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Develop a Hybrid Thermal Simulation Method for EV Motor Performance Analysis, Optimization and Select Cooling Technology

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Abstract
The EV motor generates power losses during operations. The losses are dissipated as heat by motor cooling systems. The motor parts set thermal limits for safe and efficient operations. The motor go beyond these limits will have issues like performance reduction, lifetime, and insulation degradations. An optimized cooling system eliminate these thermal issues and ensure safe, efficient operation. The optimized cooling system achieved with hybrid simulation method proposed in this paper. The method combines the LPTN modelling technique with CFD Analysis results. The proposed method capable to optimize an EV motor with temperature distributions with safe hotspots, high efficiency & torque/power density, and overload time capability. The Motor LPTN model developed for passenger car requirements with PMSM motor as target motor topology. The motor heat transfers are modelled with analytical equations to capture the dominant heat paths. The motor endspace regions analyzed with CFD simulation to calculate wall heat transfer flux as complex windings, housings present here. The motor thermal model accuracy enhanced as CFD analysis used to calculate wall heat transfer flux at motor inner walls. The hybrid thermal model gives out the motor temperatures and performance as results. This hybrid simulation method eliminates error and high effort wasted during motor design iterations. The simulation method validated with measurements with accuracy around 90 to 95 %. The hybrid simulation method suitable for sensitivity analysis, cooling system study and optimization study.
Keywords: *Air Cooled rotor, Electric vehicle (EV), Computation Fluid Dynamics (CFD), Direct Liquid Cooled EV Motor, Empirical Parameters, End Space Region, Lumped Parameter Thermal Network (LPTN), Model Fitting, Thermal Network Model, Validation, PMSM (Permanent Magnet Synchronous Motor)*

1. Introduction
Interior permanent magnet synchronous machine (IPMSM) used in electric vehicle (EV) and hybrid electric vehicle (HEV) for its higher power density and torque density. The massive heat bring challenge for safe operation of PMSM. Therefore, accurate temperature rise calculation becoming increasingly more and more important. There are three basic analysis methods: 1) lumped-parameter thermal model, 2) the finite element method (FEM) and 3) computed fluid dynamics (CFD). Mellor et al [14] studied an induction motor using the lumped parameter thermal model to calculate the average temperatures at different parts of the motor. A lumped-parameter thermal network model for radial flux PMSM [15–18] and used to calculate the average temperatures of PMSM components. The fluid flowing characteristics including gap air and coolant are studied [19–20]. Coupled electromagnetic and thermal analysis of PMSM is carried out in the paper [21] and a testing platform was established by temperature sensor and infrared thermal imager. FEM simulations can be accurate to compute temperature distributions of motor parts, but convection heat transfer coefficients generally use empirical formula, which lead to the uncertainty of results. Q.chen et al [22] studied an interior radial-flux PMSM with forced liquid (50% water+ 50% glycol) cooling in shell jacket , A lumped-parameter thermal network models for thermal design and analysis of IPMSM was divided into two stages

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combines both analytical method and CFD simulations. In the first stage, fluid can be modeled using CFD tools to compute the convective heat transfer coefficients between solid surface and fluid surface, which are necessary for FEM and lumped-parameter thermal network model. In the second stage, convection heat transfer coefficients obtained by CFD simulations can be used to amend the empirical formula. In this way, thermal model accuracy enhanced and validated with a temperature rise testing platform taking the rated load and overload into account is built to verify the above-mentioned lumped-parameter thermal network result and CFD simulation result. However, the motor endspace cooling still modelled with endspace cooling is still modelled with empirical correlation.

1.1. Problem Description

The the motor end space cooling is still modelled with empirical correlation based on flow velocity calculated using CFD simulation. This approach has two main drawbacks 1) thermal model fails to resolve non-linear velocity field in motor endspace 2) High effort demanded during model fitting with measurement data. This research paper proposes a solution by alternative CFD simulation approach address the drawbacks in motor thermal model.

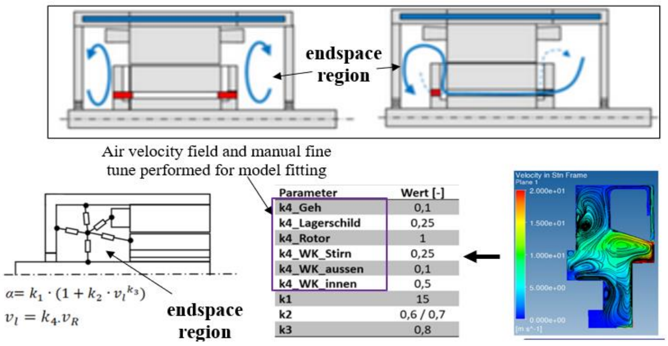

Figure 1 PMSM Motor End Space

1.2. Objective and scope

The research objective is to propose a hybrid simulation method for motor thermal model (lumped parameter) at endspace region to achieve acceptable thermal model results (~95% accuracy) and reduce effort wasted during thermal model fitting with test data. The scope of research limited only to alternative CFD model and combining existing thermal model for EV motor with dry rotor air circulation. Figure 1 shows PMSM Motor End Space

2. Motor Thermal Model

A lumped thermal network model is often used to evaluate the thermal performance of electric vehicle (EV) motors (Table 1) by breaking down the motor (Fig.2) into discrete components or regions (Fig.3), each with a uniform temperature. These regions are then connected by thermal resistances to account for heat transfer between them. By using the lumped parameter approach, you can simulate the temperature distribution within the motor and predict the thermal behavior under various operating conditions.

Table 1 PMSM Dimension and Parameters

Parameter	Value
Rated power [kW]	65
Rated speed [rpm]	4000
Stator Diameter /Length [mm]	230 mm / 94 mm
Maximum speed [rpm]	15000 rpm
Cooling technology	Stator: water jacket | rotor : dry air cooling
Water jacket flow rate	8 [l/min] @ 65 [C]
Target Pressure drop	80 [mBar] @ 8 [l/min] ,65 [C]
Length of air gap[mm]	0.75
Stator slot	48
Number of pole pair	8
Winding connections	star
Magnet grade	Rare earth magnet

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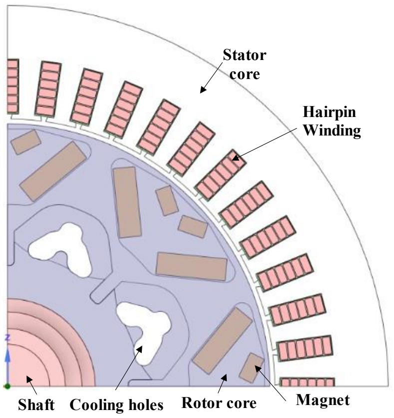

Figure 2 PMSM Geometry Model (Quarter Model)

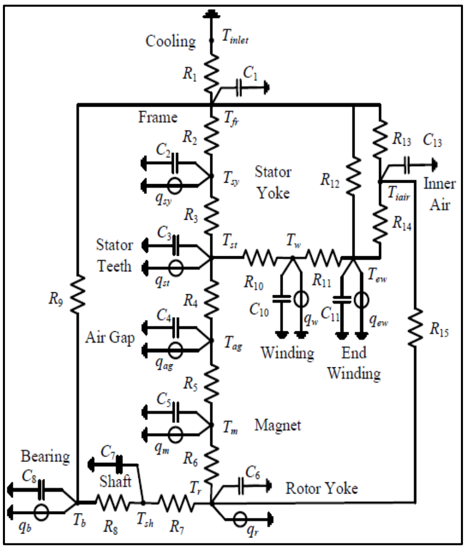

Figure 3 Motor Thermal Model

The thermal resistance between key components is crucial for understanding heat transfer and temperature rise during operation. Each component (e.g., rotor, stator, windings, housing) is modeled as a thermal node connected by thermal resistances, representing the resistance to heat flow between the components. (Refer Table 2, 3)

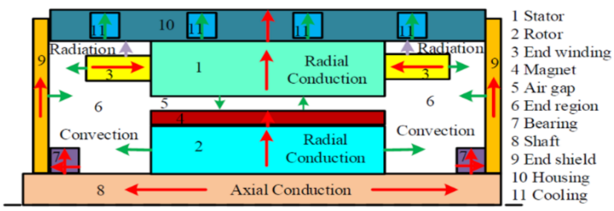

Figure 4 Heat Transfer in Motor Sections for LPTN Calculation

Table 2 Thermal Resistance Parameters

Parameters	Thermal resistance between
R1	frame and cooling system
R2	stator yoke and frame
R3	stator teeth and stator yoke
R4	Thermal resistance for air gap
R5	magnet and air gap
R6	rotor and magnet
R7	shaft and rotor
R8	bearing and shaft
R9	bearing and frame
R10	main winding and stator
R11	end winding and main winding
R12	end winding and frame
R13	inner air and frame
R14	inner air and end winding
R15	inner air and rotor

Table 3 Thermal Capacitance, Loss Parameters

Parameters	Thermal capacitance of
C1	stator frame
C2	stator yoke
C3	stator teeth
C4	air in air gap
C5	magnet
C6	rotor
C7	shaft
C8	bearing
C10	main winding
C11	end winding
C13	inner air in end region
q_{sy}, q_{st}	Losses in stator yoke and stator teeth
q_r, q_m	Losses in rotor core and magnet
q_{ag}, q_b	Friction losses in air gap and bearing
q_w, q_{ew}	Copper losses in windings and end windings

3. Solving the Thermal Model

In the steady state analysis, the final nodal temperatures are calculated by the Gauss-Siedel iterative methods and the matrix inversion theory. For the transient analysis the temperature raise of each node during time is describe by a first order differential equation solved the Runge-Kutta 4th order iterative methods, it is the preferred methods for solving the transient differential equations [13] Figure 4 shows Heat Transfer in Motor Sections.

$$\frac{d}{dt}[T] = [C]^{-1}[P] - [C]^{-1}[G][T]$$

where [T] is the temperature column vector, [C] is the thermal capacitance diagonal matrix and [G] is the thermal conductance square matrix. For the steady state analysis, the temperature variation with time can be neglected.

4. Hybrid Thermal Simulation Method: Workflow

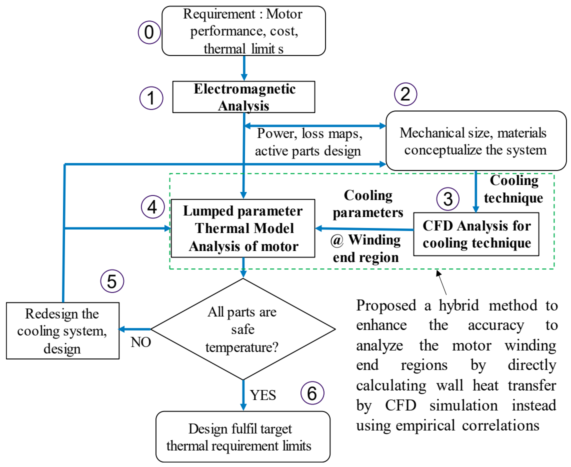

Figure 5 Flow Chart of Hybrid Simulation Workflow

5. Heat Transfer in End Region

The end-space is defined as region enclosed by end-shields, rotor, windings, stator core and housings. This area of machine cooling is known to be one of the most difficult to predict accurately. This is because the fluid flow in the end space region of an electric motor is usually much more complex than that for flow over its outer surfaces. The flow depends on many factors including the shape and length of the end winding, added inner circuit effects due to cooling holes in rotor core, the surface finish of the end sections of the rotor and turbulence.

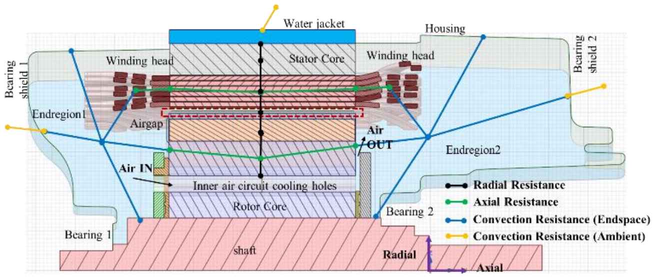

Figure 5 Local Velocity Calculated at Air Node in End Regions in Existing Thermal Model

The thermal model has Y-connected thermal circuit approach for end region air cooling effect in the frame, end windings and rotor end shown in Fig.5,6.

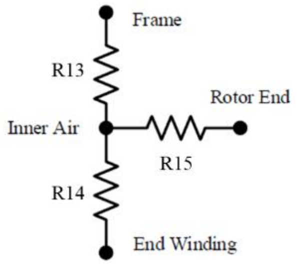

Figure 6 Inner Air Passive Cooling Model

In most of the research work ([1]-[13]) propose the use of a formulation of the form below,

$$h = k_1\,(1 + k_2\, v^{k_3})$$

h → Heat-transfer coefficient (W/m2 C).

k_1, k_2, k_3 → Curve fit coefficients.

v → Local fluid velocity (m/s)

The term k_1 accounts for natural convection and the term $k_1 k_2\, v^3$ accounts for the added forced convection due to rotation speed. The most research works (([1]-[13]) uses CFD simulation to calculate the local velocity v to estimate the heat transfer coefficients at end regions . The modern EV motors are designed with compact end regions with hair-pin windings, rotor cooling holes, sensors and housing ribs etc. This leads to a complex air flow in end regions that cause error in motor temperatures predicted by thermal, model comparison with measurements. An alternate method proposed here to enhance end regions modelling accuracy, the method directly calculate heat transfer flux at end regions walls by conjugate heat transfer CFD simulation instead using local velocity v for heat transfer coefficient calculation.

6. Determination Of End Region Wall Heat Flux In Using Conjugate Heat Transfer (CHT) Simulation

Conjugate Heat Transfer (CHT) CFD simulation combines fluid dynamics with heat transfer to model the interaction between solid and fluid domains. This type of simulation is used to understand how heat flows from solids (like an engine or motor) to surrounding fluids (such as coolant or air) and vice versa. CHT is used to determine end region wall heat

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flux at specified motor operating points . The ANSYS CFX solver used to numerically complete continuity, Navier-Stokes and total energy equations along with turbulence equations. A standard k-ω turbulence model is used. In the electric motor, two different domains are created in this exercise, one is rotating, and the other is stationary. Multiple (rotating) Reference Frame technique in steady state analysis is used. The Rotor of PMSM Motor construction in Fig. 7 shows all the major motor parts including end-winding which is considered in this study. The rotor geometry consists of disks, mold and transverse cooling holes as shown Fig. 8 with unsymmetric end regions. Due to un-symmetry around the shaft axis of the motor, the motor quarter model of end-winding is primarily considered for this study. In CHT models, stator winding modelled as actual windings with air gaps (~10 to 20 micron). The rotor and shaft axis are identified as rotational axis and stator core, stator end-winding head, housings, and bearing shields are considered as stationary walls. Rotating fluid domain represents a separate body from the winding, rotor, stator shaft, and housing walls. In the boundary condition, shaft axis and rotor axis were set as rotational reference at the speed of 500,5000,10000 &15000 r/min and the stator, housing & winding walls were set as stationary walls with temperature conditions as shown in Fig 7,8. Steady state analysis was performed and from the simulation results, Figs. 9 and 10 show the air circulation in the end-winding region. In Fig. 11 the air flow at 15000 r/min rotor speed spread more outward towards the motor with recirculation at end regions.

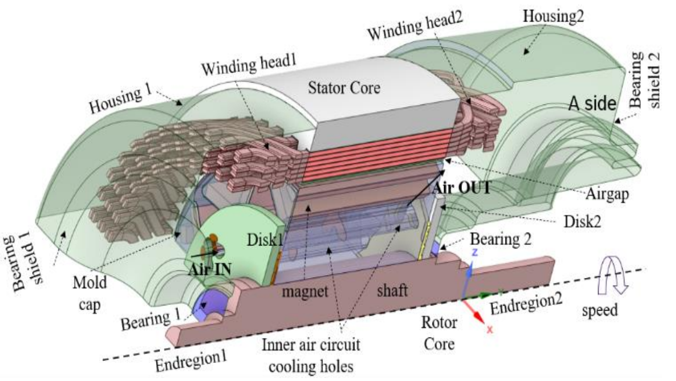

Figure7. Motor Construction 3D Quarter Model with Parts Considered for CHT Simulation

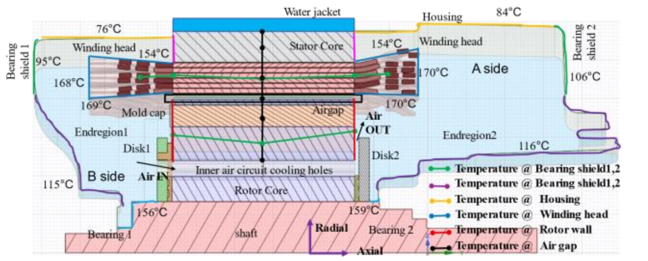

Figure8. Motor Construction with Temperature Boundary Conditions, Heat Flux Walls to Be Calculated In CHT

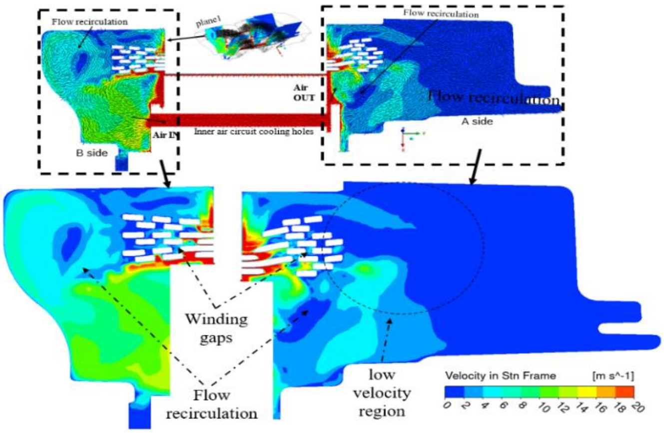

Figure 9 Air Velocity at 15000 RPM

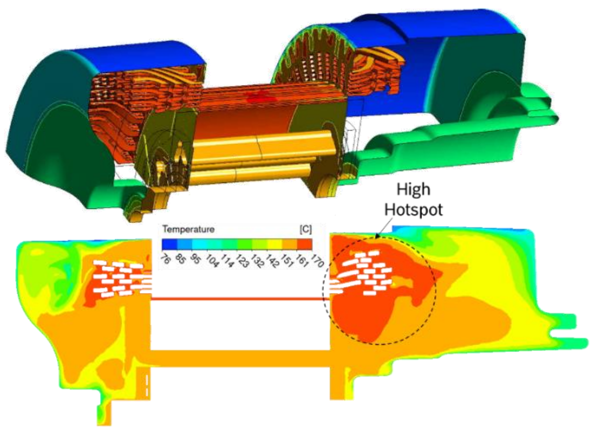

Figure 10 Temperature at 15000 RPM

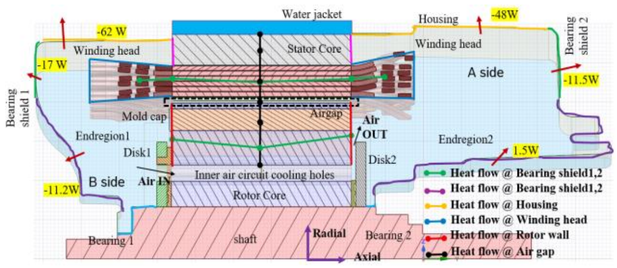

Figure 11 Heat Dissipations at 15000 RPM

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7. Validations: Thermal Model Results with Local Velocity (Air Node) & Wall Heat Flux at End Regions

The test bench has been set up to measure the temperature of the analyzed motor shown in Fig. 12. the end winding temperature measured at desired motor operating conditions. The power was supplied to a dyno motor which was used for driving the EV motor. The motor performance curve measured using test bench. The load points are selected over performance thermal measurement over full operating range. The resistance temperature detectors (RTDs) are embedded in the stator end windings of the motor for measuring the temperature. Data logger recorded the data found from the RTDs. The ambient maintained at 25°C and temperature difference between inlet and outlet kept 2–3 °C. The test motor is driven at speeds of 500,5000,10000 and 13000 RPM to measure the temperatures with 60 ,58,28 and 11 Nm torque respectively. The motor temperature measurements compared with thermal model results obtained by both methods (local velocity, wall heat flux) with CFD simulation as in table 4. The thermal model calculated using wall heat flux method predicts the temperature accurately 3 to 6 % deviations with measured data than local velocity method (10 to 13 % deviation). As wall heat flux method provide the accurate temperature measurement. The method recommended for motor cooling technique optimizations.

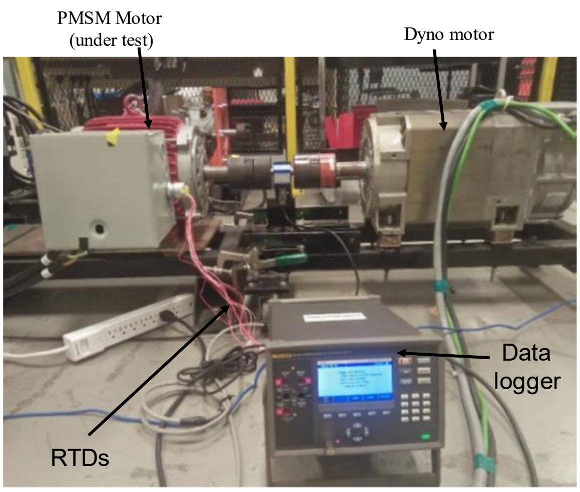

Figure 12 Measurement Setup for EV Motor with Date Logger in Laboratory

Table 4 Comparison of Test and Thermal Model Simulation

Major Motor Components	TEST	Thermal Model : LPTN					
		velocity method			heat flux method		
Load point 1: 500 RPM, 60 Nm	T [°C]	T1 [°C]	ΔT=T-T1	%	T2 [°C]	ΔT=T-T2	%
Stator core	161	140	21	13%	153	8	5%
Windings	228	202	26	12%	221	7	3%
Magnet	156	137	19	12%	147	9	6%
Rotor core	155	135	20	13%	146	9	6%
Load point 2:5000 RPM, 58 Nm	T [°C]	T1 [°C]	ΔT=T-T1	%	T2 [°C]	ΔT=T-T2	%
Stator core	166	146	20	12%	161	6	4%
Windings	218	196	22	10%	211	7	3%
Magnet	173	151	22	13%	165	8	5%
Rotor core	170	149	21	12%	164	6	4%
Load point 3:10000 RPM, 28 Nm	T [°C]	T1 [°C]	ΔT=T-T1	%	T2 [°C]	ΔT=T-T2	%
Stator core	160	142	18	11%	153	7	4%
Windings	187	169	18	10%	182	5	3%
Magnet	171	149	22	13%	163	8	5%
Rotor core	164	145	19	12%	160	4	2%
Load point 4:13000 RPM, 11 Nm	T [°C]	T1 [°C]	ΔT=T-T1	%	T2 [°C]	ΔT=T-T2	%
Stator core	161	140	21	13%	154	7	4%
Windings	174	154	20	12%	169	5	3%
Magnet	168	147	21	12%	162	6	4%
Rotor core	166	144	22	13%	160	6	3%

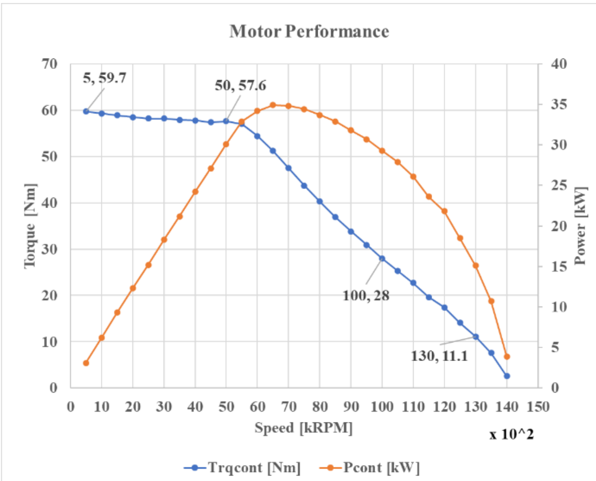

Figure 12 Motor Performance

The further difference observed in measured and calculated data can be attributed to the following, i.e.,

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a) lumped modelling approximation of the motor without circumferential heat transfer, radiations; b) Mechanical coupling devices which cause the time delay; c) Roughly estimated interface gap between stator lamination and frame which decides the heat removal; d) Unknown material thermal property data.

8. Optimization of Cooling Techniques: Thermal Model Results with Heat Flux Method

The EV motor need cooling technique to be studied to estimate optimum cooling parameters requirement for 3D design. The motor has water cooling channel and dry air cooling for rotor. The stator and rotor have limiting temperature 180°C, 142°C respectively. The cooling channel design need target heat transfer coefficients (HTC) at standard motor operating conditions (8 [l/min], 65 [C]). A sensitivity study performed using thermal model with wall heat flux method proposed in this paper.

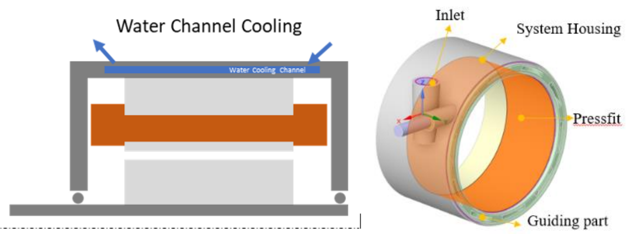

Figure 13 Motor with Water Channel, Dry Rotor Cooling Technique

The motor delivers high continuous performance achieved with cooling jacket heat transfer coefficient HTC 4600 [W/m²K]. The HTC used as input to achieve 3D cooling channel design as shown

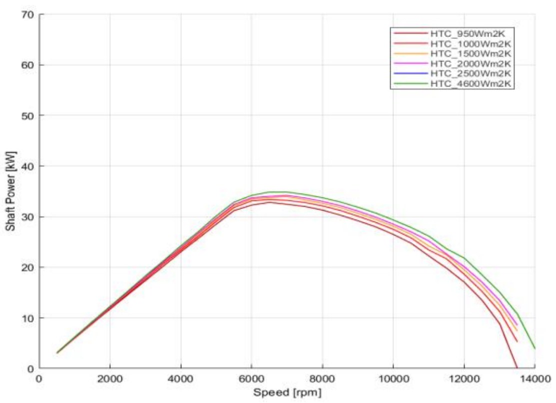

Figure 14 Optimize Cooling Technique with Thermal Model Simulation

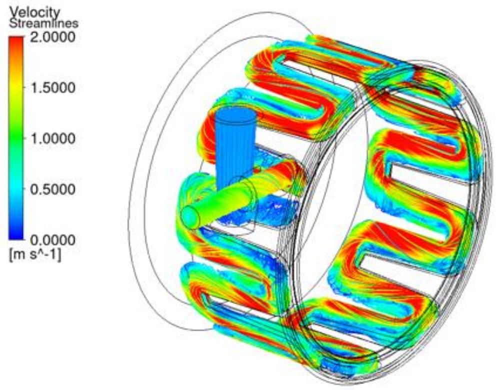

Figure 14 Result

A CFD simulation performed for meander cooling channel shown in Figure13. Th cooling channel able to produce target HTC 4600 [W/m²K] at 8 [l/min], 60 [C] with water glycol coolant. Figure 14 shows result.

Conclusion

The motor thermal model issues at endspace region are solved by combining thermal model with wall heat flux method using CFD simulation as proposed. The proposed method able to estimate the motor with acceptable accuracy (~93% accuracy) with test measurement. The method used to optimize the cooling channel to target performance. The model fitting time reduced with proposed method as proposed method does not use any empirical correlation to estimate the heat transfer coefficients with local velocity (single air node). The method can be further applied to direct liquid cooled EV motor and CFD simulation model should defined accordingly to analysis motor performance and optimization in future.

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