Multi-physical simulation of cryogenically cooled axial-flux electric motor

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Abstract

Axial-flux permanent-magnet motors offer advantages over radial-flux motors, such as higher power density and torque-to-weight ratio. However, heat losses from AC/DC effects reduce motor efficiency and lead to high temperatures. The K-AXFLUX project addresses this by developing an axial-flux motor cooled with hydrogen gas flowing through hollow copper coils in the stator. Liquid hydrogen from a storage tank enters the coils, evaporates, and exits as gas, which is then sent to a fuel cell. Multi-physical simulation using COMSOL is developed to evaluate the cooling effect induced by the hydrogen flow and the resulting temperature distribution within the stator geometry. By exploiting sectoral symmetry, the simulation models turbulent hydrogen flow as well as heat transfer in the copper coil, stator and the surrounding air. The results show that the copper coil temperature remains below 293 K, indicating effective cooling by hydrogen gas, for the given set of flow parameters. Reduction of overall temperature in the copper coil is important as it improves electrical conductivity and reduces resistive heating, further enhancing motor efficiency. The simulation model provides a basis for further optimization using surrogate modelling and Bayesian techniques to improve the thermal efficiency of the axial-flux motor.

Keywords: axial flux motor, multi physical simulation, hollow conductors, direct cooling

Introduction

The electric motor designs in the last decade have seen a significant improvement, leading to transformation in transportation and aviation industries. More and more electrical (EV), hybrid (HEV) and fuel cell (FEV) vehicles have been on the market in the last decade because they can satisfy emission regulations and increase fuel efficiencies. [1]. There are many factors which influence the performance of the motors and many ways to improve the performance of an electric motor. One of the methods is to improve the cooling design and in turn improve the performance.

To improve the cooling of the motor it is important to locate the sources, which generate heat in the electric motor. The four main heat generating sources are

- Direct current losses due to Joule effect in the copper windings
- Electromagnetic losses due to hysteresis and eddy current in both stator and rotor
- Electromagnetic losses in the insulating materials
- Mechanical losses due to friction in the bearings

Out of these four, resistive losses (DC losses) in the copper coil contribute the most to the heat generated and increase with the amount of current [2].

This heat can be extracted by direct or indirect cooling. Smaller electric motors today use indirect cooling, as they have for more than a century. A cooling fluid, water glycol in the motor housing, transports heat to a heat exchanger where it is re-cooled by air before being returned to the housing. Direct cooling is when hollow conductors are used, and a cooling fluid or gas is circulated in direct contact with the inside of the conductor. The direct cooling method has been a common practice for larger machines [3] and successfully tested for smaller machines [4].

In the scope of the project K-AXFLUX, an attempt is made to develop an axial-flux motor (Fig. 1) which is cooled with hydrogen gas passing through the hollow conducting copper coils of the stator. Liquid hydrogen from a storage tank is pumped into the inlet of the conducting copper coil and is in gaseous state at the inlet of the copper coil. The hydrogen gas from the outlet of the coil is then further sent to the fuel cell. In the scope of this paper, a multi-physical simulation model of the stator geometry is developed to evaluate the hydrogen flow behavior and the resulting temperature distribution within the stator geometry of the axial-flux motor.

Theory

The stator geometry of the motor has 72 coils around its circumference (Figure 1), and each coil, which is made of oxygen free copper, is of 3.1 m in length. The connector elements connect the conducting copper coil to the hydrogen gas supply unit at the inlet.

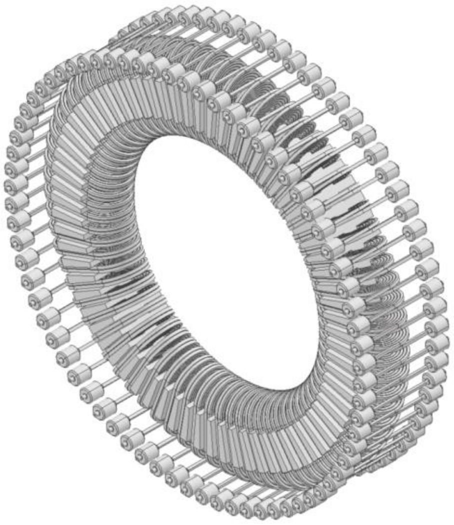
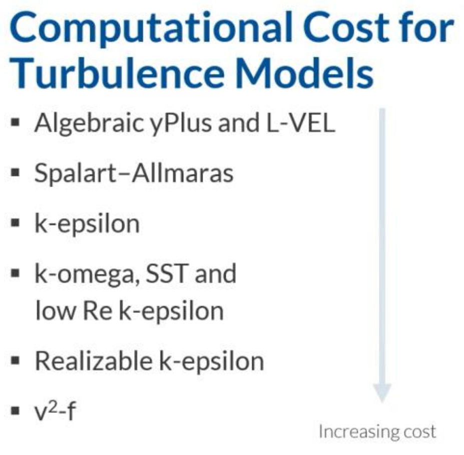


Figure 1. Stator geometry of the axial flux motor

Flows can usually be incompressible, weakly compressible and compressible. Since hydrogen gas has non negligible density changes due to pressure and is flowing inside a closed cavity, compressible flow (Ma < 0.3) suits the best and is used in the model.

Further, the Reynolds number at the inlet suggest that the flow is turbulent. Figure 2 shows the time and cost required to compute different turbulent models. The k-epsilon model was selected since it does not need wall treatment and solves quicker in comparison to other complex models (k-omega, SST etc.) though with lesser accuracy.



Computational Cost for Turbulence Models

- Algebraic yPlus and L-VEL
- Spalart–Allmaras
- k-epsilon
- k-omega, SST and low Re k-epsilon
- Realizable k-epsilon
- v^2-f

Figure 2: Computation cost of different turbulence model (Source- COMSOL, Learning-Center-Article 75241)

The governing equations used to solve the nonlinear axial flux model are as follows

Heat transfer in solids and fluids

$$\rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = Q + Q_{\mathrm{ted}},$$
$$\boldsymbol{q} = -k\nabla T \qquad [1]$$

Fluid flow- stationary

$$\rho(\mathbf{u} \cdot \nabla)\mathbf{u} = \nabla \cdot [-p\mathrm{I} + \mathbf{K}] + \mathbf{F}$$
$$\nabla \cdot (\rho \boldsymbol{u}) = 0 \qquad [2]$$

COMSOL Modelling

In any simulation it is important to exploit the design symmetry to reduce computational efforts. The stator geometry shown in Figure 1 is periodic around the center axis and therefore only a single sector (1/72nd part of the stator) is simulated (Figure 3). In reality, both sides of the sector will have the same conditions (temperature, stress etc.). To ensure this, periodic boundary conditions are essential and are applied on either side of the stator.

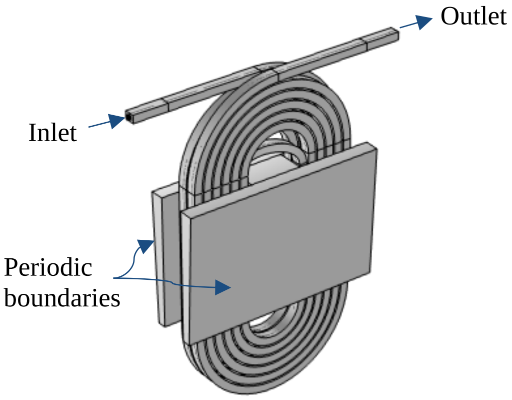


Figure 3 :Sectoral symmetric model

The initial design parameters from analytical evaluations are used as the boundary conditions in the simulation. Hydrogen gas (mass flow rate - 0.42 g/s) flows into the inlet at 50 K. At the outlet, a pressure boundary condition (p=0) with no reverse flow is defined.

The resistive heat generated in the coil is based on the analytical evaluations of the initial motor design and results in heat loss of 416 W for a single coil. Thus, the conducting copper coil is modelled as a heat source with 416 W. This heat is absorbed by the hydrogen gas flowing internally through the coils. On the outer side, the heat transfer occurs through convection with the surrounding air (h=10 W/(m^2K)).

The above defined problem involves heat transfer in solids (the stator and copper coils), heat transfer in the fluid (hydrogen gas) and turbulent flow. Thus, a non-isothermal coupling is further used to solve the physics involved. The study is highly nonlinear due to the incompressible flow and material properties such as density and conductivity being dependent on the temperature. Therefore, the study is divided into multiple steps to ensure that the solution converges.

- Step1: Turbulent flow
- Step2: Heat transfer in solids and fluid + Turbulent flow

Simulation Results

The fluid flow properties at the center of the cross section obtained from solving the non-isothermal coupling are shown in Figure 4. Heat exchange occurs between the copper and the hydrogen gas and the temperature of the gas increases along its flow length, whereas the pressure drops across the flow length due to expansion.

The velocity of the gas increases along the length, however as seen in Figure 4 the fluctuations along the flow length can be attributed to the fluid flow behavior across a curved section of the coil [5]. The fluid velocity decreases when encountering a bend in the section and again increases after the bend. Since the conducting copper coil is made of straight and curved sections, the velocity plot below shows hills and valleys on the velocity profile along the flow length.

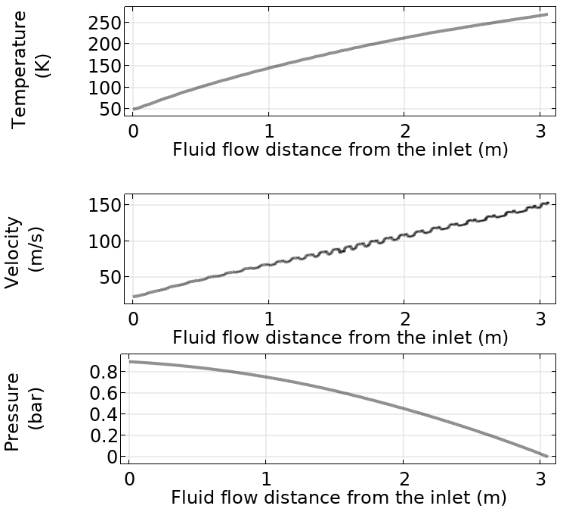


Figure 4. Pressure, velocity and temperature profile along the path of the coil evaluated at the centre

The temperature distribution in the individual stator geometry with cooling can be seen in Figure 5. The gas at the outlet attains a temperature of 268 K. This is well below room temperature and one of the most important design conditions is to have the stator temperature below 150 °C (423.15 K) so that the insulation materials within the motor do not lose their integrity. Without any cooling, the stator would theoretically reach a maximum temperature of 3500 K.

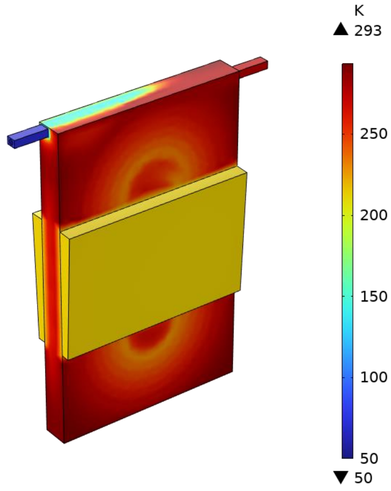


Figure 5. Temperature distribution of the stator geometry with the cooling effect

The sectoral model is then transformed into full stator model using the COMSOL sector 3D dataset in the results section and the temperature profile of the full stator is shown in Figure 6.

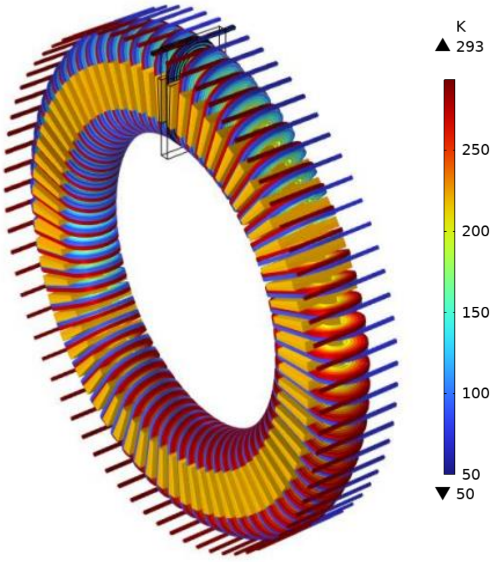


Figure 6. Temperature profile of the stator geometry

Conclusions and outlook

It is seen that the direct cooling method, using hydrogen gas as a cooling fluid, works, as the temperature drops from 3500 K to 293 K in the stator geometry. This implies that the indirect cooling method works effectively in removing heat from the conducting copper coil. The simulation model provides insights into the fluid flow behavior along the flow path. The parameters such as temperature, pressure and velocity can be further tuned to enhance the performance of direct cooling. The setup of multi-physical simulation can be used to further analyze thermal stresses, material parameter dependence on results and can be extended to study other heat sources from e.g. electromagnetic losses. Further a hardware test setup is being worked upon for the validation of the simulation model. Optimization with Bayesian and surrogate modeling technique is planned to derive an optimal set of inlet parameters such as the mass flow rate, pressure and flow temperature.

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