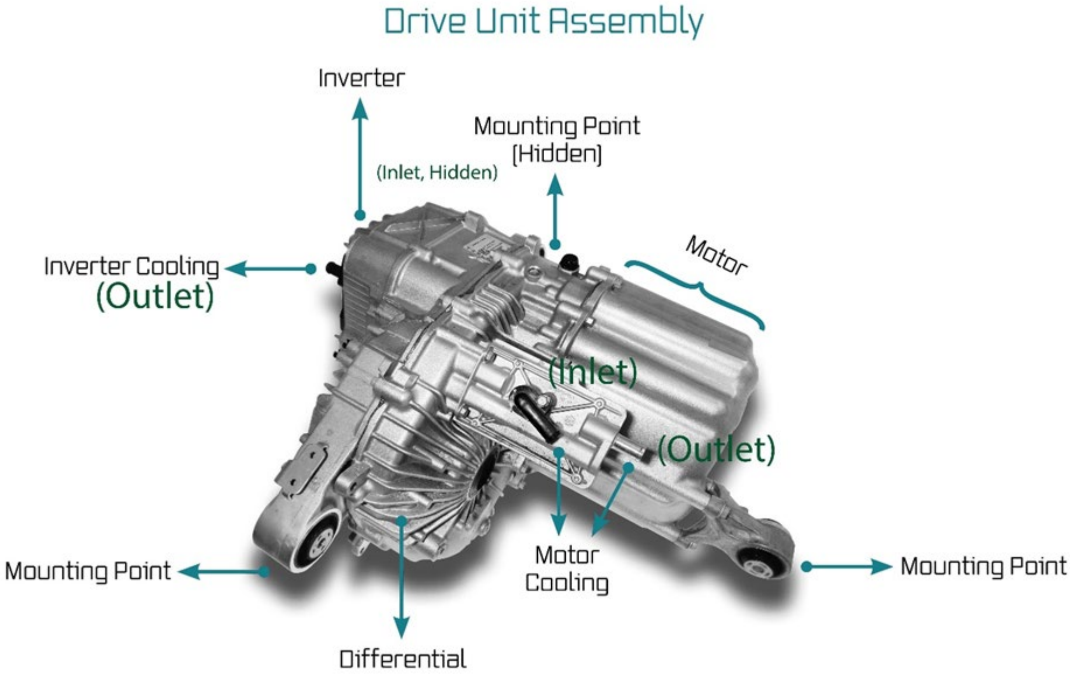

Figure 1: Tesla's electric vehicle rear powertrain.

In Tesla's motor, both rotor and stator are liquid-cooled, the rotor is cooled by jet oil, and the rotor rotates 90 degrees to the left and right of the central shaft. During rotation, this method eliminates torque unevenness pulsation. Magnets are arranged in a V shape inside the multipole motor rotor. A magnetic core is formed by inserting magnets into laminated electromagnetic steel sheets. Rotor shafts have numerous hollow parts and holes that act as oil passages, and cooling oil is dispersed by rotation to cool the rotor core and stator. Electromagnetic steel plates measuring 70 mm in diameter, 150 mm in diameter, and 0.25 mm thick make up the rotor cores (see Table 1) [6].

Table 1: Tesla's motor stator and rotor assembly parameters [6].

Number of stator slots	56
Stator lamination outer diameter	250 [mm]
Stator lamination inner diameter	150 [mm]
Lamination stack length	134 [mm]
Lamination stacking factor	0.95 (estimated)
Diameter of the winding	0.8 [mm]
End winding axial overhang	40 [mm]
Number of phases	3
Parallel paths	3
Number of turns	2

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Number of pole pairs	3
Phase resistance	0.00475 [Ω] at 20°C
Rotor lamination outer diameter	150 [mm]
Rotor lamination inner diameter	70 [mm]
Rotor lamination thickness	0.25 [mm]
Magnet dimension	33x21.5x6.5 [mm]

The Model 3/Y also has a system that allows the battery to be heated by the exhaust heat from the electric powertrain, but the Model Y is fitted with a heat pump system compatible with coolant and a set of valves known as the "Octovalve" that allow overall control of the heat flow, including the cabin HVAC, and can also be used to heat the battery using the valves to control the coolant flow path [3]. An integrated motor structure in the gearbox cools the oil with cooling water through a heat exchanger. An electric oil pump and an oil filter circulate oil to the motor. Stator cores have 56 slots, and their inner diameter is 150 mm, while their outer diameter is 250 mm, and they have a unique shape with many oil passageways.

Also, Tesla's powertrain modules make it a much more compact inverter and controller. The inverter converts direct current (DC) from the battery into alternating current (AC) to control the motor's drive and regenerative energy. The main board of the motor controller is at the top of the inverter, while the driver circuitry sends commands to the power module at the bottom. The Model Y also shares many parts with the Model 3, there are 24 SiC MOSFET modules in the inverter for the rear-wheel drive and silicon IGBTs for the front-wheel drive, which reduces conduction losses and switching losses.

Tesla's cooling system combines an innovative shaft groove with a classic cooling jacket. In parallel with cooling fluid, pipes connect power electronics and gearbox cooling units. The stator and rotor are cooled by a cold fluid coming from the heat exchanger. Coolant temperature inside rotor shafts will be higher than those inside stator shafts if all parts of the motor cooling system are connected in series. In order to achieve better performance, they developed dual mode coolant loops in their powertrain design to cool down innovative windings or stator and rotor assemblies. It is important to note that motors are designed for specific drivetrains, and even front-wheel drive and rear-wheel drive vehicles have different designs and topologies.

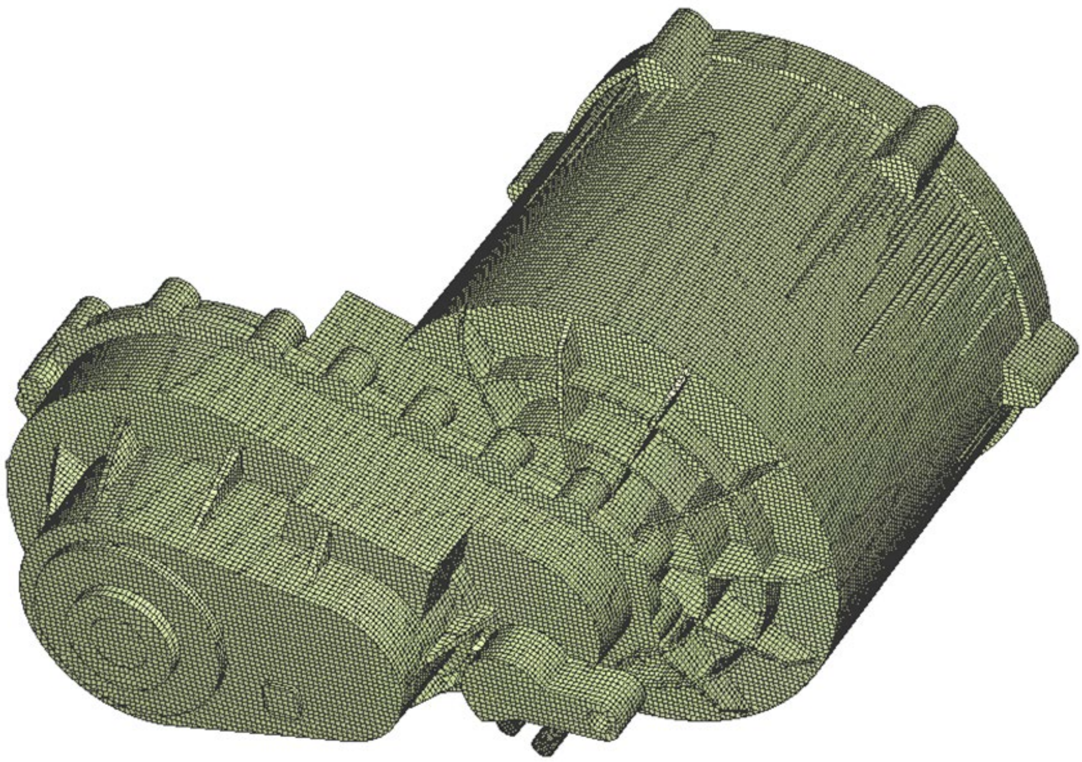

Figure 2: The overall mesh of the powertrain unit appearance.

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Figure 2 shows the overall mesh appearance of the powertrain unit in this article. Many coils with fine geometry are traditionally the most challenging aspect of motor body analysis. As an example, the stator of this motor has 96 sets of overlapping coils as shown in Figure 3. A geometry of this complexity is typically simplified, as shown in Figure 4, resulting in the integration of coils that are independent. Consequently, low, and excessively uniform temperatures result in overly optimistic predictions and increased product design risks. For mesh construction and heat flow analysis, we will maintain the original geometry of all 96 sets of coils.

The enlarged surface mesh of the eight coil sets is shown in Figure 5. Each coil is correctly and accurately meshed individually. A total of 96 coil groups have been successfully and completely meshing, breaking away from the traditional oversimplification method. After the grid technology complete and accurate generation of the calculation grid retaining the actual geometry; analyzing the heat source of the motor with electromagnetic analysis software, and then analyzing the heat flow field by setting the relevant material properties, motor speed, and other boundary conditions. There is a great deal of information in the analysis results. Aside from the internal temperature of the motor, the temperature distribution in the shafting, bearings, and gears was also analyzed to provide a more detailed reference.

A permanent magnet synchronous motor (IPMSM) will be used to drive the Model 3/Y instead of an induction motor used in all Tesla S/X products to date. In addition to the reduction in size and increased efficiency of the electric powertrain, the cooling method has changed from a water-cooled system to an oil-cooled system, resulting in a smaller and more efficient electric powertrain. A large number of hollow portions and holes in the rotor shaft serve as oil passages, and cooling oil is dispersed by rotation to simultaneously cool the rotor core and stator windings.

Oil cooling is a key feature of stator designs. In Tesla's cooling system, the stator has a traditional cooling jacket, and the shaft has an innovative spiral groove. Cooling fluid is fed to both systems in parallel, and the pipes are also connected to the power electronics and the gear box cooling units. A cold fluid directly from the heat exchanger cools the stator and rotor. A Model 3/Y stator has an oil-cooled interior, unlike the Model S/X stator, which has a cooling jacket. In addition, the stator core has 56 slots and a unique shape with many oil passageways. Passages in the laminated core are also used to receive and disperse oil.

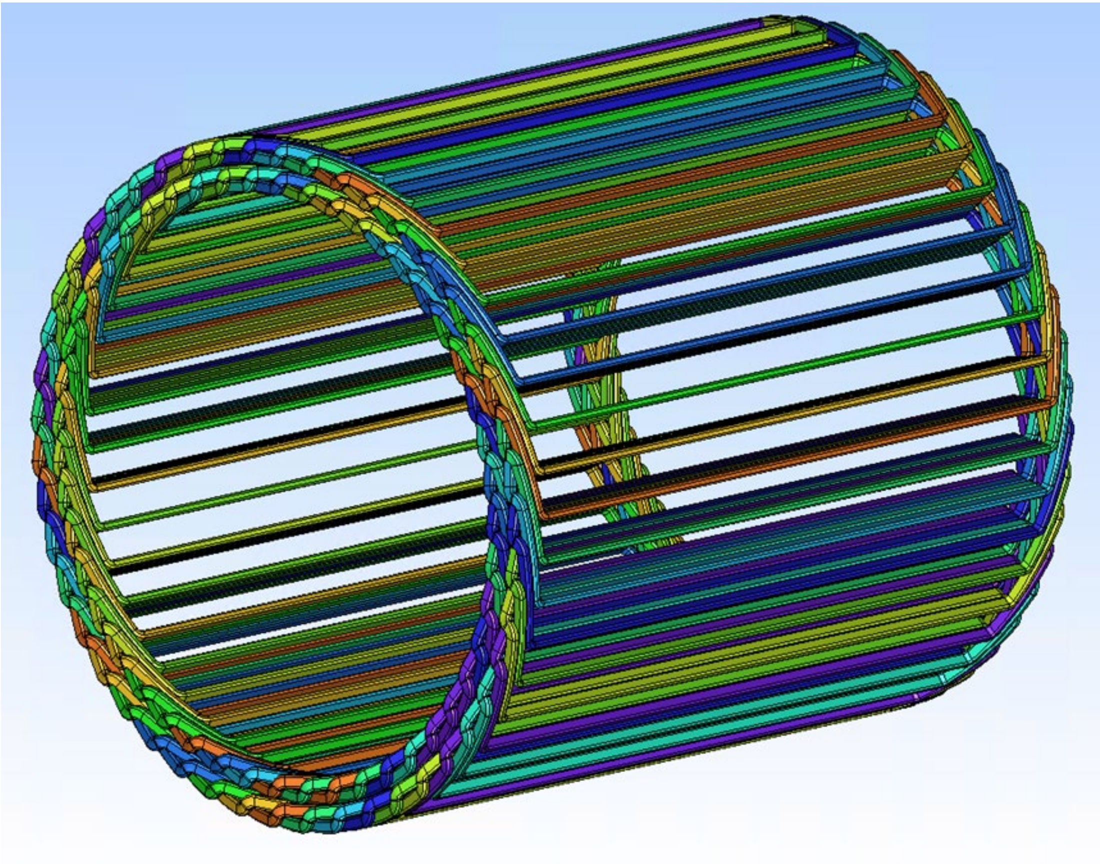

Figure 3: The stator 96 sets of overlapping coils.

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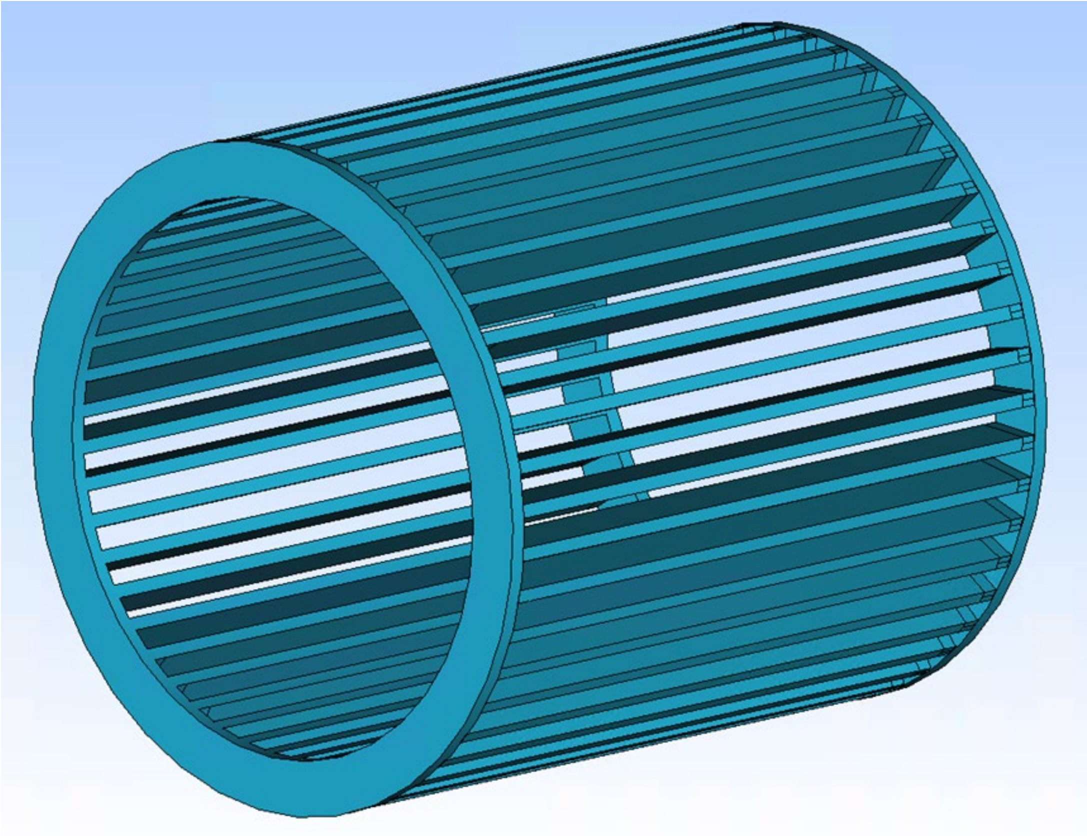

Figure 4: Simplifying the stator 96 sets of overlapping coils.

The gearbox side, which is integrated with the motor, is also connected to the heat exchanger, which cools the oil with water, along with several oil-cooled components, such as the electric oil pump and oil filter that circulate oil to the motor. Based on the numerical simulation, the stator coil is at the highest temperature, as shown in Figure 6. Thus, coupling between the stator and rotor is necessary, and the results must be analyzed simultaneously. Ambient temperatures are 20°C. By coupling the stator and rotor of the motor with the differential set, heat is transferred between the motor and the gearbox. Gear temperatures can reach 80°C, and stator temperatures can reach 380°C.

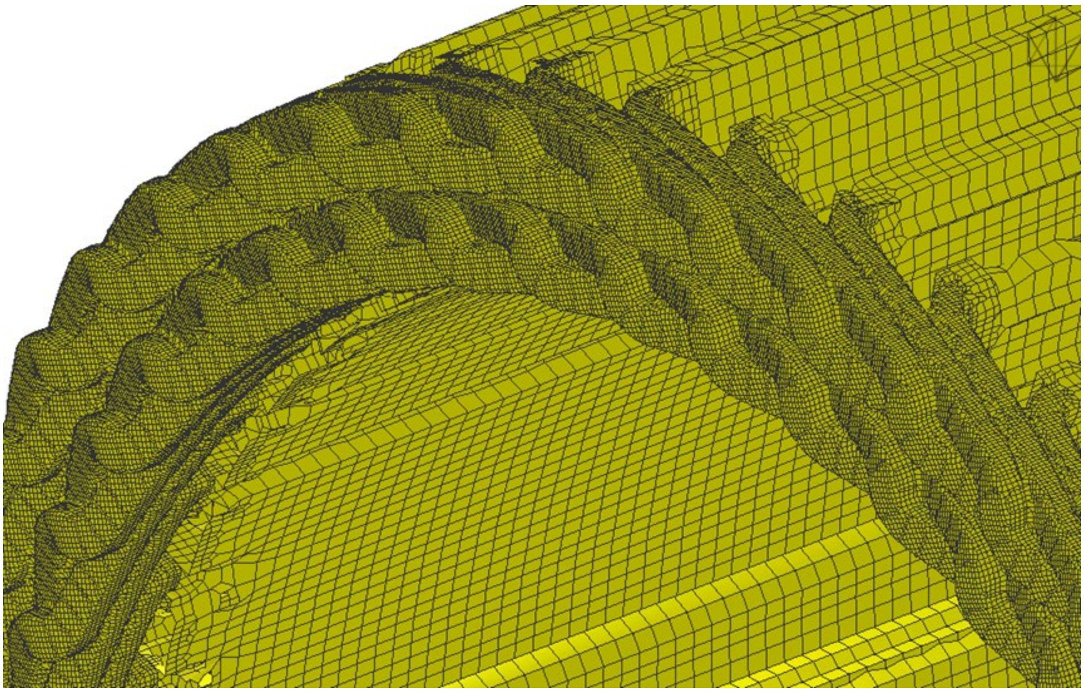

Figure 5: Mesh grid of coil surface.

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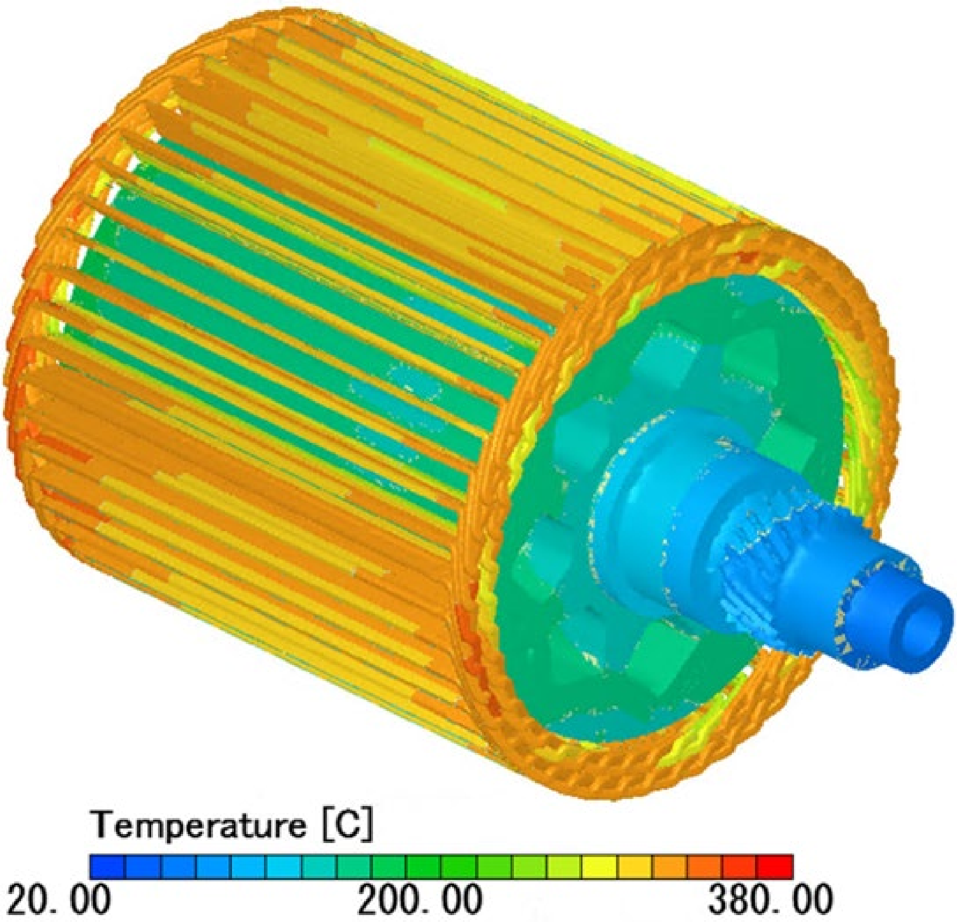

Figure 6: Temperature distribution diagram for stator and rotor.

3. Conclusions

This study presents an integrated powertrain consisting of an electric motor, a power inverter assembly, and a gearbox. By combining these components into one enclosure, weight, complexity, volume, assembly integration, and manufacturing costs are reduced. By replacing flexible, long cables with short, low-loss, rigid bus bars, components can be cooled more efficiently. An electric motor, power inverter assembly, and gearbox are thermally coupled as part of the common thermal management system. We solve the design challenges of modern liquid-cooled permanent magnet motors, including meshing windings, slots, gaps, and flow paths, in order to accurately analyze liquid-cooling temperature fields.

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