Investigation of Parameters Affecting Heat Transfer and Fluid Flow of a TEFC Electric Motor by Using Taguchi Method

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Abstract. The thermal issue is an important criterion for the design of high efficiency motor. In this study, the numerical simulation on the thermal performance of TEFC electric motor is proposed. The parameters such as fin pitch ratio, fin dimensions and fan cover location relative to the fin are discussed to investigate the effects of them and decrease the winding temperature. In order to examine the various parameters quickly without suffering from a great number of parametric computations, Taguchi method is introduced to reduce the computational effort. The case studies results show the effects of fin and fan cover configuration on average temperature rise of winding. And it is found that the fin pitch ratio has a significant influence on average temperature rise of winding. These case studies not only provide physical insight into the thermal-fluid phenomenon but also find out the optimal combination of parameters from given levels by using SN ratio. An additional simulation is performed and shows a good agreement with predicted value. The new design proposed in this study shows 4.8°C decrease in average temperature rise of winding.

1. Introduction
The thermal management of electric machine becomes more important because of the requirements for miniaturization, energy efficiency and cost reduction. Good thermal management reduce the danger of irreparable failures and increases electric motor life. Heat losses generated from the stator and rotor are transferred to the frame and end shields and dissipates through the outer fins to the atmosphere. Hence, the improvement of thermal and hydraulic performances are very important.

In recent years, some researchers devoted their efforts in investigating the thermal management of electric motor. Valenzuela and Tapia [1] performed the evaluation of the heat transfer capacity of a finned frame under the different velocities of the cooling fan. The empirical evaluation of the heat transfer coefficient of two finned frames at different speeds of the cooling fan was developed. Illagolla [2] analyzed a fin for examining the effects of the convective heat transfer for temperature distribution of the electric water pump motor by using MATHCAD. Importance of the convective heat transfer was also discussed. The results show that the temperature gradient of the fin increase along the length of the fin from base to the end when increasing the convective heat transfer coefficient. Guo [3] employed CFD modelling to obtain the distribution of air flow rate, air velocity and temperature of a 55 kW surface permanent magnet synchronous motor (SPMSM). The helpful empirical formula of heat transfer coefficients of fins were proposed for electric machines design with the same structure. A
numerical investigations have been carried out on thermal-flow characteristics of a totally enclosed fan cooled induction motor by Moon et al [4]. Four design parameters such as fin attached to frame, channel embedded in frame, duct through rotor-core and fan-cover surrounding external self-rotating fan were examined. Air flow rate of fan and temperature rise of insulated winding were considered to determine the fin array-height, thickness and pitch-attached to frame surface. And the number of channels embedded in frame was examined to look into how effective does inner-circulated-air cool down. Ulbrich et al. [5] proposed a novel approach on conjugate heat transfer problem in 2-D. In their study, a constant heat transfer coefficient between fin surface and fluid was assumed in order to describe the heat flow through rectangular fins analytically. And the optimal heat dissipation is achieved by having more but shorter fins under the condition of constant total surface area.

Taguchi method is a frequently used method to find out the optimal combination of parameters with minimum effort and cost. Many scholars use this method to optimize the electromagnetic performance, thermal performance or reduce the noise in the electric motor design [6-8]. Taguchi method shows salient usefulness in optimization design of electric motor applications.

The purposes of this study are to examine the effect of fin and fan cover geometry on the thermal and fluid characteristic of TEFC electric motor (as shown in figure 1) and minimizing the average temperature rise of winding. The obtained results from original design were validated by comparing them with experimental data. Parametric studies through CFD and Taguchi method were performed for improving thermal performance. Furthermore, the optimal case was selected using SN ratio and confirmed by an additional simulation.

![Figure 1. TEFC electric motor used in the analysis.](image1)

![Figure 2. Computational domain and boundary conditions.](image2)

2. **Mathematical model and numerical method**

2.1. *Simulation*

The governing equations to be considered are the time-averaged continuity, momentum, and energy equations. An eddy viscosity model is used to account for the effect of turbulence phenomena. In solid region, solid energy equation is employed. The boundary conditions for this problem are state as figure 2. For fluid field, no-slip boundary condition was employed for the ground (Plane CDHG). And entrainment boundary conditions were employed in other five surrounding planes. For thermal field, adiabatic boundary condition was assumed for the ground. And the other five surrounding planes were assumed as ambient temperature.

2.2. *Loss sources*
Power losses in electric motor are composed of resistive losses in stator and rotor conductors, iron losses in the magnetic circuit, additional losses and mechanical losses. In this thermal model, heat source is the average losses obtained by measurement at rated operation.

2.3. Numerical method
The thermal and fluid fields of computational domain are solved by the commercial software ANSYS FLUENT®. This conjugate heat transfer problem is assumed to be steady-state and run with an implicit and segregated solver. The multiple reference frame model (MRF) is employed to deal with the rotation parts (fan, shaft, and rotor). Unstructured mesh mainly composed of tetrahedral cells is applied for complicated geometries like frame, end shields and winding while structural mesh is applied to sweeplable parts. Fine grids are deployed where high velocity or temperature gradient takes place, including air gap between the stator and rotor, blades, fins and so on.

2.4. Taguchi method
The Taguchi method was developed by Genichi Taguchi during the 1950s. It’s a methodology for applying statistics to improve the quality of manufactured good, determine optimal design parameters of engineering, and so on. Taguchi method employs orthogonal array to investigate several design parameters with a low number of case studies. The Taguchi method is established based on the signal-to-noise ratio (S/N ratio). For analyzing the S/N ratio, three types of quality characteristics are defined, i.e. the nominal-the-better, the smaller-the-better, and the larger-the-better. In this study, the smaller-the-better quality characteristic was chosen for minimizing the average temperature rise of winding. For the smaller-the-better cases, the definition of SN Ratio can be expressed as

\[
SN = -10 \log[\bar{y}^2 + S^2]
\]  

where \(\bar{y}\) is mean value of observations, S is standard deviation. In simulation case studies, \(\bar{y} = y\), and \(S = 0\).

And the selection of L9(3^4) orthogonal array using Taguchi method shown in table 1. We define four factors to affect the average temperature rise of winding. The factors include fin pitch ratio (fin pitch/fin thickness), fin thickness, fin height and fan cover location relative to the fin (-a/b). Figure 3 shows the details of configuration. The factors with their values and their levels considered in this study were given in table 2.

### Table 1. L9(3^4) orthogonal array.

| Experiment | A | B | C | D |
|------------|---|---|---|---|
| 1          | 1 | 1 | 1 | 1 |
| 2          | 1 | 2 | 2 | 2 |
| 3          | 1 | 3 | 3 | 3 |
| 4          | 2 | 1 | 2 | 3 |
| 5          | 2 | 2 | 3 | 1 |
| 6          | 2 | 3 | 1 | 2 |
| 7          | 3 | 1 | 3 | 2 |
| 8          | 3 | 2 | 1 | 3 |
| 9          | 3 | 3 | 2 | 1 |
Table 2. Control factors and their levels.

| Factors                                      | Levels    |
|----------------------------------------------|-----------|
| A: fin pitch ratio (-)                       | 9.17 3.4 1.45 |
| B: fin thickness (mm)                        | 3 5 7    |
| C: fin height (mm)                           | 44 55 77 |
| D: fan cover location relative to the fin (-) | 0% -20% -40% |

3. Results and discussion

3.1. Validation

In thermal management of the induction motor, winding temperature is a more critical component than others. Hence, the average temperature rise of winding is compared with measurement data to verify the present numerical model, as shown in table 3. The numerical prediction for the average temperature rise of winding shows a good agreement with measurement data. The validation indicated that the thermal model and assumptions are reliable.

Table 3. Comparison of the results between measurement and simulation.

|                  | Average temperature rise |
|------------------|--------------------------|
| F#449T CFD       | 68.8                     |
| 400HP Measurement| 71.6                     |
| \(T_{amb} = 25.6^\circ C\) Error | -2.8                     |

3.2. Case studies

The thermal performance of the electric motor can be calculated for each simulation of the orthogonal array by using the observed values of the average temperature rise of winding from table 4. The results for average temperature rise of winding are presented as SN ratio for each factor at each level in figure 4. From the figure, it is clear that the average temperature rise of winding decrease with all the three factors, i.e. fin pitch ratio, fin thickness, and fin height. The rate of decrease for the average temperature rise of winding is higher for fin pitch ratio when compared with the fin thickness and fin height. It can be observed that SN ratio will increase sharply as the fin pitch ratio decreases from 9.17 to 1.45. It reveals that the increment of amount of fins improves the thermal performance. Although the flow resistance will increase as the amount of fins increase, the heat transfer area still compensate for the decrease of air flow rate under the factor setting level ranges.
Figure 4 also shows that the fin height does not have a significant influence on the SN ratio. The heat transfer area will increase as the fin height increases. However, the fin efficiency decreases with increase in fin height. And the convective heat transfer coefficient isn’t a constant from the bottom to the tip of fins. Hence, the increment of heat dissipation doesn’t proportional to the heat transfer area. The heat dissipation rate gradually slow down. The thermal phenomenon mentioned in previous discussed also show in figure 5.

The influence of fan cover location relative to the fin shows different tendency from previous factors. As the factor decrease from 0% to -20%, the diameter of fan cover outlet decrease and increase the flow resistance. The air flow rate decreases. However, the change of fan cover configuration reduce the circulation between fan cover and end shield. And the air flow will concentrate near the bottom of fins. The convective heat transfer coefficient increases and improve the heat transfer rate in high temperature region. When the factor decrease from -20% to -40% shows the opposite result. The diameter of fan cover outlet decrease and more closer to the frame. The flow resistance becomes too high and reduce the more air flow rate and flow velocity in the near frame region. It caused the negative effects on thermal performance. And the result reveals that the optimal fan cover location relative to the fin is between -20% and -40%. The flow fields also show in figure 6.

**Table 4.** Orthogonal array L9(3^4) with calculated average temperature rise of winding and SN ratio.

| Case | A   | B   | C   | D   | $y_t$ | S/N ratio |
|------|-----|-----|-----|-----|-------|-----------|
| 1    | 9.17| 3   | 44  | 0%  | 80.88 | -38.157   |
| 2    | 9.17| 5   | 55  | -20%| 77.36 | -37.770   |
| 3    | 9.17| 7   | 77  | -40%| 73.57 | -37.334   |
| 4    | 3.4 | 3   | 55  | -40%| 74.72 | -37.468   |
| 5    | 3.4 | 5   | 77  | 0%  | 73.44 | -37.318   |
| 6    | 3.4 | 7   | 44  | -20%| 70.52 | -36.966   |
| 7    | 1.45| 3   | 77  | -20%| 68.93 | -36.768   |
| 8    | 1.45| 5   | 44  | -40%| 70.75 | -36.995   |
| 9    | 1.45| 7   | 55  | 0%  | 65.88 | -36.376   |
| Ave. |     |     |     |     | 72.894| -37.2391 |

**Figure 4.** SN ratios of factor level for average temperature rise of winding.
3.3. Optimal combination of control factors

The case studies results give the whole picture of the effects of fin and fan cover configurations on the average temperature rise of winding and an optimal combination of these factors can be selected. Based on the influence of each factor shown in figure 4, it is seen that the factor-level combination (A3, B3, C3, D2) contributes to minimization of average temperature rise of winding. The optimal case can be predicted by using the empirical model:

\[ S_{N_{optimal}} = \bar{S}_N + (\bar{S}_{N_{A3}} - \bar{S}_N) + (\bar{S}_{N_{B3}} - \bar{S}_N) + (\bar{S}_{N_{C3}} - \bar{S}_N) + (\bar{S}_{N_{D2}} - \bar{S}_N) = -36.1957 \] (2)

Therefore, the predicted average temperature rise of winding in optimal case is 64.53°C. Finally, an additional simulation of optimal case was performed for confirmation. The average temperature rise of winding obtained from CFD is 63.94°C. The result shows a good agreement with prediction.

4. Conclusions

In this paper, the numerical simulation on the thermal performance of TEFC electric motor is proposed. Various parameters such as fin pitch ratio, fin dimensions and fan cover location relative to the fin were discussed in order to investigate the effects of them and decrease the winding temperature. Instead of a number of possible combinations for four parameters and three levels for each of them (\(3^4=81\)), Taguchi method was used to reduce the computational effort. With this technique, there are only 9 patterns defined by L9(3^4) orthogonal array need to be calculated. The case studies results show the effects of fin geometry and fan cover location on average temperature rise of winding and provide physical insight into the heat transfer and fluid flow phenomenon. And it is found that the fin pitch ratio has a significant influence on average temperature rise of winding. Moreover, the optimal case from given levels was selected using SN ratio and confirmed by an additional simulation. The new design proposed in this study shows 4.8°C decrease in average temperature rise of winding.

Acknowledgments

The support of TECO Electric & Machinery Co., Ltd. is gratefully acknowledged. The authors also want to thank Green electric machine division for technical advices and sharing experimental data for this research. Truly thanks to Mr. William Hu, deputy general director of TECO Group Research Institute, for providing me with comments on the research.

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