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Experimental validation of CFD modelling for heat transfer coefficient predictions in axial flux permanent magnet generators

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ABSTRACT

This paper describes the experimental validation of CFD modelling for heat transfer coefficients in an axial flux permanent magnet (AFPM) generator. A large scale low speed test rig was designed and constructed. The geometric parameters and the rotational speed of the test rig were determined by dimensional analysis, to ensure the flow characteristic remains unchanged as compared with commercial AFPM generators. The heat transfer coefficients in the test rig were measured at rotational Reynolds number, Re_ω from 0 to 2×10^6, non-dimensional flow rate, C_w up to 11,000 and gap ratio, $G = 0.016$, by using the combination of heat flux sensors and thermocouples. Due to the large size of the scaled-up rig, natural convection played a significant part in the heat transfer and this had to be compensated for in the forced convection heat transfer coefficient calculations. Extra experiments were designed and conducted to identify the effect of natural convection on the machine's cooling. The experimentally determined results were compared to heat transfer coefficients predicted by CFD models and good agreement was obtained.

1. Introduction

In the development of a rapid thermal modelling tool for axial flux permanent magnet (AFPM) machines, it is important to acquire reliable local surface heat transfer coefficients (HTC) inside the machines. The accuracy of thermal modelling is heavily dependent on the surface HTCs, especially for air-cooled machines. Thus, it is necessary to construct reliable empirical relationships between the local HTC and the size and topology of different AFPM machines by empirical parametric studies.

HTC parametric studies can be achieved either by conducting a series of experiments with different control parameters, or by using experimentally validated CFD modelling methods. The construction of a flexible test rig which is capable of evaluating a range of different sizes and topologies of axial flux machines is uneconomical and time consuming. Therefore, CFD modelling is used as an alternative. In the past decade, many CFD solvers have been developed commercially for different industrial applications but if they are to be used with confidence, it is necessary to carry out experimental validation.

The design of a large scale, through flow air ventilated AFPM machine test rig for accurate heat transfer coefficient measurement is discussed in this paper. Dimensional analysis was performed to ensure that the flow characteristic inside the large scale generator is similar to the real machine, in this case the Durham University 1.5 kW, 1500 rpm, 300 mm diameter AFPM generator (see Fig. 1). Several sets of experiments were designed and conducted on a large scale test rig. The heat transfer coefficients and temperatures obtained from these experiments are compared with CFD.

2. Review of convection heat transfer coefficient measurement techniques

Heat transfer/heat flux measurements are required in order to acquire the local surface heat transfer coefficients in AFPM machines, see Equation (1). In most literature, ambient temperature is used as the reference temperature for heat transfer coefficient calculation. For convenient, the ambient air temperature is used as the reference temperature in the entire heat transfer coefficient calculations discussed in this paper.

$$h = \frac{q}{A\left(T_{surf} - T_{ref}\right)} \quad (1)$$

where q = Heat transfer, W, A = Heat transfer surface area, m^2, T_{surf} = Surface temperature, K, T_{ref} = Reference temperature, K.

All of the heat flux experiments conducted by previous researchers [1–15] involved measuring either the effect of heat

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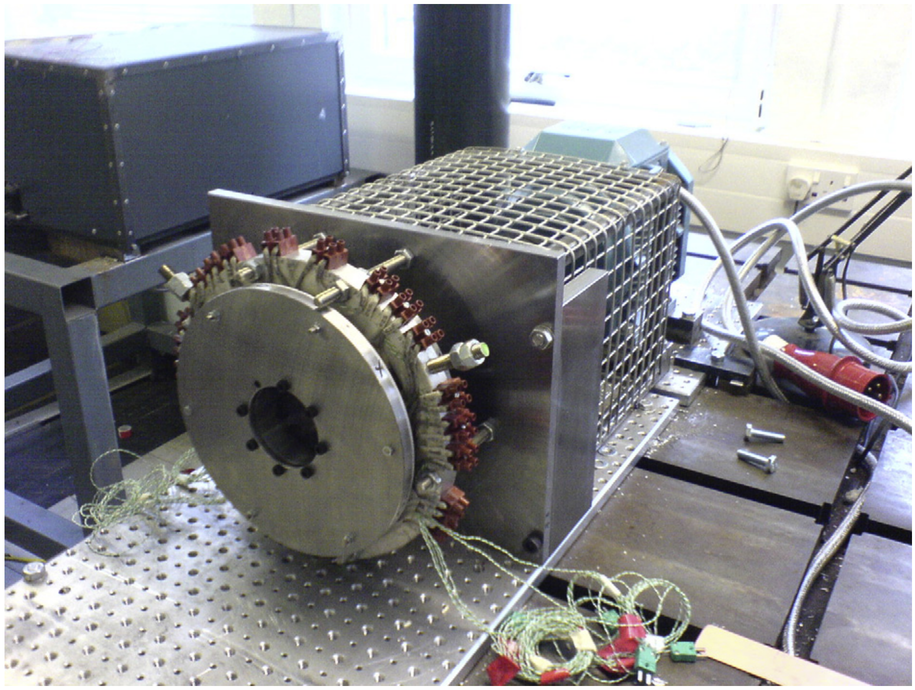

Fig. 1. Durham University 1.5 kW 1500 rpm AFPM generator.

transferred via a medium, or by spectral emissions. Childs et al. [1] and Rohsenow et al. [2] reviewed the available experimental techniques for heat transfer measurement, including: direct (or steady state) measuring methods, indirect (or transient) measuring methods and heat-mass analogy measuring methods. The authors concluded that there is no one method suitable to all applications because of the differing importance of accuracy, sensitivity, size, cost and robustness.

Direct heat transfer measuring methods involve the measurement of the local surface heat transfer while the system is in the steady state condition. One of the most commonly used devices for direct heat transfer measurement is the thin film heat flux sensor. Thin film heat flux sensors measure the temperature differences between two or several locations in a thermal insulation material of known thermal properties, to determine the local heat flux via Fourier's one dimensional law of conduction equation. The temperature difference between the top and bottom of the insulation layer can be measured by thermopiles formed by a number of thermocouple junctions. This method was first reported by Martinelli et al. [3] and a more advanced thermopile design was presented by Hartwig et al. [4].

Calibration of each heat flux sensor is essential in order to acquire accurate heat flux measurements. When the heat flux sensor is affixed to a solid surface, the existence of the sensor disrupts the geometric surface profile and the thermal conditions due to the mismatch of thermal properties. Flanders [5] stated that the error due to surface profile disruption on the indoor surface of building walls by using surface mounted heat flux sensors is the order of 10 per cent. However, the error depends on the material of sensor used. If the HFS is made of a material with very similar thermal properties to the surface on which it is mounted, the thermal distortion would be minimal, and vice versa. The modification of thermal boundary conditions due to the existence of heat flux sensors was also described by Dunn et al. [6]. He highlighted the necessity to re-calibrate the entire heat flux sensor with similar boundary conditions. The heat flux sensor calibration can be carried out by mounting the sensor on a good thermal insulator, with a known heat source. However, the calibration factor is strongly influenced by air currents or moving fluid above the sensors. Danielsson [7] found that the influence of wind on the calibration value is greatly reduced when the sensor is attached to a surface with lower thermal conductivity.

Alternatively, a common laboratory method used is the calibration of sensors against a well-defined convection correlation such as for jet impingement [8,9]. In this technique, the sensor is mounted on the surface which is exposed to a fluid jet of known geometry and flow conditions. Subsequently, the electrical signal generated in the sensor is calibrated by using the jet impingement convection correlations which have already been developed.

Another technique of determining the surface convective heat transfer coefficients is by measuring the temperature on one side of a solid surface, while actively providing heat on the other side of the solid. This is called the energy supply technique. The heat transfer coefficient is defined by the heat flux per unit temperature increase. Hence, by controlling the electric power supply of the heating devices, and by measuring the surface temperature, the surface heat transfer can be evaluated. Controlled heating on the solid surface can be achieved by means of electric heater strips, silicon heater mats or printed circuit boards [15]. For most applications, the front side of the heater device is attached on the solid surface by high temperature resistance industrial glue or epoxy resin, whereas the back side of the heater is thermally insulated by low thermal conductivity materials, such as clear plastic, fiber glass, etc. The surface temperature on the other side of the solid is measured by commercially available thin film thermocouples, resistance temperature devices (RTD) or thermal liquid crystal.

The energy supply heat transfer convection measurement technique has been used by Rule et al. [13], Radhakrishnan et al. [14] and Howey et al. [15]. Rule constructed a microscale heater array comprised of 96 platinum array heater elements measuring 2.7 mm × 2.7 mm, deposited on a quartz substrate to measure time and space-resolved heat transfer in a boiling process. The heaters were each controlled by a Wheatstone bridge circuit with op-amp feedback and a digital potentiometer, allowing heater temperature to be controlled. On the other hand, Howey combined the heat flux measurement and temperature sensing into one single device,