3D-Modeling and Analysis of Miniature Stator Design for Electrical Machines

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INTRODUCTION:

With the evolving trend of electrification in transportation, electric machines with higher power density and higher efficiency are demanded which results in the thermal limit of the stator winding becoming more of a key constraint. Excessive conductor heating not only limits allowed current density, but also strains the electrical insulation needed in coils and adversely affects the reliability and meantime-between-failure. A direct cooling method is used in this analysis and air is in direct contact with the stator winding by flowing over the conductor. This Analysis also compares two stator material, PEEK and Alumina and compares the peak temperatures in both the cases and a parametric analysis is performed looking at peak temperature and pressure drop for different inlet velocities and current density combinations. The stator design is part of the dual rotor motor concept shown below.

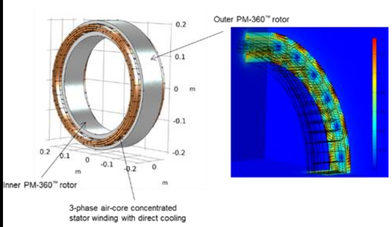

Figure 1. Example geometry for a dual rotor motor based on AML's PM-360 magnets (left) and magnetic flux distribution (right)

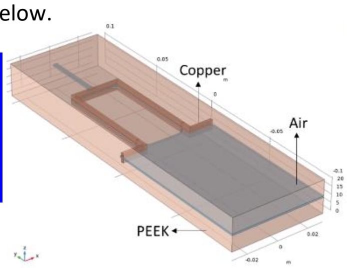

Figure 2. Geometry of miniature stator with 1 pole and 1 phase

GEOMETRY:

The geometry is a miniature stator design (1 pole and 1 phase) and the has two layers of copper sitting on a support structure separated by an air gap. Both PEEK and Alumina are tested as the support structure materials and their impact on peak temperatures is compared. The PEEK support substrate is 60 mm X 200 mm X 21 mm and the air gap is 1 mm. The copper is 388 mm long and the cross-section of the copper is 1.6 mm X 2.5 mm. The inlet air flow cross-section is 60 mm X 1 mm and the outlet cross-section is 2.6 mm X 1 mm.

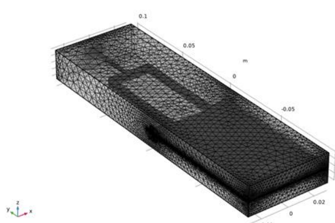

Figure 3. Sample Mesh (1209210 elements)

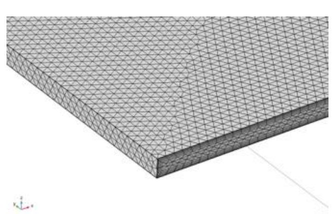

Figure 4. Fluid Domain Mesh (506675 elements)

GOVERNING EQUATIONS:

CONTINUITY: $\nabla.(\rho u) = 0$

MOMENTUM: $\rho(u.\nabla)u = \left[-pI + (\mu + \mu_T)(\nabla u + (\nabla u)^T) - \frac{2}{3}\mu(\nabla.u)I\right] + F$

K- ε FORMULATION :

$$\rho(u.\nabla)k = \nabla.\left[\left(\mu + \frac{\mu_T}{\sigma_k}\right)\nabla k\right] + P_k - \rho\varepsilon$$

$$\rho(u.\nabla)\varepsilon = \nabla.\left[\left(\mu + \frac{\mu_T}{\sigma_\varepsilon}\right)\nabla\varepsilon\right] + C_{\varepsilon 1}\frac{\varepsilon}{k}P_k - C_{\varepsilon 2}\rho\frac{\varepsilon^2}{k}, \; \mu_T = \rho C_\mu \frac{k^2}{\varepsilon}$$

ENERGY: $\rho C_p u.\nabla T = Q + \nabla(k\nabla T)$

BOUNDARY CONDITIONS:

Velocity Inlet : $u = -u_0 n$

Pressure Outlet : $[-pI + K]n = -\hat{p}_0 n$

Thermal Insulation : $-n.(k\nabla T) = 0$

Heat Source : $Q = Q_0$, $Q_0 = f.\rho_r J^2 * volume$

RESULTS:

Using the turbulent flow with k- ε formulation and heat transfer in solids and fluids, the stationary study is simulated in COMSOL. For PEEK as substrate the peak temperature is 422 K and pressure drop across the stator is 1935 Pa and for Alumina the peak temperature is 404 K and the pressure drop is the 1938 Pa. Parametric analysis was set up to the study the effects of velocity and current density on peak temperature and pressure drop across the stator. The inlet velocity is varied from 1.5 m/s to 5m/s with a step size of 0.5 m/s and the current density has been varied from 20 A/mm^2 to 30 A/mm^2 with a step size of 2 A/mm^2.

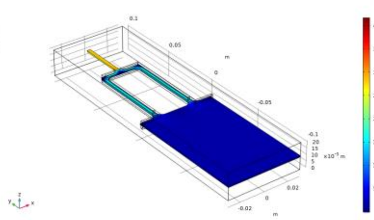

Figure 5. Velocity Profile

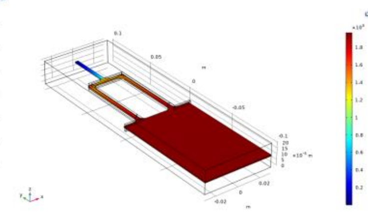

Figure 6. Pressure Profile

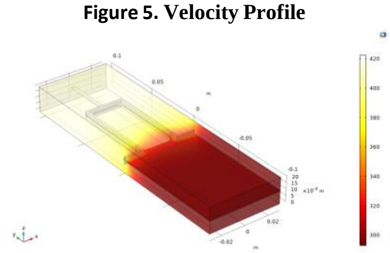

Figure 7. Temperature Profile (PEEK)

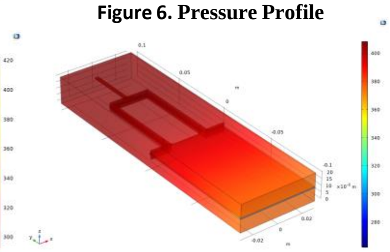

Figure 8. Temperature Profile (Alumina)

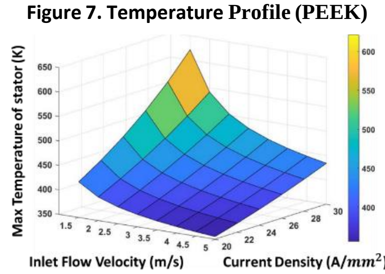

Figure 9. Peak Temperature Surface plot

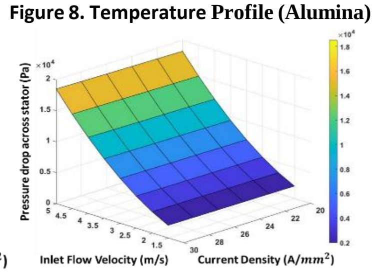

Figure 10. Pressure drop Surface plot

CONCLUSION:

The simulation results demonstrate that when using Alumina as the stator support material the peak temperature was 5% lower when compared to PEEK as support material for the stator. The reason being the thermal conductivity of Alumina is 10 times higher than that of PEEK and thus heat transfer is better. A parametric analysis was performed showing higher the velocity leads to a decrease in peak temperature. It was shown that as the inlet velocity increase from 1.5 to 5 m/s the peak temperature decreases by 16%, but the tradeoff is pressure loss as it increases by 810%. The effects of current density were also analyzed and for a 50% increase in current density of the conductor the peak temperature increases by 41%. The pressure drop change is minimal as the flow conditions don't change and only the thermal properties of the material changes due to the increase in temperature leading to 3% increase in pressure drop. This steady state thermal analysis provides valuable guidance for designing such stator configuration and acts as a good base for future experimental tests and validations. The miniature stator will be fabricated and tested to validate the design experimentally.