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Calculation and analysis of complex fluid flow and thermal fields in a fully air-cooled hydrogenerator

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ABSTRACT

Fully air-cooled hydrogenerators are applied widely in power stations because of advantages such as high efficiency, simple structure, and easy maintenance. This study investigated fully air-cooled hydrogenerators, and a three-dimensional fluid and thermal coupling analysis model of a hydrogenerator was proposed. Using the finite volume method, the changes in complex fluid velocity in the stator and rotor zones at different times were determined. Additionally, temperature changes in metal parts and insulation in the hydrogenerator were investigated with respect to time from the start to steady state operation of a hydrogenerator. In the study, the time required for the temperatures of different hydrogenerator parts to reach a steady state was predicted. Following the starting of the hydrogenerator, the temperature distribution of different parts at the same time and the changes in the temperature distribution of parts at different times were determined in the hydrogenerator. The surface heat-transfer coefficient distribution law on the surfaces of rotor exciting winding was studied. The calculated temperature result was compared with the measured value, and the results indicated that the calculated value of temperature agreed well with the measured value. Thus, the study indicated the feasibility of designing a fully air-cooled hydrogenerator from a thermal analysis viewpoint.

1. Introduction

Compared with other conventional energy sources, water energy possesses advantages including large capacity and the lack of environmental pollution. Water energy is a clean energy source that can be converted to electrical energy by a hydrogenerator. Large hydrogenerators are important energy conversion devices in hydropower stations. Generally, the temperatures of the parts in the hydrogenerator are high under both the rated phase and leading phase operations. In particular, the temperatures of the parts are higher under the leading phase operation. Extremely high temperatures could result in insulation aging and even burning of the parts. A failure that occurs in a hydrogenerator causes immense economic losses and affects the reliability of the electrical power system. Increases in the unit capacity of hydrogenerators have led to gradual increases in the electromagnetic and thermal loads of a hydrogenerator. Overheating problems in air-cooled hydrogenerators are becoming increasingly serious and affecting the safe and steady operations of large air-cooled hydrogenerators. Therefore, studies on complex fluid flow and temperature distribution of parts in a large air-cooled hydrogenerator have considerable engineering significance and pose challenges and difficulties for designers. An in-depth study of the fluid field and temperature field during the entire operation of a hydrogenerator necessitates calculation and examination of the changes in fluid flow and metal part temperatures in the hydrogenerator with respect to time from the start to steady state operation of a hydrogenerator.

Previous studies extensively investigated the physical field of a hydrogenerator. Traxler-Samek et al. presented a computation method in which power loss, airflow, and temperature calculations (thermal network) for the largest air-cooled hydrogenerators in the world were coupled in an iterative process [1]. Toussant et al. focused on a CFD analysis of ventilation flow for a scale model hydrogenerator [2]. Liang et al. performed finite-element calculations of a 3-D transient electromagnetic field in the end region and a decrease in the eddy-current loss in the stator end clamping plate of a large hydrogenerator [3]. Akiror et al. studied the rotational flux distribution in the stator of a hydrogenerator under different operating conditions [4]. Several experts and researchers also

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extensively examined the physical field of electrical machines [5–13]. However, most extant studies examined the numerical simulation of fluid dynamics and thermal behavior of forced air-cooled generators in a steady state. Hence, there is a paucity of studies that focus on three-dimensional transient fluid flow and temperature of parts in the hydrogenerator at different times from the start to steady state operation of a hydrogenerator.

In this study, a large hydrogenerator was used as an example to propose a three-dimensional fluid and thermal coupling analysis model of a hydrogenerator. Three-dimensional transient fluid flow and temperature of parts in the hydrogenerator were researched under a 500 MW operating condition. Based on the theory of fluid mechanics and heat transfer, the changes in complex fluid velocity in the stator and rotor zones at different times were analyzed. Meanwhile, the temperature changes in the metal parts and insulation in the hydrogenerator with respect to time were studied from the start to steady state operation of a hydrogenerator using the finite volume method. Additionally, following the starting of a hydrogenerator, the temperature distribution of different parts at the same time and the changes in the temperature distribution of parts at different times were determined in the hydrogenerator. The surface heat-transfer coefficient distribution law on the surfaces of rotor exciting winding was studied. The calculation method in this study can be applied to calculate fluid fields and temperature fields in various electric machines. Furthermore, fluid velocity distribution and temperature distribution of parts in various electrical machines can be determined using the proposed method. The findings of the study will provide an important theoretical basis for research on ventilation design and structural optimization of large hydrogenerators.

2. Fluid and thermal coupling analysis model of a hydrogenerator

2.1. Modeling of coupling analysis

The hydrogenerator used in this study can be operated under load conditions of 500 MW, 600 MW, and 700 MW. The fluid flow distribution and temperature fields of parts in the hydrogenerator were studied in detail under the 500 MW operating condition. Table 1 shows the basic parameters of the hydrogenerator under the 500 MW operating condition.

Based on the symmetry of the actual structure in the hydrogenerator, a 3-D fluid and thermal coupling analysis model of the hydrogenerator was selected as corresponding to half an axial segment along the axial direction and a pair of rotor poles along the circumferential direction as shown in Fig. 1. The 3-D fluid and thermal coupling analysis model of the hydrogenerator included fluid zone, stator solid zone, and rotor solid zone. The main parts of the fluid zone included the fluid in the stator ventilation duct, fluid in the air-gap between the stator and rotor, fluid between rotor poles, fluid between rotor magnetic yokes, and fluid in the rotor support. Additionally, the solving region included rotor support inlet, stator ventilation outlet, and rotor end outlet as shown in Fig. 1(a). The main parts of the stator solid zone included stator tooth, stator yoke, upper and lower copper coils, stator winding insulation, slot wedge, and layer insulation as shown in Fig. 1(b).

Table 1
Basic parameters of the hydrogenerator under the 500 MW operating condition.

Power (MW)	500	Frequency (Hz)	50
Voltage (kV)	20	Speed (r/min)	75
Current (A)	16038.8	Power factor	0.9
Rotor poles	80	Insulation class	F

The main parts of the rotor solid zone included pole shoe, pole body, rotor exciting winding, support plate, rotor damper winding insulation, rotor damper winding, rotor magnet yoke, rotor pole-body insulation, press plate, rotor end ring, and wind board among rotor magnetic yokes as shown in Fig. 1(c). The total number of elements for the CFD and heat transfer in the 3-D fluid and thermal coupling analysis model of the hydrogenerator corresponded to 17418472. Fig. 2 shows the hydrogenerator rotor.

2.2. Mathematical equations of 3-D transient fluid and the thermal coupling field

The rotor rotated versus the stator from the start to steady state operation of the hydrogenerator. Based on the theory of fluid mechanics and heat transfer, it is necessary to satisfy the laws of mass conservation, momentum conservation, and energy conservation during the calculation of the 3-D fluid and thermal coupling field in the hydrogenerator. The mathematical equations of the coupling field can be expressed as shown below.

The law of mass conservation is expressed as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0, \tag{1}$$

Where t denotes the time, ρ denotes the fluid density, $\vec{v}$ and denotes the velocity vector.

The law of momentum conservation is expressed as follows:

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot (\overline{\overline{\tau}}) + \rho \vec{g} + \vec{F} \tag{2}$$

where p denotes the static pressure, $\overline{\overline{\tau}}$ denotes the stress tensor, and $\rho \vec{g}$ and $\vec{F}$ denote the gravitational body force and external body forces, respectively.

The stress tensor $\overline{\overline{\tau}}$ is given by the following expression:

$$\overline{\overline{\tau}} = \mu \left[\left(\nabla \vec{v} + \nabla \vec{v}^{T} \right) - \frac{2}{3} \nabla \cdot \vec{v} I \right], \tag{3}$$

where μ denotes the molecular viscosity, I denotes the unit tensor, and the second term on the right hand side denotes the effect of volume dilation.

The law of energy conservation is expressed as follows:

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot (\vec{v}(\rho E + p)) = \nabla \cdot \left(k_{eff} \nabla T - \sum_j h_j \vec{J}_j + \left(\tau_{eff} \cdot \vec{v} \right) \right) + S_h \tag{4}$$

where k_{eff} denotes the effective conductivity. Additionally, $\vec{J}_j$ denotes the diffusion flux of species j. The first three terms on the right-hand side of Equation (4) represent energy transfer due to conduction, species diffusion, and viscous dissipation, respectively. Additionally, S_h includes the heat of chemical reaction and any other volumetric heat sources.

The heat transfer equation is expressed as follows:

$$\frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z}\left(\lambda_z \frac{\partial}{\partial z} \right) + q_v = \rho c \frac{\partial T}{\partial t}, \tag{5}$$

where λ_x, λ_y, and λ_z denote the thermal conductivity coefficient in the x, y, and z directions, respectively, and q_v denotes the heat density.

Some reasonable assumptions and boundary conditions for the 3-D fluid and thermal coupling analysis model of the