Cooling of Automotive Traction Motors: Schemes, Examples, and Computation Methods

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***Abstract*—This paper presents a comprehensive overview of the latest studies and analyses of the cooling technologies and computation methods for the automotive traction motors. Various cooling methods, including the natural, forced air, forced liquid, and phase change types, are discussed with the pros and cons of each method being compared. The key factors for optimizing the heat transfer efficiency of each cooling system are highlighted here. Furthermore, the real-life examples of these methods, applied in the latest automotive traction motor prototypes and products, have been set out and evaluated. Finally, the analytical and numerical techniques describing the nature and performance of different cooling schemes have been explained and addressed. This paper provides guidelines for selecting the appropriate cooling methods and estimating the performance of them in the early stages of their design.**

***Index Terms*—Automotive applications, cooling, numerical analysis, thermal analysis, traction motors.**

Nomenclature

A	Cross-sectional area of heat path (m^2).
A_l	Linear current density (kA/m).
A_i, A_o	Inlet and outlet cross-sectional areas (m^2).
c_p	Specific heat capacity (J/kg).
D	Diameter (m).
f_s, f_r	Friction loss factor (dimensionless).
g	Gravitational attraction force (m/s^2).
Gr	Grashof number (dimensionless).
H	Fin extension (m).
h	Heat transfer coefficient (W/m^{2}K).
h_l	Latent heat (kJ/kg).
k	Loss coefficient (dimensionless).
J	Current density (A/mm^2).
L	Length of the surface (m).
N	Number of fins (dimensionless).
Nu_{Natural}	Natural Nusselt number (dimensionless).
Nu_{Forced}	Forced Nusselt number (dimensionless).
Δp	Pressure drop (Pa).
Pr	Prandtl number (dimensionless).
R	Convection thermal resistance (K/W).
Re	Reynold number (dimensionless).
Re_r	Rotational Reynold number (dimensionless).
T_w, T_f	Wall and fluid temperatures (K).
ΔT	Temperature difference (K).
S	Fin pitch (m).
V	Axial velocity (m/s).
V_r	Tangential velocity (m/s).
μ	Dynamic viscosity (Pa·s).
λ	Thermal conductivity (W/m·K).
ρ	Density (kg/m^3).
β	Coefficient of the expansion (dimensionless).
σ	Tangential stress (kPa).

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I. Introduction

While operating an electric motor, heat is generated due to the electromagnetic losses, mechanical power losses, and other stray losses that take place in various components within an electric motor. Through conduction, convection, and/or radiation, the thermal energy is transferred to a cooling medium [1] on the basis of a temperature difference between the hot and cold bodies. However, a detailed thermal management is essential during critical operating conditions, such as overload running, phase changing, and/or asymmetric faults, to avoid failures that are usually due to the local hot spot formation, and material degradation [2]–[5]. Furthermore, the topic of magnetic losses and heat generation governs the performance of the electromagnetic efficiency and longer life expectancy. First, excessively high temperatures can cause accelerated insulation aging [6] and deterioration within some essential components, such as winding conductors [7]. Second, the remanence and coercivity of the rare earth magnets are inversely proportional to the temperature. As a result of which partial or full demagnetization at higher temperatures may occur [8], [9]. In case of the ferrite and recycled magnets [10], [11], the lower rotor temperatures may significantly boost the torque density and/or efficiency

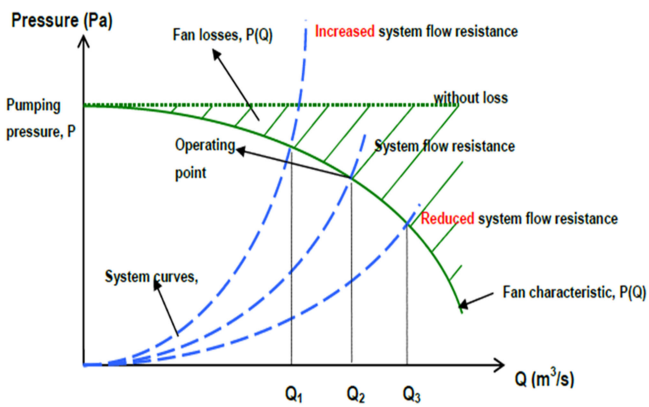

Fig. 4. Typical fan characteristic curve [35].

Fig. 5. Axial fan with forward-swept and inclined blades [39].

adding geometrical modification such as cutting multiple air slots into the shaft, rotor, or the stator core [36].

In a fan-based cooling system, the fan provides a differential pressure to make the coolant air flow. Fig. 4 shows the relationship between the fan characteristic and the motor enclosure system resistance curve, as well as the operating pressure and the flow rate at the intersection point. The bending of the fan characteristic curve is due to the energy losses, and can be improved by optimizing the aerodynamic structure of the blades. A new kind of axial fan with forward-swept and inclined blades is employed in [37]–[39] to reduce the ventilation resistance inside an electric motor, as illustrated in Fig. 5. Further enhancement in cooling can be achieved by various retrofit methods, such as adding internal air baffles to an EFC motor [40], or by interrupting any combination of flows from occurring especially at high rotor speed [35], as shown in Fig. 6.

One of the major challenges associated with fan cooling is the emission of acoustic noise, especially at a high-speed fan operation. Several noise mitigation methods have been proposed in the literature by using the following approaches:

1) forward-swept inclined fans [37], [38];
2) a better aero-foil shape blade cross section [41];
3) inlet bell-mouth entry [42];
4) composite materials for blades [42];
5) reduced number of blades [41], [42];
6) irregular-pitch-blade fan [30], [42], [43];

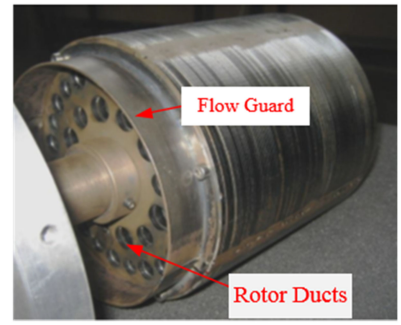

Fig. 6. Arrangement of flow guard [35].

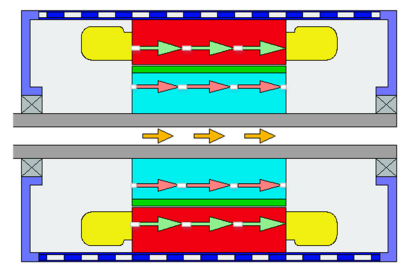

Fig. 7. Forced-liquid cooling models.

7) a mixed flow (both axial and radial) fan [41].

2) Forced Liquid: A forced-liquid cooling solution is suitable in particular applications, especially for high-power electric motors, where the requisite outputs cannot be attained by EFC or OFC motors. Forced-liquid cooling approaches such as those that are designed for electric motors are presented in Fig. 7. In such a cooling system, the forced liquid passes through the housing jacket, stator channels, and/or rotor channels. However, the forced-liquid cooling system suffers from a number of weaknesses, such as stains, corrosion, leakage, and contamination. The remaining stains inside of cooling channels may lead to a significant rise in flow resistance, which causes a decrease in the cooling effectiveness. The most common liquid coolant in thermal management of electric motors is water. The reason why water is chosen is primarily due to the high relative heat capacity of this liquid. In addition, a number of components are available for commercial applications, such as ethylene glycol and water (EGW) 50/50 and engine oil.

a) Housing water jacket: The cooling via a housing jacket is the most common forced-cooling approach. This is where the liquid flows through the cooling channels situated in a thermally conductive frame above the stator stack [17], [44]–[46]. The heat generated in the coils, as well as in the stator and rotor laminations, is initially transferred to the cooling housing through conduction, and is then transferred to the ambient environment via convection in the coolant fluid. The efficiency of the liquid cooling technique heavily depends on the geometrical clearance and the resultant thermal resistance between the laminated stator core and the cooling housing.

The effects of different parameters on the contact thermal resistance between the laminated stator core and the frame,

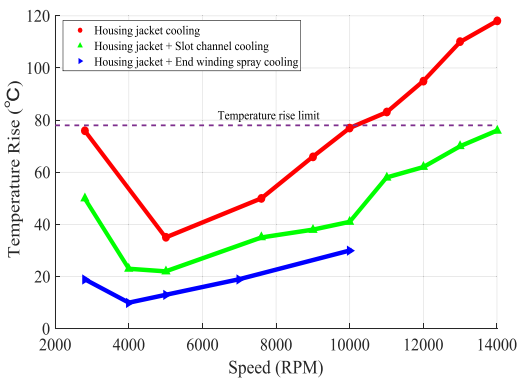

Fig. 14. Performance comparison for various cooling systems [16].

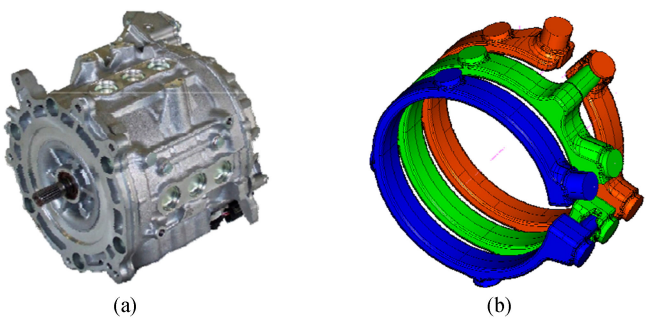

Fig. 15. (a) Nissan-leaf electric motor. (b) Model of cooling water.

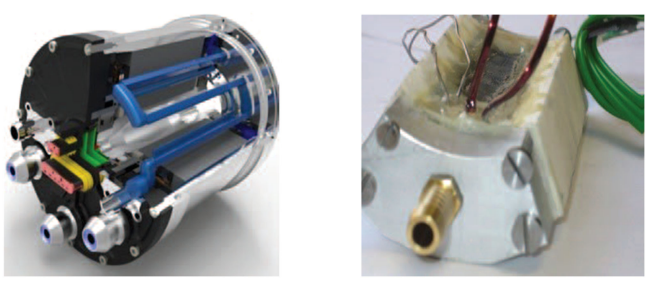

Fig. 16. Slot duct cooling for the whole motor (left) and single teeth prototype (right) [55].

frame above the stator stack in parallel using EGW 50/50 as a coolant to ensure a sufficient cooling performance.

In Fig. 16 [57], a forced cooling fluid flows through the slot cooling tubes (with the option of being connected in series or parallel). The slot cooling tubes are placed inside the winding slots, adjacent to the coils.

A plurality of heat pipes are inserted in the stator slots in [60], as displayed in Fig. 17(a). All the heat pipes are extended into a cooling chamber that can be filled with oil or some other cooling fluid. Another example in [75], Fig. 17(b) discloses a heat pipe that is located in the motor hollow axle, where a metallic plate as a heat exchanger is mounted at the end of the heat pipe.

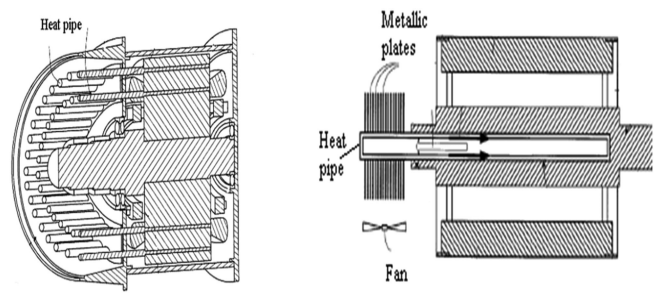

Fig. 17. Motor assembly with heat pipe cooling system [71], [73].

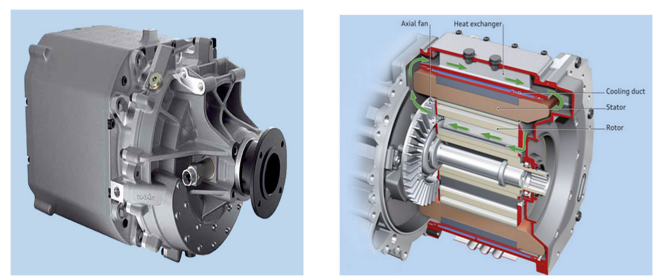

Fig. 18. Zytek high power density PMSM with dual cooling system [76].

Zytek electric traction motor [76], as shown in Fig. 18, is based on a dual cooling system, a self-ventilated cooling where internal forced air flows through the rotor axial ducts, as well as the air gap of the motor, in combination with a housing water jacket. The recirculating air brings heat from the inner motor to the heat exchanger.

A list of the various cooling methods installed in the latest traction motors has been provided in Table II.

IV. Computation Methods

An accurate understanding of the cooling performance in an electric motor is a prerequisite of an accurate and efficient thermal design. The key parameters to achieve this goal are the convection heat transfer, flow resistance, and fan performance in case of fan cooled systems, etc., while the common approaches include analytical lumped-circuit and numerical methods.

The analytical approach can be subdivided into two main calculation types: heat-transfer and flow-network analyses. Both of them are based on readily available empirical correlations in the thermal analytical literature and have the advantage of being fast. In the lumped-circuit thermal network, the convection heat transfer between the surface of the motor components and the coolant is described by convection thermal resistance defined as (9). The temperature of the motor components allow predictions based on the convection thermal resistances for a given power distribution. In the flow network, a drop in pressure takes place due to the flow restrictions (e.g., friction, expansion, and contraction). Any loss in pressure is usually quantified with an empirical loss coefficient (k) based on the flow of kinetic energy, defined as (10). The dimensionless correlations used for

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