Numerical model for thermal calculation analysis of the wheel hub motor for electric car verified by laboratory tests

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Abstract. The article concerns the thermal analysis of an electric motor for mounting in a wheel hub of an electric car. The CFD model was calibrated on the basis of the results of laboratory tests of the prototype electric motor. The analysis was aimed at recognizing the possibility of increasing the load capacity of an electric motor through the use of dielectric materials with higher thermal conductivity than those used in the actual prototype. The authors presented the problem of heat removal from motors in wheel hubs, construction of the electric motor, the calculation model and analysis of calculation results.

1. Introduction
With the growing interest in electric cars, various directions related to electric drives are being developed. Recently, one of the most recognizable trends in the field of traction electric motors are electric motors for mounting in the hub of a vehicle. The solution is not new, it was first used by Ferdinand Porsche at the turn of the 19th and 20th century to create the world's first hybrid car [1].

With the development of electromobility, the idea of placing motors in wheels is being developed again [2, 3, 4, 5, 6, 7, 8, 9]. Motors of this type can be widely used in the electric vehicle industry for application from small city cars, cars and family cars, to delivery vans and buses. Łukasiewicz Research Network – Institute of Electrical Drives and Machines KOMEL has undertaken research and design works that will enable the provision of services related to the design and production of this type of electric motors for various types of vehicles. This article presents analysis of construction of this type of motors in terms of the possibility of effective heat removal, which will allow to obtain the best drive parameters of the electric motor while maintaining the lowest possible mass.

In the case of electric motors for installation in the wheel hubs of cars, the reduction of weight while maintaining high performance parameters is extremely important, because the weight of the electric motor is an additional unsprung mass for the suspension system. Reducing the weight of the electric motor also has a positive effect on the drives of the central structure, because it reduces the mass of the entire drive and increases the space under the hood of the car.

Main advantages of this type of drive are elimination of elements mediating in the transmission of torque between the electric motor and the vehicle wheel, providing space under the hood, introducing new vehicle control capabilities due to application of torque in each motor, and possibility of using hybrid systems. This solution, in order to be able to be used, requires meeting a number of challenges, one of the most important is removal of heat from the motor winding.

One of the main aspects when designing an electric motor with compact design is adequate limitation of power losses in its individual elements, which can affect possible parameters of work. In the vast majority of design solutions for electric motors, the main source of heat is winding, which maximum operating temperature limits thermal resistance of insulation. In the case of permanent
magnet motors, in the construction of an electromagnetic circuit, winding occurs only in the stator. Generated power losses in the form of heat are discharged through the air and the magnetic core to the hull of the electric motor or other elements such as support elements on which the stator is mounted, as in the electric motor presented in this article. Thermally, the most loaded parts of winding are its ends, because as a standard, their construction is located outside the stator slot and do not adhere to the core.

Owing to appropriate calculations, similar to other publications [10, 11, 12, 13, 14, 15, 16, 17] the influence of different materials used for construction of the motor on its thermal state can be analysed.

2. Construction of the considered wheel hub motor

The prototype motor is based on bearing and braking system from Fiat Panda III, while the external dimensions were limited by the dimensions of the 17-inch rim (figure 1). The motor consists of two main components: the rotor and the stator. The source of heat in this type of machine are losses in the rotor (magnets, a yoke of the electromagnetic circuit) and in the stator (winding, core). A significant part of losses are those in the stator. To ensure adequate heat recovery from this element in the stator supporting structure, a water jacket was made and the empty space between was filled with a thermoconductive resin. Figure 2 shows the cross section of the 3D model of the electric motor.

![Figure 1. A prototype of a wheel hub motor SMZs200S32 for electric car: front view (on the left) and back view (on the right).](image1)

![Figure 2. 3D model of the SMZs200S32 electric motor: cross section of motor with rim and tire (on the left) and cross section of the motor (on the right), 1 – rim and tire, 2 – rotor, 3 – stator, 4 – winding ends, 5 – epoxy resin, 6 – stator core, 7 – cooling system jacket with flow channels, 8 – braking drum, 9 – bearing system, 10 – magnet.](image2)
The cooling system of the tested electric motor uses different ways of removing heat from winding. The first is standard for all electric motors and includes a path for heat transfer from winding in the stator slots to the magnetic core of the stator. An important thermal resistance for this path is slot insulation resistance, which protects winding against electric breakdown. Another way to remove heat from winding in the motor under test is the path between the winding end and the cooling system jacket. The path is largely dependent on the thermal resistance of the epoxy resin used. In standard solutions of electric motors, not encapsulated in epoxy resin, it is the temperature of the ends of winding surrounded by air that is the highest.

In the carried out tests, the temperature of stator winding has a significant influence on the work parameters of the electric motor. It is in winding that its parameters, such as rated torque, maximum torque, related to its overload and long-term overload, will depend on it, and more precisely on its insulation class. The torque of the electric motor has a direct effect on the driving characteristics of the car, its acceleration, driving dynamics, the maximum elevation to which it can enter and the maximum speed with which it can move.

As a part of the work carried out, a prototype motor and its laboratory tests were performed. Temperature sensors in key components have been installed in the motor, including stator windings in both magnetic core slots, and in the ends. Based on the results of laboratory tests, the model for thermal calculations has been verified. In the subsequent stages of the work, motor simulations of operation were carried out considering changes in thermal conductivity parameters of the materials: epoxy resin and slot insulation.

**Figure 3.** Laboratory stand for testing electric motor SMZs200S32.

### 3. Calculation on the model for CFD analysis

The analysis included in the article was carried out for the motor work point: \( P_m = 35 \text{ kW}, \ T_m = 350 \text{ Nm}, \ n = 950 \text{ rpm} \). This is the point corresponding to the Fiat Panda car on a hill with a slope of 12% at a speed of 70 km/h, assuming that the vehicle drive consists of two electric motors mounted in the wheels of the rear axle of the car.

In the CFD analysis, the model was additionally supplemented with a cooling medium in the water jacket channels. It also assumed substitute parameters of thermal resistances: \( R_S \) – thermal resistance corresponding to the pressure between the core and the water jacket construction, \( R_Z \) – the thermal resistance corresponding to the slot insulation (figure 4).

In the boundary conditions of the model (figure 5), ambient temperature, temperature of the rotor interaction (upper surface of the stator), flow rate of the cooling medium, its type and temperature were considered. The following thermal conductivities of individual elements were assumed: load-bearing element – \( \lambda_k = 150 \text{ W/mK} \) (aluminium alloy AlSi9Mg), stator core – \( \lambda_{bx,y} = 25 \text{ W/mK} \) (in the plane of electrotechnical sheets), \( \lambda_{bx,z} = 2 \text{ W/mK} \) (perpendicular to the plane electrotechnical plates), winding \( \lambda_{ux} = 2 \text{ W/mK} \) (perpendicular to the wires) and \( \lambda_{oxy} = 290 \text{ W/mK} \) (along the wires), determined on the basis of the experience of KOMEL Institute and taken from the literature [18, 19, 20, 21, 22, 23].
Figure 4. The calculation model of the motor stator: 1 – stator bearing element with a water jacket, 2 – stator core, 3 – winding, 4 – thermo-conductive resin, 5 – radiator, $R_z$ – substitute thermal resistance of slot insulation, $R_s$ – thermal resistance between the jacket and stator core, $R_t$ – thermal resistance between the jacket and the heatsink.

Figure 5. Discrete model for thermal calculations of the considered electric motor.

Figure 6. Arrangement of thermocouples in the tested prototype (on the left) and calculated temperature distribution for the working point of the electric motor: $P_{\text{in}} = 35$ kW (on the right): 1 – winding in the nursery (right side), 2 – winding in the nursery (left side), 3 – winding end (right side), 4 – winding end (left side), 5 – heat sink (right side), 6 – radiator (left side), 7 – stator core (right side), 8 – stator core (left side), 9 – coat (right side), 10 – coat (left side).
During the calibration process, in the stator model, ambient temperature, rotor temperature, coolant temperature, measured and calculated losses in the winding ($\Delta P_{Cu} = 1560$W) and stator core ($\Delta P_{Fe} = 900$W) were taken, and then thermal resistance parameters were corrected in order to obtain the expected convergence of numerical calculation results with an experiment ($\leq 1^\circ$C) for a given steady state. As a result of calibration, the following values of thermal resistances were determined: $R_z = 0.0018 \text{ m}^2\text{K/W}$, $R_S = 0.00148 \text{ m}^2\text{K/W}$, $R_r = 0.00065 \text{ m}^2\text{K/W}$. The temperature recorded during the experiment and obtained as a result of calculations using a calibrated model for a power of 35kW are summarized in Table 1 (figure 6).

Table 1. Comparison of the results of calculation with the results of laboratory tests.

| Point (figure 6) | Measurements | Calculations | Difference |
|------------------|--------------|--------------|------------|
| 1                | 94.0         | 93.5         | 0.5        |
| 2                | 92.3         | 91.6         | 0.7        |
| 3                | 95.8         | 94.8         | 1.0        |
| 4                | 88.9         | 88.2         | 0.7        |
| 5                | 47.5         | 46.9         | 0.6        |
| 6                | 57.5         | 58.5         | 1.0        |
| 7                | 50.4         | 49.7         | 0.7        |
| 8                | 60.8         | 61.6         | 0.8        |
| 9                | 36.8         | 36.5         | 0.3        |
| 10               | 44.6         | 45.4         | 0.8        |
| in               | 24.1         | 24.1         | -          |
| out              | 27.7         | 28.0         | 0.3        |
| amb              | 28.0         | 28.0         | -          |

*a cooling water temperature at the inlet.
*b cooling water temperature at the outlet.
*c ambient temperature.

For the computational model prepared this way, the temperature difference between calculations and results of the experiment does not exceed $1^\circ$C, which confirms that the adopted calculation model has been properly calibrated. Then, simulations of the operation of the considered electric motor were performed for the same work point, making changes in the thermal conductivity of selected dielectric materials in the model – an epoxy resin surrounding the winding front and slot insulation in the magnetic core.

Table 2 presents calculation results for different thermal conductivities of the epoxy resin. The results are presented in the function of coolant flow. According to them, for a flow of 0 l/min winding temperature more than twice exceeds the permissible operating temperature of winding ($180^\circ$C). Application of flow even at 2.5 l/min allows to significantly reduce the temperature. Winding temperature differences for the use of different resins reach about $7^\circ$C, in the case of a difference between a resin with a thermal conductivity of 1.2 W/mK and a resin with a thermal conductivity of 3.5 W/mK. The temperature difference depending on the flow value is up to approx. $12^\circ$C, regardless of the thermal conductivity of the resin.

Figure 7 presents winding temperature characteristics as a function of the coolant flow value for different thermal conductivity of the epoxy resin used. From the course of the characteristics, it can be seen that the coolant flow rate has the greatest impact up to approx. 5 l/min. At a flow rate of 10 l/min, the greater thermal conductivity of the epoxy resin from 1.2 W/mK to 1.5 W/mK allowed for a
reduction in temperature of approx. 3°C. The temperature difference between successive resin values is even lower.

The analysis shows that the use of twice the coolant flow from 10 l/min to 5 l/min and the resin with a conductivity of 2.5 W/mK will get the same winding temperature as for the resin used in the prototype of the electric motor (1.2 W/mK). Such a change may allow the use of a smaller pump in the cooling system which may translate into energy savings.

**Table 2.** Calculated motor winding temperature for different values of thermal conductivity of the epoxy resin as a function of the coolant flow value.

| Coolant flow Q (l/min) | The temperature of the motor winding θ_{Cu} (°C) |
|------------------------|--------------------------------------------------|
|                        | λ = 1.2 (W/mK) | λ = 1.5 (W/mK) | λ = 2.0 (W/mK) | λ = 2.5 (W/mK) | λ = 3.0 (W/mK) | λ = 3.5 (W/mK) |
| 10                     | 99.0           | 96.2           | 94.5           | 93.2           | 92.2           | 91.3           |
| 5                      | 104            | 102            | 100            | 99             | 98             | 97             |
| 2.5                    | 110            | 109            | 107            | 105            | 104            | 103            |
| 0                      | 431            | 429            | 428            | 427            | 426            | 425            |

Six slot insulation variants were adopted for calculations. The first variant represents the insulation actually used in the prototype motor. The motor uses insulating material with thickness of 0.3 mm and a thermal conductivity of 0.13 W/mK. On this basis, the insulation resistance $R_i$ has been calculated. Subsequent variants assume that the insulating materials have the same dielectric properties as the original material, for which their thickness in all cases is constant, equal to 0.3 mm. However, the thermal conductivity changes. For materials 2-5, the conductivity varies from 0.3 W/mK to 0.9 W/mK. The values have been selected on the basis of insulating materials available on the market. Materials with a conductivity above 0.5 W/mK are already difficult to access and relatively very expensive. The last material is an innovative solution because it reproduces ceramic insulation made of corundum. Corundum is aluminium oxide ($\text{Al}_2\text{O}_3$), it has a high thermal conductivity of up to 35 W/mK. On the basis of the model of substitute thermal resistance of slot insulation and the calculated insulation resistance selected in the framework of the calibration, the resistance of the crevice $R_{Z1}$ was determined. $R_{Z1}$ is the resistance resulting from the technology of making a wound stator that includes, among other things, the contact of insulating material with a magnetic core, which is in fact not ideal. The calculations were made for different values of coolant flow in the cooling system and for the electric motor version with encapsulated winding in epoxy resin and for the version without encapsulated winding.

$$R_i = \frac{d}{\lambda}$$

(1)

$$R_Z = R_i + R_{Z1}$$

(2)

where:

- $R_i$ [m²K/W] – calculated insulation resistance
- $R_{Z1}$ [m²K/W] – resistance resulting from the technology, between the slot insulation and the magnetic core
- $R_Z$ [m²K/W] – substitute thermal resistance of slot insulation
- $d$ [mm] – assumed thickness of slot insulation
- $\lambda$ [W/mK] – thermal conductivity of slot insulation

On the basis of results presented in figure 8, it can be observed that the change in the thermal conductivity of insulation has more impact in the case of the model without resin (resin replaced with air) then in the case with epoxy resin (figure 9). In the case of the model without resin, it can be seen
that increasing the thermal conductivity of insulation from 0.75 W/mK is no longer effective, only a significant increase, e.g. up to 35 W/mK, allows a noticeable reduction in the winding operating temperature. In the case of a model with winding encapsulated in an epoxy resin, the effect of thermal insulation resistance is much smaller. The use of corundum insulation slightly lowered the temperature of winding in relation to insulation used in the prototype electric motor.

Figure 7. Calculated characteristics of the winding temperature of the electric motor as a function of the coolant flow, for different values of thermal conductivity of the resin.

Figure 8. Calculated characteristics of the winding temperature as a function of coolant flow for different thermal conductivities of the slot insulation – model without resin.
Figure 9. Calculated characteristics of the winding temperature as a function of coolant flow for different thermal conductivities of the slot insulation – model with resin.

Table 3. Calculated resistance used in calculations.

| $d$ (mm) | $\lambda$ (W/mK) | $R_i$ (m²K/W) | $R_{Z1}$ (m²K/W) | $R_Z$ (m²K/W) |
|---------|------------------|---------------|------------------|---------------|
| 1       | 0.3              | 0.13          | 0.002308         | 0.000316      | 0.002624      |
| 2       | 0.3              | 0.30          | 0.001000         | 0.000316      | 0.001316      |
| 3       | 0.3              | 0.45          | 0.000667         | 0.000316      | 0.000982      |
| 4       | 0.3              | 0.75          | 0.000400         | 0.000316      | 0.000716      |
| 5       | 0.3              | 0.90          | 0.000333         | 0.000316      | 0.000649      |
| 6       | 0.3              | 35            | 0.00000857       | 0.000316      | 0.000324      |

4. Conclusions

The numerical calculations of MES and CFD allow to determine the operating parameters of the electric motor. Due to the calculations carried out, the minimum flow values of the cooling medium can be determined considering the maximum permissible operating temperatures of the machine. It is also possible to determine the recommended value of the cooling medium flow, above which there is no significant improvement in the efficiency of the cooling system, but only the hydraulic resistance increases negatively.

Calculations on the calibrated model allow for a wide analysis of the motor structure in terms of thermal aspects. Laboratory tests have made it possible to estimate the thermal resistance $R_{Z1}$, which is the sum of the technological aspects of stator slot insulation. The extensive analysis allowed to determine the possibility of modifying the motor in the direction of lowering the winding operation temperature by changing the epoxy resin used in the motor to resins with higher thermal conductivities. In the case of commercially available resins, it should be noted that with the increasing thermal conductivity, the mechanical parameters of the resin deteriorate, which directly affects the possibility of its use in an electric motor for electric cars. For resins with higher thermal conductivity, usually the process of potting the winding and stator is more demanding because it is related to the
potting regime in the appropriate temperature sequence. Resins with higher thermal conductivity also have less penetration and tendency to crack. It should be remembered that the resin in this type of solutions combines elements with various heat-shrinking properties, i.e. stator magnetic core, copper windings, and aluminium jacket of the cooling system.

Analysis of the change in the slot insulation showed that with such an efficient cooling system, using a labyrinth with cooling liquid flow and epoxy resin, supporting heat from the winding to the cooling system only a significant increase in insulation resistance allows for a noticeable change. Based on the calculations made, the constructor can consider the direction of motor design modification and consider its cost-effectiveness. While the calculations confirmed the applicability of the cooling liquid flow and the use of the resin, the reason for reducing the thermal resistance of the slot and resin insulation is no longer so obvious. A computational model prepared and calibrated on the basis of laboratory tests allows to determine the development directions of a given electric motor structure and save testing costs and costs of making subsequent prototypes, which design changes will have no effect.

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