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# Determination of natural convection heat transfer coefficient over the fin side of a coil system

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ABSTRACT

This paper presents a thermal study to define the appropriate correlations allowing the determination of the convective heat transfer coefficient over large parallel rectangular fins for a permanent magnet synchronous generator coil. For this purpose, an experimental setup is developed for both horizontal and vertical orientations and different input currents. The experimental results are compared with the analytical method, based on correlations proposed in the literature, which are generally limited for a small range of heat sinks. The results show that the analytical calculation based on Jone's correlation for the horizontal case and Tari's correlation for the vertical case, have good agreement with the experimental data. These correlations are experimentally validated for the calculation of the natural convection coefficients of large rectangular fins arrangement too.



## 1. Introduction

The extended surface, which is called a fin is the preferred cooling method in the natural convection mode to enhance the heat transfer rate between the surface and the cooling fluid in electrical machines and other electrical devices. The fin and heat sink technologies are a subset of the passive cooling methods and have several advantages over the active ones, such as energy saving, affordability, reliability, and ease of manufacturing [1].

Rectangular cross section shaped plate fins on a flat base are the most common types of fins used in different electrical devices. In the natural convection mode, the characteristics of fins, e.g., length, height, and spacing between the fins play an important role on the maximum heat transfer rate. Therefore, there is a number of studies dedicated to find out the optimal parameters of the fin's geometry. Based on these findings, other studies have tried to define empirical correlations to determine the convection coefficient [2]. The parallel rectangular cross section fins on a flat base are generally used in vertical and horizontal configurations. There are many studies focused on finding the amount of natural heat transfer either experimentally or analytically. E.g., Jones and Smith [3], Van Del Pol and Tierney [4], Elenbaas [5], Rao [6], Baskaya [7] and Tari [2,8].

On the other hand, according to other studies, e.g., Rao [6], Ahmadi [1] and Boglietti [9], between 20 and 40% of the total heat transfer is extracted by the radiation phenomenon. Thus, the radiation heat extraction in parallel with the natural convection has a great effect on the total heat dissipation.

As mentioned above, there is a number of empirical correlations to calculate the natural heat transfer from parallel arrangement of rectangular cross section plate fins on a flat base in both horizontal and vertical configurations. Each of these correlations have been developed based on different ranges of Rayleigh number (*Ra*), Prandtl number (*Pr*) and fin's characteristics. Most of these correlations have been developed and used for small fins' size and spacing. In large electrical machines and devices, the fins' size and spacing are increasing. Therefore, it is important to find the appropriate correlation among the existing ones, which can describe the heat dissipation in these cases.

In this paper, we determine the appropriate correlations for large electrical machines with rectangular flat fin arrangements in horizontal and vertical orientations by means of analytical and experimental methods, based on the correlations proposed in the literature, which are generally limited to a small range of heat sinks. We also consider the impact of the fin on the natural heat transfer and the temperature of the plate fin array. For this purpose, one segment of the stator coil of a permanent magnet synchronous generator consisting of rectangular fin arrangements is investigated in both horizontal and vertical configurations.

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## 2. Empirical correlations

There are many empirical correlations for the rectangular fin arrangement with flat base. In this paper, the empirical correlations based on the scientific research of Jones and Smith [3], Van Del Pol and Tierney [4] and Tari [2,8] are discussed. According to Fig. 1, the configurations investigated are divided into two main categories: rectangular isothermal fins on a horizontal surface and rectangular isothermal fins on a vertical surface [10].

### 2.1. Rectangular isothermal fins on a horizontal surface

Fig. 1a shows rectangular fins on a horizontal surface. In 1970, Jones and Smith derived an empirical correlation to determine the natural heat transfer from horizontal fins [3]. They assumed the fins as U-shape horizontal channels and based on this assumption they developed their correlation by using the dimensionless Nusselt number

$$Nu = 0.00067 \cdot Gr \cdot Pr \cdot \left\{1 - e^{(-7640/G \cdot Pr)^{0.44}}\right\}^{1.7}, \tag{1}$$

where $Gr$ is Grashof number and $Pr$ is Prandtl number.

In this case, they have defined the fin space ($S$) as the characteristic length. According to (1), the Nusselt number is determined without considering the fins' size.

While in [8], Tari and Mehrtash defined an empirical correlation for the natural heat transfer from upward horizontal plate-fin heat sinks according to the fin characteristics. For this purpose, they defined a modified Grashof number as:

$$Gr' = Gr \cdot \left(\frac{H}{L}\right)^{0.5} \cdot \left(\frac{S}{H}\right)^{0.38}, \tag{2}$$

where $H$ (m) and $L$ (m) are respectively the fin height and length. The Nusselt number is then expressed as:

$$Nu = 0.0915 \cdot (Gr' \cdot Pr)^{0.436}. \tag{3}$$

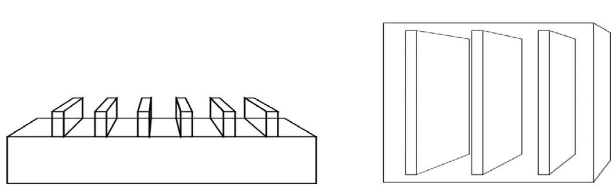
### 2.2. Rectangular isothermal fins on a vertical surface

The rectangular isothermal fins on vertical base plate is the common heat sink configuration. A number of research have been published about calculating the natural heat transfer from this configuration. One of the earliest research about this configuration is back to Van De Pol research in 1973. In [4], he also described the vertical fin configuration as a U-shape vertical channel. In this case, the Nusselt number was defined as:

$$Nu = \frac{r}{H} \cdot \frac{Gr \cdot Pr}{Z} \cdot \left[1 - e^{-Z \cdot \left(\frac{0.5}{(r/H) \cdot Gr \cdot Pr}\right)^{0.75}}\right], \tag{4}$$

where $Z$ is defined as:

$$Z = 24 \cdot \frac{1 - 0.483 \cdot e^{-0.17/\alpha}}{\left[(1 + \alpha/2) \cdot (1 + (1 - e^{-0.83 \cdot \alpha}) \cdot (9.14 \cdot \sqrt{\alpha} \cdot e^{-465 \cdot S} - 0.61))\right]^3}, \tag{5}$$



(a) (b)

**Fig. 1.** Investigated configurations: (a) rectangular isothermal fins on a horizontal surface, (b) rectangular isothermal fins on a vertical surface.

$\alpha$ is the channel aspect ratio and $r$ (m) the characteristic length.

In [2], Tari and Mehrtash introduced a new empirical correlation for the calculation of the Nusselt number from a vertical heat sink. They defined a new modified Grashof number as:

$$Gr' = Gr \cdot \left(\frac{H}{L}\right)^{0.5} \cdot \left(\frac{S}{H}\right), \tag{6}$$

and based on the modified Grashof number, they defined the Nusselt number as:

$$Nu = 0.0929 \cdot (Gr' \cdot Pr)^{0.5} \text{ for } Gr' \cdot Pr < 250, \tag{7a}$$

$$Nu = 0.2413 \cdot (Gr' \cdot Pr)^{1/3} \text{ for } 250 < Gr' \cdot Pr < 10^6. \tag{7b}$$

Finally, the natural convection coefficient $h_c$ is calculated from the Nusselt number as [11]:

$$h_c = \frac{Nu \cdot k}{L_c}, \tag{8}$$

where $k$ (W/m K) is the fluid thermal conductivity and $L_c$ (m) is the characteristic length of the cooling surface.

## 3. Experimental setup and procedure

The objective of the experimental work in this paper is to assess the natural heat transfer coefficient from the fin section of the stator coil of a permanent magnet generator in the horizontal and vertical orientations. Yet another objective is to compare the analytical data to experimental data for finding the appropriate empirical correlation in both cases and verify the accuracy of these correlations.

From previous research works [12] and [13], the stator coil used in this investigation consists of six different faces as shown in Fig. 2. To consider the natural convection from the fin's side, the heat flux flow should be confined only to the fin side. To achieve this, we created an insulation box according to the dimensions of the coil by means of foam insulation boards with thickness of 10 cm. Fig. 3 shows the coil box and the fins' side of the coil in vertical and horizontal configurations. Since the foam insulation material has low thermal conductivity $k = 0.3$ (W/m K), the thermal flux flow is restricted to the open surface. Therefore, the box is operating as a semi-closed calorimeter. Another important point about the box is the temperature operation point; as the foam insulation board can handle temperatures up to 90 °C, during the experiment, the coil temperature should not exceed that temperature. Furthermore, in order to protect the test bench from external heating source and bulk fluid motion as well as increasing the accuracy of the results, the experimental setup is located in a closed room

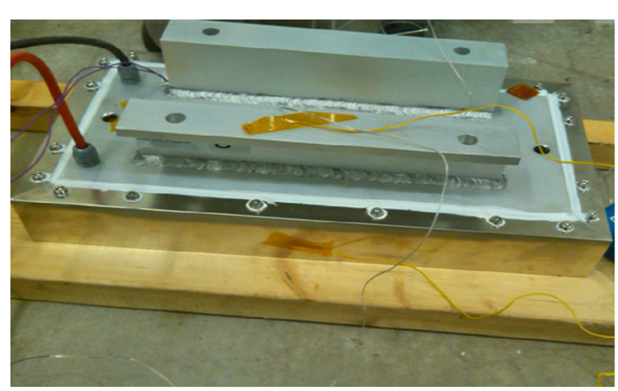


**Fig. 2.** The coil module used in the experimental work.