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Electromagnetic–Thermal Characteristics Analysis of a Tubular Permanent Magnet Linear Generator for Free-Piston Engines

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Abstract: Temperature rise of the tubular permanent magnet linear generator (TPMLG) might lead to insulation failure and demagnetization of permanent magnets, affecting the safe and stable operation of other equipment and the entire system. Herein, a bidirectional electromagnetic–thermal coupling method for analyzing the electromagnetic loss and thermal characteristics of a TPMLG considering the effect of increased temperature on the permanent magnet was proposed. To study the electromagnetic–thermal characteristics of the TPMLG under stable power generation, a two-dimensional electromagnetic field model and a three-dimensional temperature field model were established and coupled. The temperature field of the TPMLG was numerically calculated using computational fluid dynamics over finite volume method under natural air cooling and forced air cooling conditions. Effects of loss and air flow velocity on the steady temperature field were investigated. Results indicated that copper loss increased by 24.5% considering the influence of temperature rise. The windings' top central position in the TPMLG was the spot with the highest temperature of 127.8 °C and there was a potential demagnetization risk for the permanent magnets. Some reference for future research of clarifying thermal characteristics and cooling design was provided.

Keywords: tubular permanent magnet linear motor; electromagnetic–thermal bidirectional coupling; finite volume method; temperature field



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1. Introduction

As an advanced power unit that directly couples free-piston engines (FPEs) and linear generators (LGs), the free-piston engine generator (FPEG) has received widespread attention, and has been well applied in hybrid electric vehicles [1,2]. The FPEG, combining traditional power and the clean electric drive mode, can not only fully utilize existing fuel but also adapt well to various novel fuels and power technologies. During the energy conversion process, the LG acts as the critical component of the FPEG prototype, influencing power generating performance and reliability of the entire system [3].

Linear generators possess the advantages of fine control features, high thrust density, and good dynamic characteristics. In recent years, different types of LGs have been used for wave energy converters [4,5] and FPEs [6–8]. Compared with other types of LGs, permanent magnet linear generators (PMLGs) are widely used in converting kinetic energy of linear motion into electricity, especially with FPEs due to high efficiency and power density [9]. Furthermore, various topologies of the PMLG have been proposed [10]. Among the commonly applied topologies for PMLGs, the tubular one allows better exploitation of the permanent magnet flux, reducing size and end effects [11].

Along with increasing power density and progressively compact structures, heating and temperature rise become the crux in various applications of LGs [12]. Heating problems affect the reliability of LGs, lead to thermal deformation, and cause temperature rise potentially influencing the performance of other adjacent apparatuses. In order to achieve high thrust, it is necessary to increase the current of the coils, which leads to severe

temperature rise in windings [13]. For PMLGs with long-term reciprocating motion, the temperature rise is particularly serious, bringing about a series of problems, such as irreversible demagnetization of permanent magnets, reduced efficiency, shortened lifespan, and insulation deterioration. The high-temperature problems of LGs severely restrict improvement in power generation performance [14]. Obviously, accurately clarifying thermal characteristics is of increasing significance in the design, manufacture, optimization, and application of linear generators.

Up till now, many researchers have been making efforts in the analysis of the LG temperature field [14,15], and mainstream approaches include a lumped-parameter thermal network [16,17], numerical techniques [18–20], and hybrid thermal analysis combining two methods [21,22]. Among the numerical methods, finite element method (FEM) and finite volume method (FVM) [23,24] are most used. Computational fluid dynamics (CFD) over FVM is commonly used to calculate convection heat transfer coefficients and FEM can model heat conduction of solid components more accurately than the thermal network method. The application occasions of the thermal network and numerical methods are different. All the methods have both advantages and disadvantages, so the methodology selection is a trade-off between cost and value.

Vese et al. [11] proposed a multi-physics model of a permanent magnet linear motor by analyzing a one-direction coupling of electromagnetic and thermal fields, and obtained two-dimensional axisymmetric finite element steady-state and transient solutions for the permanent magnet linear motor prototype. The iron loss of magnetic field results was used as the main heat generation source for a three-dimensional finite element thermal simulation to obtain the temperature distribution of the permanent magnet linear motor. Gong et al. [19] conducted a comprehensive study on a double-sided linear induction motor as a braking system with different displacement speeds. Considering both the edge effect and multi-physics factors of the linear motor, a three-dimensional FEM thermal model of the studied linear motor was built. A temperature field model and an electromagnetic field model were two-way coupled and startup thrust force was calculated and analyzed.

Lu et al. [21] studied the thermal performance of a 12-slot and 14-pole permanent magnet linear motor under water cooling conditions. Two corresponding models were established using FEM and thermal network, and thermal characteristics of the permanent magnet linear motor under continuous, short-term, and intermittent operating conditions was obtained. The results obtained by the two methods were compared and analyzed through experiments. The impact of the water-cooling system on the overall temperature rise distribution of the linear motor was investigated. Sun et al. [6] developed a plate moving-magnet LG for an opposed piston FPEG. To prevent demagnetization from causing unstable operation of the LG, a CFD model was established using FEM and the temperature field was analyzed. It was found that the air-cooling condition was enough to meet the heat dissipation requirement under long-term stable operation.

Liu et al. [24] proposed a simplified fluid model separated from the coupled calculation of a permanent magnet linear motor. Interpolation and polynomial fitting were used to compute the average velocity of the surfaces. Steady-state temperature distribution characteristics were then calculated by a coupled model. The simplified fluid model greatly reduced the computational time of the electromagnetic–fluid–thermal coupling simulation without sacrificing computational accuracy. Pei et al. [22] investigated the temperature rise characteristics of a coreless permanent magnet synchronous linear motor under different conditions, using thermal–fluid–solid coupling FEM and thermal network analysis as the modeling methods. A water-cooled structure suitable for a coreless double-layer permanent magnet synchronous linear motor was designed and the heat dissipation effects of different topologies were compared and analyzed. Then, a response surface model was developed to obtain maximum sustainable current and electromagnetic performance.

According to the literature, the study of the LG temperature field is increasingly receiving attention from scholars, and various simulation and experimental methods are being tried to estimate the temperature field. Reasonable distribution of the LG temperature

field can ensure its safe and reliable operation and service life. LGs have multi-physics field coupling characteristics, and relationships of electromagnetism, heat, and fluid are quite complex [25,26]. The accuracy of electromagnetic loss calculation has a significant influence on the temperature rise calculation. However, the influence of temperature rise on the material performance of the motor is ignored in one-way coupled simulation, which inevitably leads to differences between the calculated results and the actual values. During the actual operation of the electric machine, the electromagnetic field and temperature field are coupled and affect each other. Therefore, it is necessary to study and analyze the bidirectional coupling of electromagnetic and thermal fields considering the influence of temperature on material properties to obtain more accurate temperature field distribution. Thus, electromagnetic–thermal characteristics could be understood more thoroughly, allowing better cooling to be provided for LGs [27], ensuring stable operation at appropriate operating temperatures.

In this paper, an electromagnetic–thermal bidirectional coupling was adopted to calculate the temperature field distribution of the TPMLG. The structure of the FPEG system was introduced and the main parameters of the TPMLG prototype analyzed were provided. Furthermore, a two-dimensional electromagnetic field and three-dimensional temperature field coupling model was erected to analyze thermal characteristics under different air-cooling conditions. Then, the temperature field of the TPMLG was investigated. Consequently, change patterns of the steady temperature field with loss and air flow velocity were analyzed. This study could provide some reference for material selection and support for cooling design of LGs.

2. Structures of the FPEG System and TPMLG

2.1. FPEG System

Figure 1 illustrates the free-piston engine generator system in the form of double cylinders with double pistons utilized in our research. The FPEG system comprises an FPEG prototype with three subsystems, which undertake tasks of air intake, load, and data collection and control, respectively.

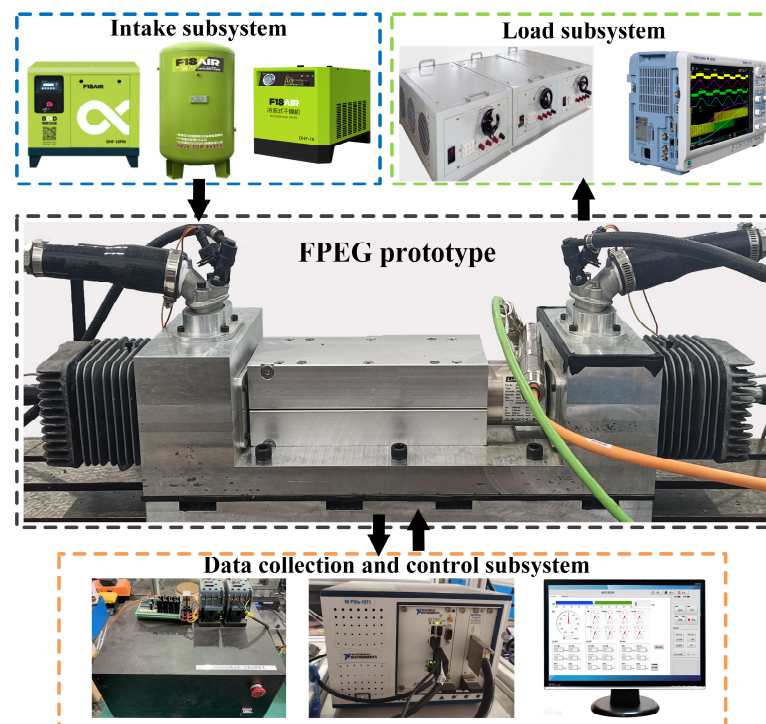


Figure 1. Free-piston engine generator system.

The FPEG prototype consists of two FPEs with connecting rods attached to a single LG positioned centrally. The FPEG's unique reciprocating motion without a crankshaft makes it compact in structure with reduced friction loss. Driven by gas pressure exerted from fuel combustion in the cylinders, the reciprocating movement of the mover creates a travelling magnetic field within the LG. Magnetic induction lines are cut by windings, ultimately generating electricity. The air intake subsystem can adjust the intake pressure of fresh air and dry the air, and the load subsystem is used to simulate load conditions in the stable power generation process.

2.2. TPMLG

The LG significantly impacts the performance of the whole system in terms of thrust density, power generation efficiency, response time, and integrated control. In this paper, a moving-magnetic TPMLG utilized for the FPEG prototype is investigated.

The 3-D schematic structure model of TPMLG is shown in Figure 2, divided into the stator assembly and the mover assembly. The stator assembly is composed of a stator core, windings, slot wedges, and a bearing. The stator core is laminated by silicon steel sheets in the axial direction, giving it orthotropic characteristics in thermal conduction. The windings are made in the form of single-layer concentrated pie windings, wound with multiple strands of copper coils. The ring-shaped windings are arranged in accordance with a certain phase sequence and connected in a star connection scheme. Slot wedges fix the windings embedded in the stator core to prevent detachment of the windings from the slots, and produce an effect in insulation. The bearing supports keep a distance between the stator and the mover, and there is an air gap between the stator and the mover.

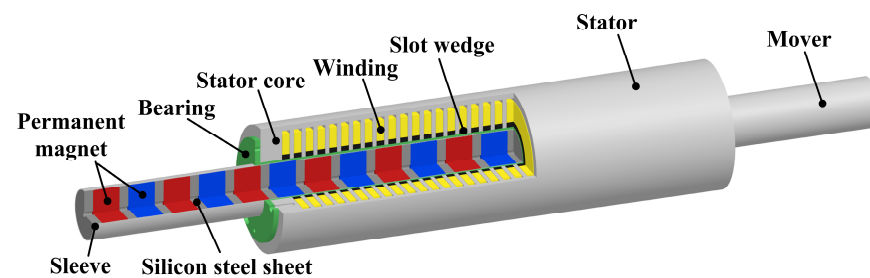


Figure 2. 3-D schematic structure model of the TPMLG.

The mover assembly is comprised of NdFeB magnets, silicon steel sheets and a stainless-steel sleeve. The PMs and annular silicon steel sheets are alternately joined in sequence in the mover, and a thin smooth stainless-steel sleeve is set on the outer surface of the mover. The main parameters of the TPMLG are listed in Table 1 [3].

Table 1. Main parameters of the TPMLG.

Parameters	Values	Unit
Stator tooth width	2.3	mm
Stator slot width	4.4	mm
Stator slot number	36	-
Stator outer diameter	70	mm
Stator yoke thickness	3	mm
Stator length	240	mm
Permanent magnet diameter	27	mm
Permanent magnet length	15	mm
Pole pitch	20	mm
Mover outer diameter	28	mm
Mover length	490	mm

3. Electromagnetic–Thermal Bidirectional Coupling Model Formulation of TPMLG

3.1. Electromagnetic Finite Element Model of the TPMLG and Loss Calculation

The TPMLG is rotationally symmetrical around the central axis. Compared with the precise electromagnetic loss calculation of a three-dimensional model, a two-dimensional model can significantly reduce overall computational time and keep the loss values within an acceptable error range. Furthermore, the establishment of a finite element model merely necessitates the involvement of relevant topologies and components within the magnetic circuit, allowing for the simplification or omission of insignificant elements and minuscule parts. On account of the structural characteristics of the LG and the above considerations, a transient two-dimensional finite element model of the TPMLG was constructed by Maxwell 2022 R1 software, as illustrated in Figure 3. The finite element model consists of the stator core (stator yoke and stator tooth), winding A (red), winding B (blue), winding C (yellow), slot wedges, permanent magnets, silicon steel sheets, and a stainless-steel sleeve. Some basic material properties are sourced from the Maxwell 2022 R1 software while the others need to be set [28]. The electromagnetic properties can be adjusted according to different temperatures by setting object temperature and enabling the thermal modifier.

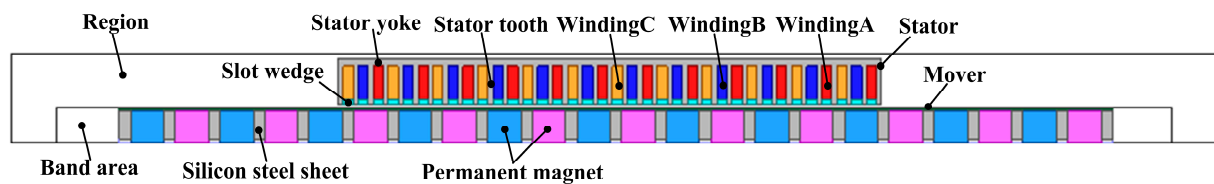


Figure 3. Finite element model of the TPMLG.

To study the losses in the power generation process, the model is simulated under the load condition of stable power generation, when it works at the working frequency of 30 Hz and the stroke of 110 mm. The external circuit excitation is applied in the excitation and the Dirichlet boundary with a value of zero is set for the boundary condition. The resistance of each phase winding is $3\ \Omega$, and the load resistance of each phase is $15\ \Omega$. The electrical energy produced by the LG is consumed by load resistance. The band area is modelled to cover the whole length of the mover's stroke and the region is modelled to guarantee continuity and integrity of the model.

Losses generated in energy conversion from electrical energy to kinetic energy directly led to the temperature rise of the LG. The losses in the TPMLG mainly incorporate copper loss, core loss, and eddy current loss. The 2-D transient electromagnetic field simulation is applied to calculate the losses of the LG.

The copper loss accounts for the greatest proportion of the total loss. Ignoring the skin effect and proximity effect, the copper loss is computed based on Joule's law as follows [29]:

$$P_{Cu} = I_A^2 R_A + I_B^2 R_B + I_C^2 R_C \quad (1)$$

$$R = R_0 \cdot [1 + \theta(T - T_0)] \quad (2)$$

where P_{Cu} represents copper loss; I represents the phase current; R represents resistance; subscripts A, B, C represent the A-phase, B-phase, and C-phase windings, respectively; θ is the temperature coefficient of resistance; T is the actual temperature; and subscript 0 represents the basic ambient temperature.

For permanent magnet motors, temperature rise can affect the permeability of the permanent magnets, and the magnetic field excitation provided by the permanent magnets affects the loss calculation results of the motor's electromagnetic field. Therefore, the linear demagnetization characteristics of NeFdB magnets are considered and the temperature coefficients of relative permeability and magnet coercivity need to be set. According to

the classical Bertotti's core loss theory, the core loss includes hysteresis loss, classical eddy current loss and excess loss [30,31]:

$$P_{Fe} = K_h f B_m^2 + K_c (f B_m)^2 + K_e (f B_m)^{1.5} \quad (3)$$

where P_{Fe} denotes core loss; K_h denotes hysteresis core loss coefficient; K_c denotes classical eddy current core loss coefficient; K_e denotes excess core loss coefficient; f denotes frequency; and B_m denotes amplitude of flux density. The core loss is calculated by setting the three core loss coefficients of the stator material in the software and mainly depends on the magnetic flux density amplitude of the electromagnetic field analysis.

Average eddy current loss of the permanent magnets (PMs) in single cycle is calculated as below:

$$P_{edd} = \frac{1}{T_e} \int \sum_{i=1}^n \frac{J_e^2 V_e}{\sigma} dt \quad (4)$$

where P_{edd} indicates eddy current loss; T_e represents time of each cycle; J_e represents eddy current density of each element; σ represents the electrical conductivity; V_e represents element volume; and n represents the number of total elements.

3.2. Thermal–Fluid Finite Volume Model of the TPMLG

The temperature field analysis is quite complex as the multi-physics field requires comprehensive consideration. To lighten the burden of large computation, the solved domain is minimized, and some factors which are trivial for the temperature field are neglected. Hence, simplifying assumptions are proposed as below:

1. Considering high thermal conductivity and the symmetric structure, it is assumed that the temperatures of the windings and permanent magnets are uniformly distributed in the circumferential direction when the electromagnetic properties of the materials are modified with temperature.
2. Some characteristics which are difficult to model are ignored, such as chamfers, fillets, through-holes, and threaded holes.
3. Mechanical loss and radiative heat transfer are neglected.

Based on the assumptions, a 3-D thermal–fluid finite volume model of the TPMLG enclosed with ambient air was established by Fluent 2022 R1 software in this study. The model is shown in Figure 4. The stator core, the windings, a casing, slot wedges, PMs, silicon steel sheets, the stainless-steel sleeve, and an air enclosure outside the TPMLG are included in the model.

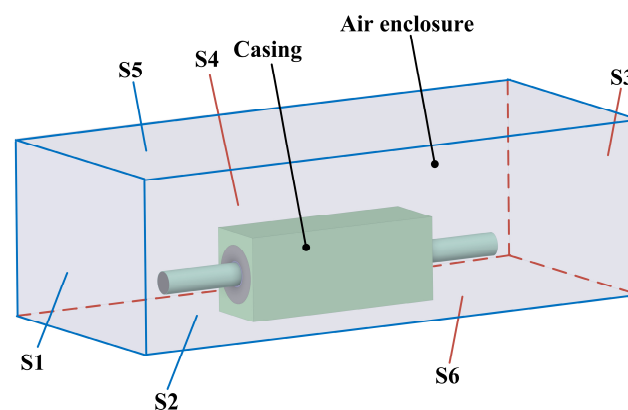


Figure 4. 3-D simplified physical model of the TPMLG.

Mesh quality is extremely important for the precision and convergence of FVM analysis results. The 3-D TPMLG simplified physical model is meshed with hexahedral elements, encompassing a total of 12,424,469 nodes and 2,856,453 elements. The meshes of small size regions, narrow flow areas and near wall boundary layers are required to be refined

appropriately, as shown in Figure 5. Five air inflation layers are set on the surfaces of the LG as the boundary layers, using the smooth-transition method.

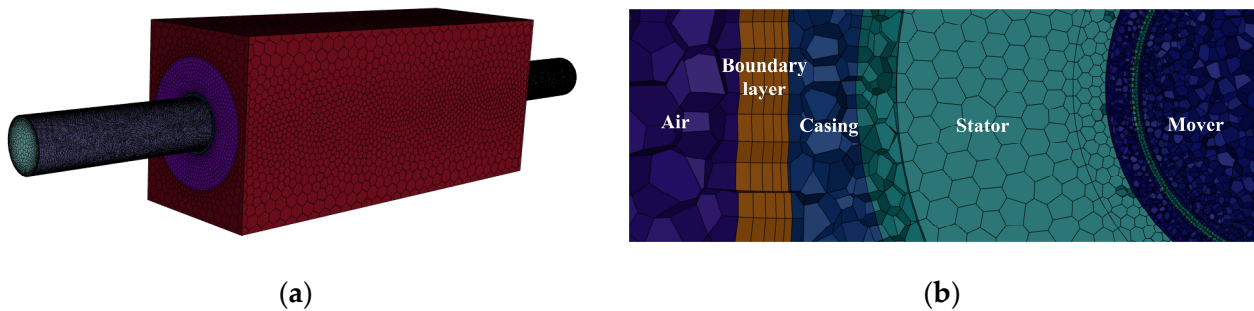


Figure 5. Mesh of the TPMLG physical model: (a) linear generator; (b) local axial section.

3.2.1. Fundamentals of Thermal–Fluid Analysis

Heat conduction in the solid region and the heat balance equation on the fluid–solid interface are considered in the solution domain. Heat transfer equations in steady-state form ignoring the time term for the 3-D temperature field of the TPMLG are expressed as follows:

$$\frac{\partial T}{\partial x} \left(\lambda_x \frac{\partial T}{\partial x} \right) + \frac{\partial T}{\partial y} \left(\lambda_y \frac{\partial T}{\partial y} \right) + \frac{\partial T}{\partial z} \left(\lambda_z \frac{\partial T}{\partial z} \right) + \dot{q} = 0 \quad (5)$$

$$-\lambda \frac{\partial T}{\partial n} = \phi = -h(T_w - T_f) \quad (6)$$

where T refers to temperature; λ_x , λ_y , λ_z indicate thermal conductivities in three directions of the rectangular coordinate system, respectively; $\dot{q}$ indicates heat generated per unit volume; n indicates the normal direction of the wall surface; ϕ is heat flux; h is the convective heat transfer coefficient; T_w represents wall temperature; and T_f represents fluid temperature.

The fluid flow problems are solved by the Navier–Stokes equation, shown as follows:

$$\frac{\partial V}{\partial t} + (V \cdot \nabla) V = f - \frac{1}{\rho} \nabla p + \frac{\mu}{\rho} \nabla^2 V \quad (7)$$

where V is velocity vector; f is body force per unit volume of fluid; ρ is fluid density; p is pressure; and μ is fluid dynamic viscosity.

3.2.2. Boundary Conditions

Boundary conditions as a group of particular solutions are required to be definite conditions of thermal simulation. As can be seen from Figure 4, in the case of natural air cooling, the side surfaces S1, S2, S3, and S4 of the air domain are set as velocity inlet boundaries, and the upper surface S5 is set as a pressure outlet boundary. The bottom surface S6 is set as the wall boundary considering its direct contract with the platform of the test rig, and the thermal boundary condition is set as the Dirichlet boundary condition considering the wall thickness of the base. In the case of forced air cooling, air comes from one side and leaves from the other side. Therefore, the left-side surface S1 of the air domain is set as the velocity inlet boundary, while the right-side surface S3 is set as the pressure outlet boundary. The remaining surfaces are set as wall boundaries.

In the CFD simulation using FVM, convective heat transfer coefficients can be gained from the fluid and thermal coupling field analysis directly. The interface between fluid and solid is set as the coupled boundary. Compared with the limitation that traditional motor temperature simulation uses analytical or empirical-based correlations to acquire the equivalent convective heat transfer coefficients for convection boundaries, FVM calculation results are more accurate. In addition, the ambient temperature is 40 °C and a standard atmospheric pressure is applied.

3.2.3. Air Flow

The air flow condition should be judged first to select a proper turbulence model, significantly affecting results of air-cooling simulation. Dimensionless numbers are compared with critical values to judge air flow state transition. The critical value varies depending on the specific flow conditions and geometries involved. The Grashof number Gr plays a significant role in natural convection phenomena equivalent to that of the Reynolds number in forced convection phenomena. Gr is the principal criterion for the transition from laminar flow to turbulent flow in natural convection [32–34], which is mathematically given by the equation below:

$$Gr = \frac{g\alpha_V\Delta T l^3}{\nu^2} \quad (8)$$

where g refers to gravitational acceleration; α_V refers to volume expansion coefficient; ΔT refers to excess temperature; l represents characteristic length; and ν represents kinematic viscosity. For vertical planes and horizontal columns, the Grashof number of air in natural convection is calculated to be less than 10^8 . For horizontal planes, the Rayleigh number Ra is adopted as the criterion for judgment on the transition of heat transfer law [32], which is defined as:

$$Ra = GrPr = \frac{g l^3 \alpha_V \Delta T}{\nu a} \quad (9)$$

where Pr is the Prandtl number and a is thermal diffusivity. The Rayleigh number of air in natural convection is also estimated to be smaller than 10^8 . Thus, the flow condition of air is laminar flow and the laminar model is employed in the natural cooling simulation. In the forced air-cooling simulation, the standard k - ϵ turbulence model and the scalable wall function are used.

3.2.4. Thermal Conductivity

Accurate determination of thermal parameters in the LG is a prerequisite for effective simulation before calculating thermal characteristics. Thermal conductivity plays an important role in the heat transfer process, affecting heat transfer rate and temperature distribution. Great differences among material thermal conductivities of the TPMLG result in distinct temperature differences among components of the TPMLG, which is especially evident between metal materials and insulation materials.

In the TPMLG, the windings are formed by copper wires which are integrated very closely without gaps among copper wires. The windings are wrapped by insulation paper on the outer surface of approximately 0.5 mm in thickness. Its thickness is too thin to model in the simulation. Therefore, a wall thickness thermal boundary is applied to simulate the thermal resistance effect of the insulation paper which is not displayed in the simplified physical model. Heat transfer is regarded as one-dimensional steady heat conduction inside the thin wall. The thermal conductivities of the materials used for the TPMLG are listed in Table 2 [23,29].

Table 2. Thermal conductivities of different components.

Components	Thermal Conductivity W/(m·K)
stator core	42.5/42.5/3.5
PM	6.4
casing	13.4
winding	387.6
sleeve	202
insulation paper	0.14
slot wedge	0.5
air	0.0272

3.3. Electromagnetic–Thermal Bidirectional Coupling Analysis

During the operation of the mover, the stator core, the windings, and the PMs heat up and serve as the heat sources for the entire heat transfer process. After the establishment of the electromagnetic model and thermal–fluid model, a bidirectional iterative coupling relationship between the electromagnetic field and the thermal–fluid field is built.

The coupling calculation process of electromagnetic and thermal–fluid fields is shown in Figure 6. In the first iteration, calculated temperature is assigned an initial value as the initial temperature to assign corresponding material electromagnetic characteristic parameters in the coupling analysis. After a preliminary electromagnetic analysis, electromagnetic loss data of different parts from the electromagnetic field is loaded into the thermal–fluid field as energy sources for temperature calculation through volumetric mapping. At the same time, temperature rise will also have an impact on the distribution of the electromagnetic field. The diagram of the electromagnetic–thermal coupling module connection is shown in Figure 7. The electromagnetic and thermal fields of the TPMLG interact with each other. New temperature field distribution data from the temperature field simulation is conversely transmitted to the electromagnetic field to update the material properties, thereby recalculating the electromagnetic loss under different temperature conditions. A feedback iterator module is added into the module of the electromagnetic–thermal analysis for iterative convergence. After several iterative processes, the temperature distribution of the LG finally converges within the margin of relative error ε . The maximum temperatures of the major components, which are the windings and the PMs, are selected to calculate relative temperature differences ΔT_w and ΔT_{PM} . Once both the temperature differences of the two adjacent iterations meet the permissible relative error ε , the coupling calculation is done. The coupling iterative process greatly reduces the final temperature calculation error.

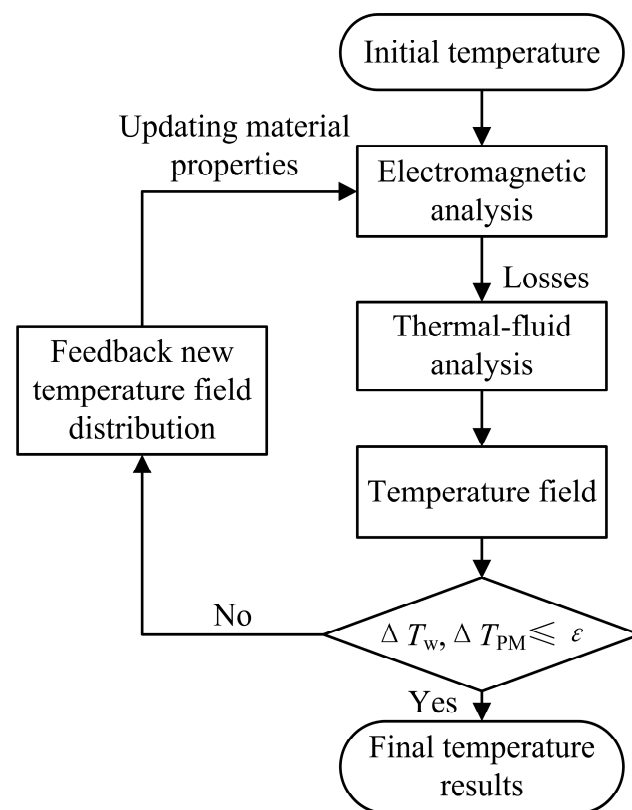


Figure 6. Calculation flow chart of electromagnetic–thermal coupling analysis.

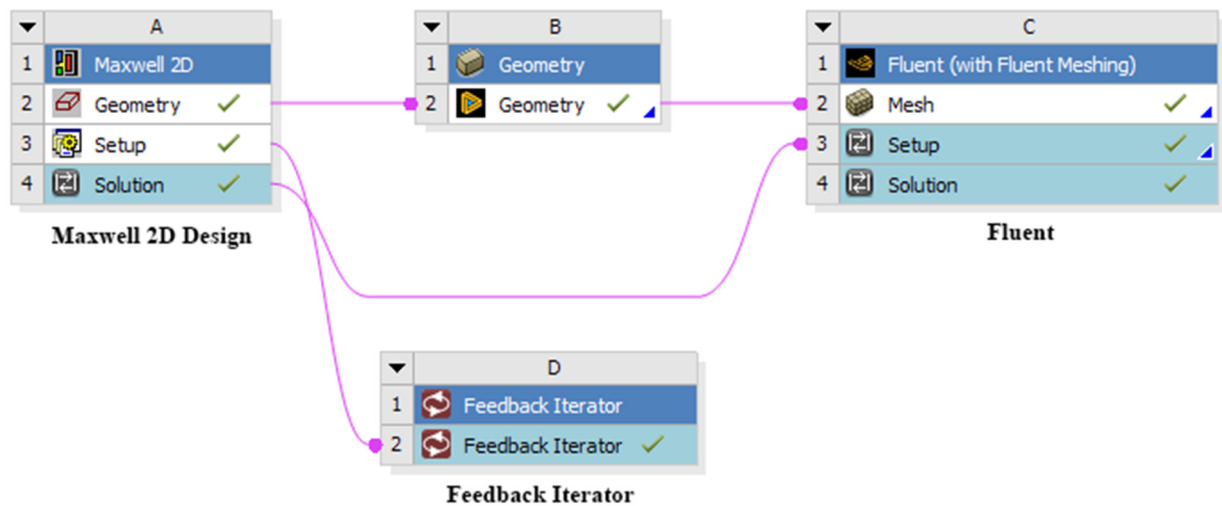


Figure 7. Electromagnetic–thermal coupling module connection diagram.

4. Analysis and Discussions

4.1. Temperature Field Distribution of TPMLG

The steady heat transfer and fluid equations under previous assumptions were solved by software Fluent with boundary conditions and material properties. The temperature field distribution and variation rules were obtained. Firstly steady-state temperature results under the natural air-cooling condition are presented.

Figure 8 depicts the temperature field contour of the TPMLG at the middle longitudinal section. The TPMLG temperature gradient can be clearly seen declining from the inside to the outside. Particularly in the axial direction, the temperatures of the windings and the permanent magnets decrease from the axially central position to both ends cooled by ambient air directly. The temperature at the top of the windings' central position is the highest, reaching 127.8 °C, as shown in Figure 8. The insulation causes a noticeable temperature difference between the windings and the stator, contributing to the high temperature increment of the stator winding and the slot insulation. There is a temperature difference of approximately 10–20 degrees between the upper and the bottom surfaces, due to the heat conduction between the bottom surface of the LG and the base. A certain amount of heat is transferred to the base, affecting the surrounding temperature and may bring heat load to other equipment of the FPEG system.

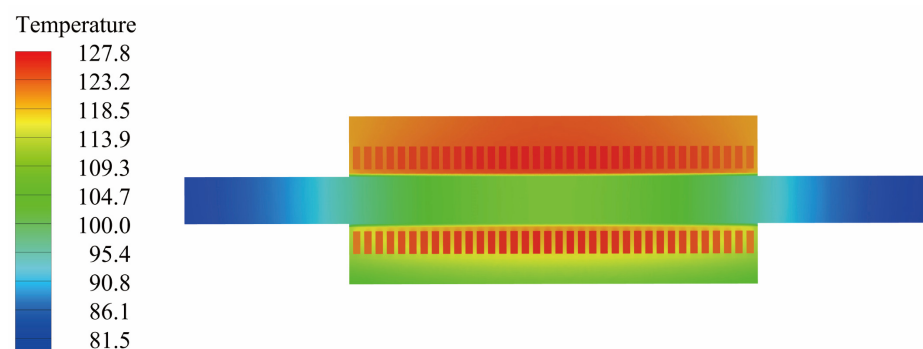


Figure 8. Temperature contour of the TPMLG at the middle longitudinal section (in °C).

The temperature contour of the windings is presented in Figure 9. The temperature at the top of the windings is higher than that of the bottom, and the temperature in the middle of the windings is higher than those at both ends. The highest temperature of the windings is located at the top of the central position. This is because it is not exposed to the air. Heat is transferred from the top of the central position to ambient air through insulation,

the stator, and the casing, hence the heat transfer resistance is higher than other parts of the windings. Therefore, it is the part with the worst heat-dissipation condition. The temperature of every part in the windings is lower than the maximum allowable working temperature for the standard of class F insulation. Therefore, the temperature distribution of the windings is relatively reasonable.

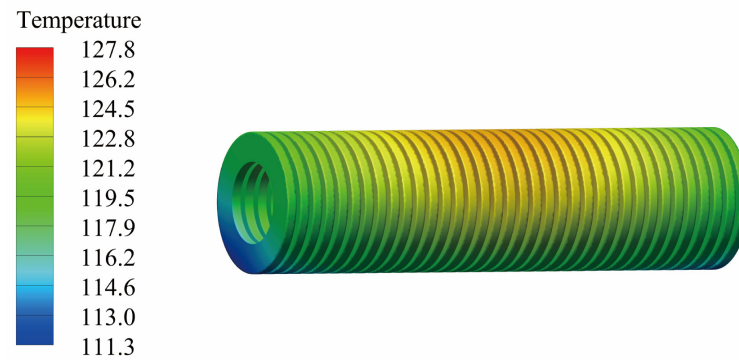


Figure 9. Temperature contour of the windings (in °C).

The temperature contour of the permanent magnets embedded in the mover is depicted in Figure 10. In comparison with the windings, the overall temperature field of permanent magnets is lower, because the eddy current loss of the permanent magnets is much smaller than the copper loss of the windings. Similarly, the temperature of the permanent magnets shows a downward trend from the axial center to both ends along the axial direction. Due to the long length of the mover, temperature differs significantly between external air and the air gap, resulting in different heat-dissipation conditions. Conversely, the temperature field of the PMs is more homogeneous than that of the windings in the circumferential direction owing to more uniform heat dissipation conditions and the lower height.

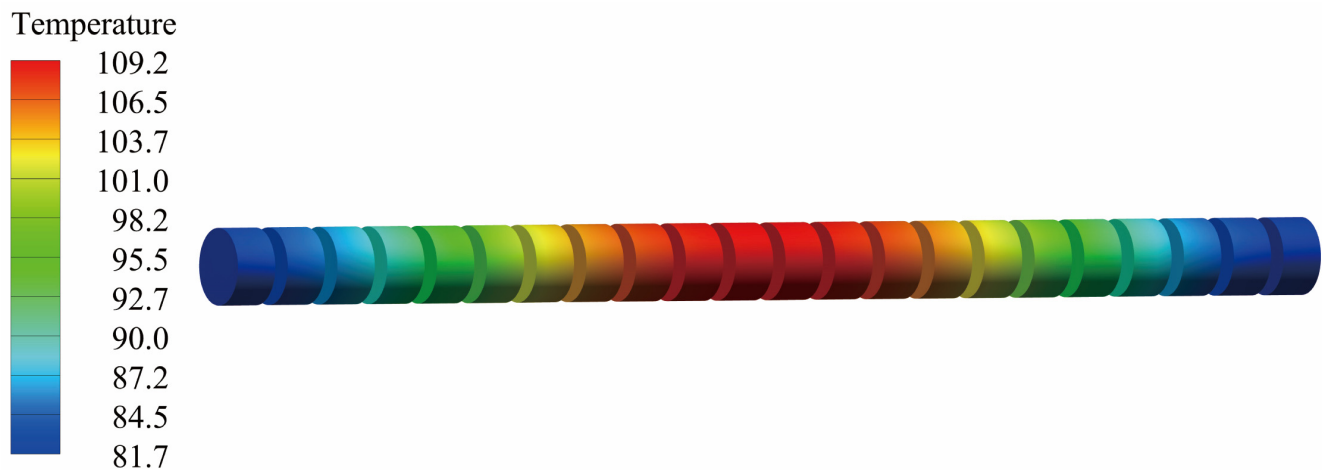


Figure 10. Temperature contour of the permanent magnets (in °C).

Although the eddy current loss in the permanent magnets is relatively small, the fluctuation in temperature of the PMs extends over a range of 27.5 °C, indicating poor heat dissipation conditions for internal permanent magnets. The top temperature of the PMs reaches 109.2 °C. Though the temperature is lower than the limited operating temperature, there is still a potential risk of demagnetization in case the TPMLG is placed in an enclosed structure with poor heat dissipation. The only two paths for the PMs to dissipate heat are through convective heat exchange with air and heat conduction with connecting rods, so air gap heat dissipation is crucial for suppressing the temperature rise of the permanent

magnets. Demagnetization of PMs is the main failure form of PMLGs, which should be focused on seriously.

The maximum and the average temperatures of the windings, the permanent magnets, and the stator are presented in Figure 11. The non-uniformity of temperature distribution in each component can be determined based on the difference between the maximum temperature and the average temperature. The temperature differences are 1.9 °C, 5.0 °C, and 12.1 °C. The copper has excellent thermal conductivity while the slot insulation thermal conductivity is poor, resulting in uniform temperature distribution in the windings and a noticeable temperature difference between the windings and the stator. The inhomogeneity of temperature distribution of the windings, the permanent magnets, and the stator increases sequentially corresponding to the decreasing thermal conductivity coefficients of each component exactly.

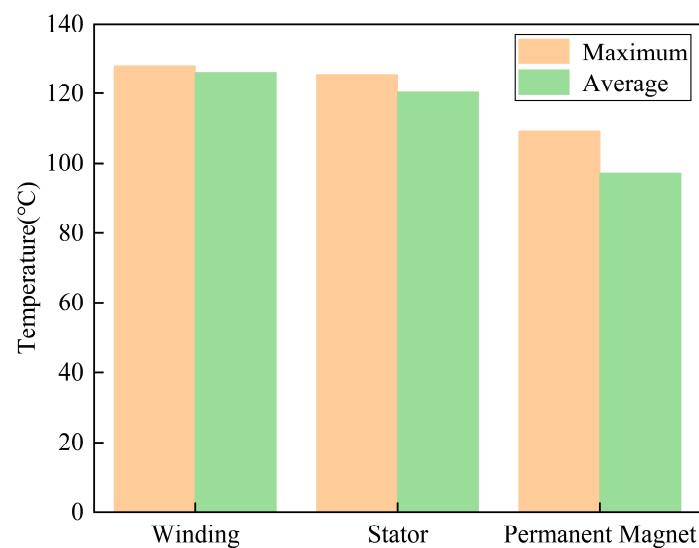


Figure 11. Maximum and average temperatures of the components in the TPMLG (in °C).

4.2. Influence of Loss on Temperature Rise

In the coupling iterative process, losses of different components in the LG vary with the temperature field distribution and the impact of loss variation on the temperature field is investigated.

Figures 12 and 13 illustrate the changes in the losses and temperature with iterations, respectively. After each iteration, the temperature field results of the windings become higher than the previous ones, hence the next higher initial value of temperature is set. As a result, the resistance of the windings along with the copper loss continuously grows in the iterative process, which conversely increases the calculated temperature. The copper loss as the main part of loss, increased by 28.1 W, corresponds to an increasing ratio of 24.5%. Contrary to the upward trend of copper loss, the residual flux density and magnetic coercivity decrease with increasing temperature of the PMs, which leads to the reduced loss of the PMs.

As the iterative process progresses, changes in calculated temperature get smaller. After five iterations there is almost no change in the temperature field and relative temperature errors are within the error range. The maximum temperature of the windings increases by 15.2 °C from the beginning to the last iteration, accompanied by a 14.9 °C rise in the final average temperature. The final maximum temperature of the PMs increases by 11.1 °C, with the final average temperature increasing by 8.8 °C. In addition, the temperature results of the first iteration and the final iteration reflect the gap between one-way coupling and bidirectional coupling.

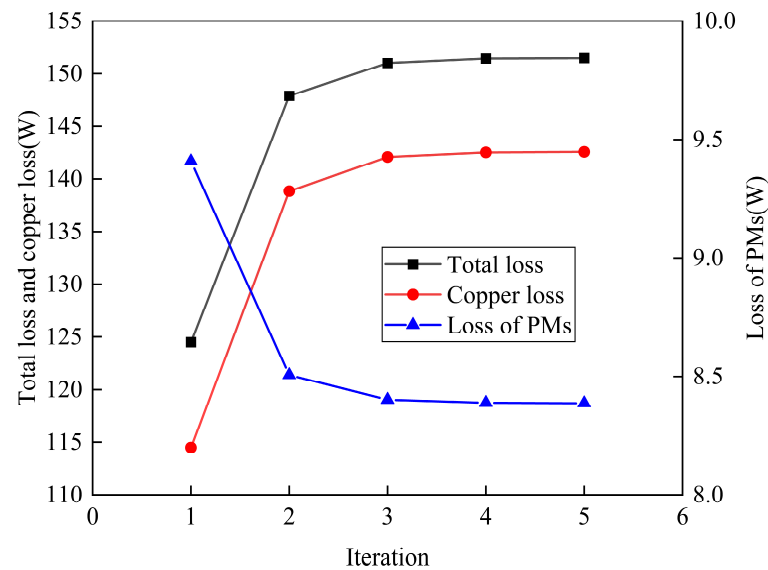


Figure 12. Variation of the losses with iterations.

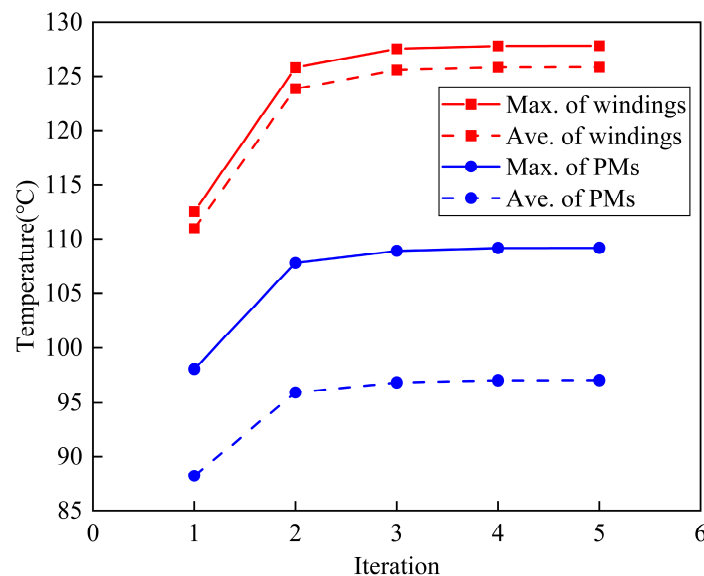


Figure 13. Maximum and average temperature with iterations.

4.3. Influence of Air Flow Velocity on Temperature Rise

Steady-state temperature results under the forced air-cooling condition are presented in this section. The velocity of cooling air flow is a crucial factor affecting temperature greatly under forced convective heat transfer. Therefore, the change rules of the temperature field of the TPMLG under different air flow velocities are analyzed when cooling air is in the state of fully developed turbulence.

Figure 14 depicts variations of the maximum temperatures in the windings and the PMs influenced by the air flow velocity. As the wind speed increases, there is a suppression in the temperature rise observed in each component of the TPMLG. When the wind speed rises from 1 m/s to 3 m/s, the temperatures of the stator windings and the PMs experience a reduction of 22.0 °C and 10.6 °C, respectively, with corresponding decreasing ratios of 19.0% and 15.4%, respectively. The reduction of temperature rise for the PMs caused by air flow is not as significant as that of the stator windings because the PMs have a lower temperature and thereby less heat dissipation. When the air flow velocity is low, the cooling effect is significant. As the air flow velocity increases, due to negative marginal effects, the effect of the air flow velocity on suppressing temperature rise gradually decreases.

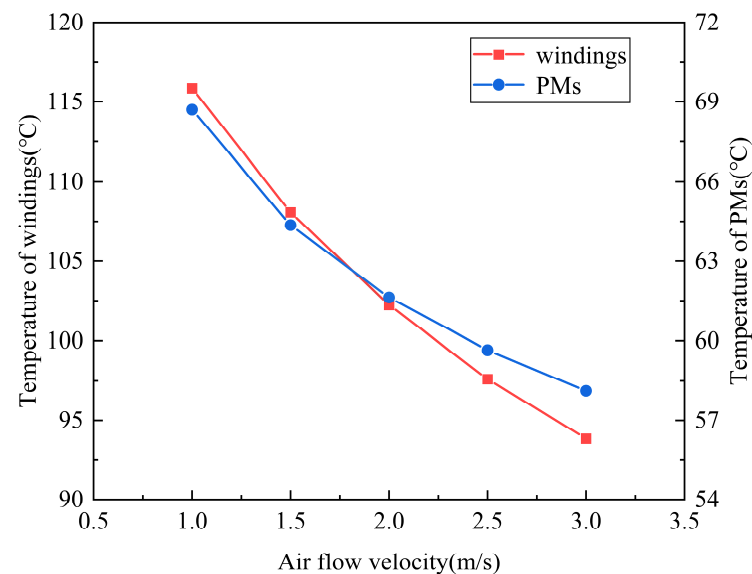


Figure 14. Maximum temperatures of the windings and the PMs with the air flow velocity.

5. Conclusions

In this paper, an electromagnetic–thermal bidirectional coupling model of TPMLG is proposed and electromagnetic–thermal characteristics of TPMLG are investigated. The loss calculated in the electromagnetic field is adopted as the heat source for temperature field calculation, and the temperature field distribution calculated in the thermal–fluid field determines the material properties in an electromagnetic field. The temperature distribution of TPMLG is analyzed, and the following conclusions are drawn.

The hottest spot of the TPMLG appears at the top of the central position in the windings. Due to the top temperature of the PMs reaching 109.2 °C, there is a potential risk of demagnetization resulting from an excessive temperature rise due to insufficient heat dissipation. Through calculation, the insulation in the TPMLG is proved to avoid failure under the high temperature of the windings.

The main loss comes from copper loss. One-way coupling analysis without considering effects of temperature changes on material properties leads to an error of 24.5% in calculating copper loss compared to bidirectional coupling.

High air flow velocity helps to promote the convective heat transfer in the TPMLG. As the air flow velocity rises from 1 m/s to 3 m/s, the maximum temperature of major components of the TPMLG decreases by over 15%. However, as the air flow velocity continues to rise, the cooling effect increment provided by the increased velocity gradually weakens.

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