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Taylor-Couette-Poiseuille flow and heat transfer in an annular channel with a slotted rotor

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ABSTRACT

This paper investigates a Taylor-Couette-Poiseuille flow in an annular channel of a slotted rotating inner cylinder, corresponding to a salient pole hydrogenerator. The purpose of this study is to improve the understanding of flow and thermal phenomena in electrical machines using a simplified scale model. The validation of the numerical model for a specific configuration is first shown by comparing the results with the experimental data. A parametric study is also performed to investigate all main flow regimes and to derive correlations in terms of the Nusselt number distribution on the rotor pole face and sides. The results show that the Nusselt number is proportional to the tangential Reynolds number to the power 1/7 in the pole and inductive faces trailing side. This relationship is similar to the one encountered in classical Taylor-Couette-Poiseuille flows between two concentric and smooth cylinders.

1. Introduction

Salient pole synchronous machines convert the mechanical energy of water turbines into electrical energy. Although their efficiencies are greater than 95%, part of the mechanical energy available is lost in the form of heat. This heat must be efficiently evacuated to avoid overheating of the electrical components of the generator which can induce a rapid deterioration of the insulation material and, in some cases, lead to machine failure.

The cooling of a hydrogenerator is ensured by circulating a fluid (generally air) through the various generator components before it is directed toward a cooler where the heat is extracted. Understanding the flow dynamics and heat transfer mechanisms in the generator components (i.e., end-winding, pole face, etc.) is critical to ensure their efficient operation. To this end, experimental measurements on hydrogenerators can be performed. However, such measurements are costly, time-consuming and access to real machines is often limited.

Numerical tools such as Computational Fluid Dynamics (CFD) are increasingly used to characterize the thermofluid behaviour of large electrical machines. However, the geometric and flow complexity require the validation of simulation results from such numerical models which have not yet achieved a sufficient degree of maturity to be used alone.

The use of a laboratory scale model thus seems the best solution to acquire data for the validation of numerical models without the limitations associated with in situ measurements. This approach has been chosen by EDF (Électricité de France), LAMIH-CNRS (Université Lille Nord-de-France) and IREQ (Institut de Recherche d'Hydro-Québec), for whom a common strategy was established to share knowledge in the field of hydrogenerator thermofluid analysis.

Some experimental work has been undertaken in the past, but the majority of such studies have focused on only one particular component of the hydrogenerator. For example [9], developed an integral method to calculate the air flow rate across the coolers by scanning the flow with an anemometer. Furthermore [6], proposed an indirect method to measure the air flow across the coolers by applying the principle of conservation of energy in conjunction with measurements of the mass flow rate of the water, and the inlet and outlet temperatures of both fluids. More recently [10], performed measurements on a simplified model of a hydrogenerator

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Nomenclature

Latin symbols

$D_h = 2\frac{\pi(R_2^2-R_1^2)-nlp}{\pi(R_2+R_1)+np}$ Hydraulic diameter (m)
$e = R_2 - R_1$ Air gap (m)
$Gr_{Dh} = g\beta\Delta TD_h^3/\nu^2$ Grashof number
h Heat transfer coefficient (W/m^2 K)
H Rotor height (m)
l Pole width (m)
n Number of poles
$Nu = hD_h/\lambda$ Nusselt number
p Pole depth (m)
R_1 Rotor radius (m)
R_2 Stator inner radius (m)
$Re_a = V_zD_h/\nu$ Axial Reynolds number
$Re_t = \omega R_1D_h/\nu$ Tangential Reynolds number
$Ri_{Dh} = Gr_{Dh}/Re_{Dh}^2$ Richardson number
T Temperature (°C)
$Ta = \omega^2R_1\left(\frac{D_h}{2}\right)^3/\nu^2$ Taylor number
V_z Axial velocity (m/s)

Greek symbols

β Coefficient of thermal expansion (K^{-1})
θ Angle (°)
ν Kinematic viscosity (m^2/s)
ω Rotational speed (rad/s)
$\Gamma = H/D_h$ Elongation of the airgap (m)

to determine air flow rates across the stator and enclosure.

An experimental campaign was also carried out by Ref. [2] wherein the flow in static (cooler exit, pit opening, covers, and air gap) and rotating (interpole) components of a hydrogenerator scale model was characterized through particle image velocimetry (PIV) measurements. Some authors have performed experiments as well to determine heat transfer coefficients on active components of a generator. For example [5], obtained correlations between heat transfer coefficients on the leading and trailing faces of a salient pole and by comparing measured values with semi-empirical equations from earlier studies and found acceptable agreement. Moreover [22], performed heat transfer measurements on a salient pole generator and developed empirical correlations for the heat transfer coefficient on the pole sides and pole face. The authors found that, on the pole sides, heat transfer depends on the ratio of axial to tangential velocity (swirl parameter), whereas on the pole face it is mainly affected by the tangential velocity.

In a similar study by Ref. [19], temperature measurements on a four-pole synchronous generator were performed and equations for the heat transfer coefficient on the pole surface were derived. The local heat transfer coefficient was found to vary significantly across the pole surface and to be strongly related to the rotational speed. In another study by Ref. [8] aiming to measure the heat transfer correlations on the surface of a four-slots rotating cylinder placed in an annular channel, an axial speed and radial speed dependency was found, as well as a higher heat transfer on the leading edge than on the trailing edge of the rotor pole. More recently [12], demonstrated the validity of using an inverse algorithm to compute the time dependent heat flux on the rotor and stator surfaces of a high speed electric motor. Lastly [25], performed a hybrid numerical/experimental study to investigate (from temperature measurements) the heat transfer coefficient distribution on the pole face of a hydrogenerator scale model's rotor.

Recently, CFD has been used to tackle the problem of generator cooling and, although more computationally expensive than Lumped-Parameter Thermal Network (LPTN), it allows a more detailed and accurate analysis of the flow. For this reason, CFD is increasingly being used to improve the cooling efficiency of generators ([11]). Indeed [17,26], used it to simulate the cooling airflow and to determine convective heat transfer in different components. Furthermore [21], conducted a validation study by comparing measured and predicted local heat transfer coefficients. While the numerical model well predicted the overall trend of the heat transfer coefficient on the pole surface, the computed values were up to 30% lower than the measured ones. According to [23], more accurate results can be obtained using a Conjugate Heat Transfer (CHT) computation involving the coupling of flow and thermal simulations. Ref. [27] undertook such a study with a complete CHT analysis of a hydrogenerator and partially validated their results with experimental data.

This paper pursues the investigation of thermofluid phenomena in hydrogenerators that was undertaken by Ref. [16], namely the effect of a Taylor-Couette-Poiseuille flow on the heat transfer at the surface of a slotted rotating inner cylinder. The objective is to use CHT simulations to enrich the knowledge on flow and thermal transfer phenomena within electrical machines.

The present paper is subdivided into four sections. The scale model design is first presented. Then, the numerical models are detailed and validated for a specific configuration by comparing the results with the experimental data obtained from the scale model. Finally, a parametric study of flow regimes is performed and heat transfer correlations are extracted.

2. Scale model design

Understanding complex phenomena such as heat transfer in rotating parts of the machine is quite challenging, especially considering the limited experimental data due to restricted access and difficulties of performing measurements on actual generators.

Such data can serve to validate numerical models that allow a better comprehension of thermal and flow dynamics in generators. For this reason, a hydrogenerator scale model was designed and built at EDF/LAMIH-CNRS. This model is a simplified version of generators prototypes in EDF production plants, since it lacks active electromagnetic elements. Thus, the thermal analogy compared to a real configuration is not fully respected (especially in the notch region). Using the EDF/LAMIH-CNRS scale model of a hydrogenerator, temperatures on the rotor pole face can be measured and then compared with the numerical values obtained from Ansys-CFX, and *Code_Saturne 3.0* coupled with SYRTHES 4.0. After validating the numerical models, a parametric study is performed to investigate all main flow regimes and to derive correlations for the Nusselt number distribution on the rotor pole face and sides.

As illustrated in Fig. 1, the scale model is in an open loop ventilation circuit. The air is driven by a fan and is directed by two static air guides located upstream and downstream of the rotor/stator system. The main simplifications in the scale model include the omission of the coils and the ducts in the stator. It can be noted that the geometry has a periodicity of 1/10.

The stator is a transparent cylindrical plate comprising a flat