International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:4, No:7, 2010

# Two-dimensional Heat Conduction of Direct Cooling in the Rotor of an Electrical Generator (Numerical Analysis)

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***Abstract*—**Two-dimensional heat conduction within a composed solid material with a constant internal heat generation has been investigated numerically in a sector of the rotor a generator. The heat transfer between two adjacent materials is assumed to be purely conduction. Boundary conditions are assumed to be forced convection on the fluid side and adiabatic on symmetry lines. The control volume method is applied for the diffusion energy equation. Physical coordinates are transformed to the general curvilinear coordinates. Then by using a line-by-line method, the temperature distribution in a sector of the rotor has been determined. Finally, the results are normalized and the effect of cooling fluid on the maximum temperature of insulation is investigated.

***Keywords*—**general curvilinear coordinates , jacobian, control volume.

## I. INTRODUCTION

INCREASING world wide demand for electrical power and exclusive industrial application of generators in producing electricity has led to their significant role in the modern life. Therefore any attempt for increasing the proficiency of these devices would be of considerable value. In order to develop generators operating beyond their present performance limit, efficient cooling systems with the least amount of thermal loss and the highest efficiency are required. Particularly with respect to the operational reliability and avoiding damage of components, it is then necessary to know a detailed history of temperature rise for a system and to predict critical points.

Simple generator systems are preferred for thermal power generation because of their better operability and maintainability, and their lower cost. To meet these customer requirements, the authors have endeavored to expand the capacity range of a simple indirectly cooled system by developing a large-capacity air-cooled generator and a large-capacity hydrogen-cooled generator. Two hydrogen-cooled generators of up to 600MVA-class have been developed for both combined-cycle and coal-fired thermal power plants. These are the largest indirectly hydrogen-cooled generators in the world [1].

Recently, intensive efforts have been made to increase the highest unit rating. A 300 MVA air cooled generator series has been introduced in 1996 [2] which has extended to 500 MVA in 2000 [3]. Hitachi, led. has developed a 250-MVA large capacity, air-cooled generator. This is a high-efficiency air-cooled generator that makes maximum use of an ICVS (inner cooler ventilation system) [4]. The main contributions to this huge development are optimization of the cooling system and change to class F utilization, combined with the introduction of a class H insulation system besides a slight enlargement of the size of machine.

To achieve desired development, inventors recommend several upgrades to the common systems such as cooling accompanied with mixing on downstream of the cooler [5], circulation of the cooling air at super atmospheric pressure in the casing [6], and augmentation of end winding cooling [7]. Also, there are various interesting topics for researchers such as rotor-stator gap flow analysis and experiments [8], numerical analysis rotor-stator gap flow [9], and approximate analysis of steady state heat conduction [10].

**Nomenclature**

| | | | |
|---|---|---|---|
| A | Surface of control volume | $T\infty$ | Coolant inlet temp. |
| $A_c$ | Flow cross section | V | Volume |
| $C_p$ | Specific heat capacity | $N_u$ | Nusselt number |
| $D_h$ | Hydraulic diameter | p | Wetted perimeter |
| d | Radius difference | $p_r$ | Prandtl number |
| $f_e$ | Ratio of grid to face distances | $q''$ | Heat lux |
| $g'''$ | Energy generation | R | Radius |
| h | Convection coefficient | t | Time |
| i | Number of grid in x direction | T | Temprature |
| j | Number of grid in y direction | $T_a$ | Taylor number |
| K | Thermal conductivity | $T_s$ | Surface temperature |
| e | Effective | $p_r$ | Prandtl number |
| n | Normal direction to the surface | | |

**Greek Symbols**

| | | | |
|---|---|---|---|
| $\alpha$ | Thermal diffusivity | $\upsilon$ | Kinematics viscosity |
| $\zeta$ | General coordinate component | $\rho$ | Density |
| $\eta$ | General coordinate component | $\Omega$ | Angular speed |
| $\theta$ | Non-dimensional temperature | | |

The output of a generator is usually limited by the temperature of either the stator or rotor winding. Other temperatures are normally less important. Winding are classified according to two system of cooling. In the case of indirect cooling, the copper winding has no direct contact with the coolant. Either the insulation outer surface or the surrounding laminated core is cooled shown in Fig. 1.

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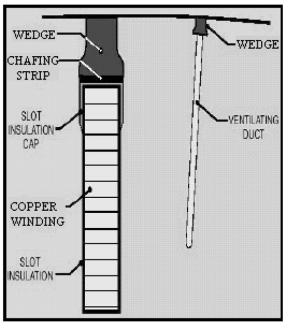

Fig. 1 Indirect cooled coil slot.

Indirect cooling is a constructively simple and low cost solution as long as it is adequate for the needs. In the case of direct cooling the coolant is brought into direct contact with the winding copper e.g. by hollow conductors is shown in Fig.2.

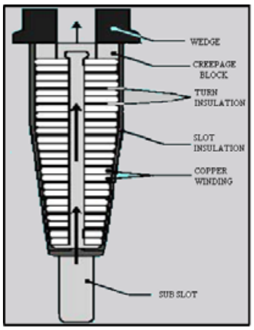

Fig. 2 direct cooled coil slot

Analytical methods such as separation of variable and conformal mapping leading to a solution in closed form are incapable to simulate complex geometry with the desired accuracy. The deficiency in analytical methods has been largely eliminated by numerical methods such as finite difference, control volume, and finite element [11, 12, 13]. The first two methods produce the same linear set of equation by different approach. Wise and McElroy [14] compares finite element of heat transfer using both flat plates element and curved element to simulate the toroid and parabolas .They also used the method of finite difference for the same problems, which locates the nodes at the centroid of the element. Their results show that significant errors will be generated when flat plate elements are applied unless the mesh size is sufficiently small. These errors can be introduced due to lack of curvature at boundary. Finite difference can cause skewing of the isotherms in certain border line such as around an irregular gap. This can be overcome by placing nodes at the edge of the gap. These results show the finite difference is more accurate if a small number of elements used.

Composed solid materials are subject of many fields of industry; especially in fields that heat transfer has a major role, which itself severs complexity of analysis; hence numerical analyses have been largely applied. Also, the analysis of heat conduction problem in complex geometry such as sector of generator involves the determination of the temperature distribution within the solid as a function of both time and position, which is a complicated subject. Kabba and Ledent [15] used heat diffusion analysis in a heterogeneous structure of the maize ear to determine the temperature changes within it. Antonopoulos and Tzivandis [16] used a finite difference method for solving unsteady heat conduction in a ceiling slab. Maged and shaarawi [17] and Ferreira and Yanagihara [18] investigated transient heat conduction in eccentrical hollow cylinder and in a 3D elliptical cylinder by general coordinate system.

In the present work, temperature distribution in a two-dimensional sector of a generator with constant internal heat generation is determined numerically. The insulated and convection boundary conditions are used for symmetry lines and hydrogen cooling sides, respectively. An implicit control volume approach is used for discretizing the energy equation and then the discretized equation is solved by a line-by-line scheme. Since the sector of a generator is made of composed material, in each specific material mesh is generated separately by an elliptical scheme and is then converted by a non-orthogonal transformation from physical to computational domain. The energy equation is solved for all grids in the computational domain and the calculated temperatures are converted in the physical domain afterwards.

## II. PHYSICAL MODEL

Fig. 3 shows a basic mechanical outline for a typical generator filed.

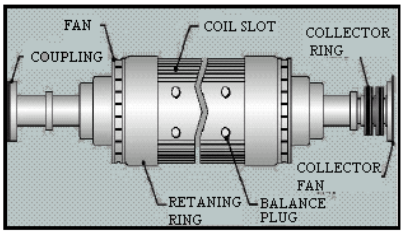

Fig. 3 Generator field

A rotor of a generator is shown schematically in Fig. 4. The cross section of rotor contains some segment, which include some sectors. Each sector contains of three or more main components such as slot, insulations and core (made of steel), as shown in Fig. 5.

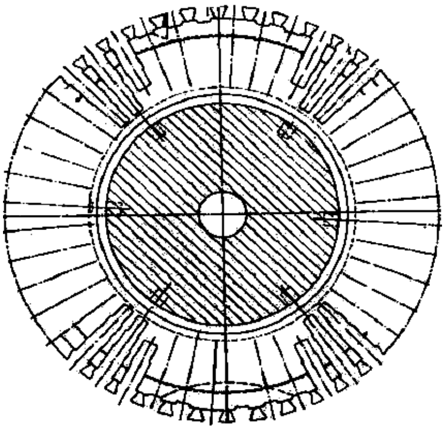

Fig. 4 Cross-section of rotor.

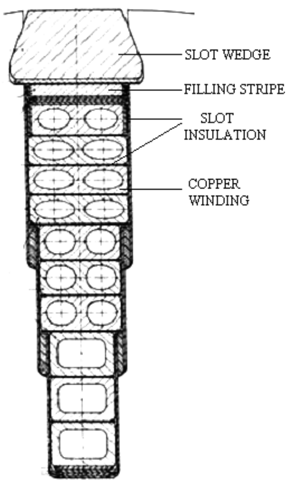

Fig. 5 Rotor wire cross-section.

The copper elements transmit current and are insulated from steel by special electrical insulations. Since the sectors of a segment are symmetric, an individual sector is analyzed. While the electricity current is transmitted by copper wire, the required magnetic filed is produced in the core [19, 20].

Since all instruments, which produce or operate by electrical power, dissipate heat loss, generating electricity is accompanied by heat loss in wires. The heat loss depends on thermal resistant of the material and the amount of the electrical power. As the generated electrical power in a generator is very high, the winding heat losses are considerable. Thus, temperature rise in the insulation must be taken into account.

The dissipated heat is exhausted to the outer surfaces, i.e. the back of core and air gap surfaces, through convective mode of heat transfer.

## III. MATHEMATICAL MODEL

The general form of the heat conduction equation in a solid with internal energy generation [21] is given by

$$\frac{\partial}{\partial t}(\rho C_p T) = \nabla.(K\nabla T) + g''' \tag{1}$$

The heat conduction equation can be integrated on a control volume, and the divergence theorem applied. The energy equation in the index form can be written as follows[12].

$$\begin{gathered}\frac{\partial}{\partial t}\iiint \rho C_p T dV - \iiint g''' dV = K\iint \overrightarrow{\nabla} T.\overrightarrow{dA} \\ \left(\rho C_p \frac{\partial T}{\partial t} - g'''\right)V_{i,j} = K\sum_{m=1}^{6} \overrightarrow{\nabla} T.\overrightarrow{dA}\end{gathered} \tag{2}$$

The equation is transformed to a general curvilinear coordinates system which is related to physical coordinates by following equation.[12, 13].

$$\begin{gathered}x = x(\xi,\eta) \\ y = y\ \xi(\ \eta\ )\end{gathered} \tag{3}$$

The index form of the diffusion energy equation in general coordinates system can be written as follows [12].

$$\frac{\partial T}{\partial t}V_{I,J} = \alpha\sum_{m=1}^{4}(B_m\frac{\partial T}{\partial \xi} + C_m\frac{\partial T}{\partial \eta}) \tag{4}$$

Where $B_m$ and $C_m$ has the following definitions:

$$\begin{gathered}B_m = (\xi_x dA_x + \xi_y dA_y)_m \\ C_m = (\eta_x dA_x + \eta_y dA_y)_m\end{gathered} \tag{5}$$

## IV. BOUNDARY CONDITION

Since rotor is cooled by fluid; the convection boundary condition is applicable, convection heat transfer through the surface to the cooling fluid is balanced by the conduction heat transfer through control volume [22].

$$K(\nabla T)_{S,n} = hA(T_s - T_\infty) \tag{6}$$

Where $T_s$, $T_\infty$, K, h, and index $n$ refer to temperature of control volume adjacent to the surface, temperature of the cooling fluid, conductivity of solid, convection coefficient of cooling fluid, and normal direction to the surface, respectively. Furthermore insulation boundary condition is necessary for symmetry lines of the rotor where the cross section is cut:

$$K(\nabla T)_{S,n} = 0 \tag{7}$$

Nusselt number for the gap between two coaxial cylinders rotating in the same direction is developed by Leont and Kirdyashin [23]. This equation is used for calculating convection coefficient of the flow between rotating rotor and stationary stator of the generator. The effect of axial flow has been neglected. They recommend two equations for different ranges of Taylor number, which are as follows:

$$\begin{gathered}Nu = 0.212\Pr^{0.4} Ta^{1/4} \qquad 1708 \le Ta \le 45000 \\ Nu = 0.108\Pr^{0.4} Ta^{1/3} \qquad Ta \ge 45000\end{gathered} \tag{8}$$

Where the Taylor number is the ratio of centrifugal force to viscous force and is calculated by follow equation

$$Ta = 4\left(\frac{\Omega_1 R_1^2 - \Omega_2 R_2^2}{R_2^2 - R_1^2}\right)\frac{\Omega_1 d^4}{\upsilon^2} \tag{9}$$

Where $d = R_2 - R_1$, $\Omega_1$ and $\Omega_2$ are angular speed, $R_1$ and $R_2$ are radii of inner and outer cylinders respectively.

## V. COMPOSITE MATERIAL EFFECT

As the segment contains of different materials i.e. copper, steel, insulation, the effect of material on heat transfer must be considered. Each material is discretized separately to generate mesh within this sub domain. Then the sector has been built by sub domains and considered as one domain for computation. Thermal conductivity, density, heat capacity, and heat generation of each grid is considered with respect to its material. In the other hand, the face of control volume for all adjacent materials must be conformed on their interfaces so that each control volume is filled only by one material. For these common interfaces located between two materials, $K$ and $\alpha$ are calculated by using a harmonic average of their corresponding value for two adjacent grids (P and E) [11] as

$$K_e = \left( \frac{1 - f_e}{K_P} + \frac{f_e}{K_E} \right)^{-1} \tag{10}$$

Where $f_e$ refers to the ratio of grid to face distances as follows:

$$f_e = \frac{(\delta x)_{e^+}}{(\delta x)_{e^-}} \tag{11}$$

## VI. NUMERICAL SOLUTION

To simulate the temperature within the sector of generator, boundary fitted mesh and elliptical scheme are used for generating the numerical grid mesh in each material [11]. Thermal properties of each material are attributed to grids within it, and then the total sector is considered as an integrated domain with different thermal properties in grids. Internal heat generation is considered, except in copper, for its thermal resistance across the transmitted electric and steel, for its resistance across electric current generated by magnetic field. Internal heat generation is considered for copper because of its resistance against the electricity current and magnetic losses in steel is neglected.

Coefficients of equation (5) are applied to relocate diffusion energy equation (1) in general coordinates. Then the set of linear equations are solved by using a line-by-line method in each time step [11]. The steady state temperature distribution in numerical domain can be calculated by marching in time and using convergence criterion. Convergence criterion is used as the ratio of temperature difference in two subsequent time steps to its final value to be less than $10^{-6}$. Finally, the temperature distribution is transmitted to physical domain.

TABLE I THERMAL PROPERTIES OF ROTOR MATERIALS

| Material | $K$ $(W/m^0K)$ | $C_p$ $(J/m^{3\,0}K)$ | $\rho$ $(Kg/m^3)$ |
|---|---|---|---|
| Steel | 80.2 | 447 | 7870 |
| Copper | 401 | 385 | 8933 |
| Fiberglass insulation | 0.035 | 1210 | 40 |
| Protective stripe | 1.4 | 750 | 2500 |

## VII. RESULTS

The thermal and geometrical characteristics of the rotor for a typical generator have been shown in table (1) and (2). The characteristics of different coolants are also given in table (3).
Temperature distribution and isotherm lines in sector of the rotor a generator is shown in Fig. 6 and 7 respectively.

TABLE II THE CHARACTERISTICS OF ROTOR

| Parameter | | |
|---|---|---|
| Rotor radius | (m) | 0.5 |
| Width of copper | (m) | 0.031 |
| Length of copper | (m) | 0.170 |
| Width of steel | (m) | 0.02108 |
| Thickness of fiberglass insulation | (m) | 0.004 |
| Number of numerical grids | (m) | 20130 |
| Total heat loss in copper | (W) | 200000 |
| Total heat loss in steel | (W) | 0 |
| Generator power | (MW) | 150 |
| Velocity of coolant fluid | (m/s) | 40 |
| Rotated speed of rotor | (rpm) | 3000 |
| Rotational speed of stator | (rpm) | 0 |
| Inlet temperature of coolant fluid | $(^\circ C)$ | 50 |

TABLE III THERMAL CHARACTERISTIC OF DIFFERENT COOLANT FLUIDS

| Coolant fluid | $K \times 10^{-3}$ $(W/m^0K)$ | $\nu \times 10^{-6}$ $(m^2/s)$ | Pr |
|---|---|---|---|
| Water at 300 $^\circ K$ | 613 | 0.857 | 5.83 |
| Air at 300 $^\circ K$ | 26.3 | 15.89 | .707 |
| Hydrogen at 300 $^\circ K$ | 183 | 111 | 0.701 |

The highest temperature is obtained for copper and its isolations. The reason can be described by high rate of heat generation in the copper, which is separated by insulations from steel. The most important concern in thermal analysis of the rotor is the performance of insulations, which are sensitive to high temperatures and their operation is demolished under a critical temperature.

Thus, the thermal design of a generator must be such that the maximum generated temperature to be less than the critical temperature.

Although using a better cooling or thermal insulation will lead to better proficiencies, there are electrical limitations in utilizing different insulations So in this analysis the effect of coolant and its temperature is investigated on a common generator.

Generators are mainly cooled by air, hydrogen, water and oil. Convection coefficients for air, water and hydrogen, which are most common fluids in generator cooling, are calculated from Eq. (8) and given in table (4). The velocity and inlet temperature of the fluid is considered to be constant.

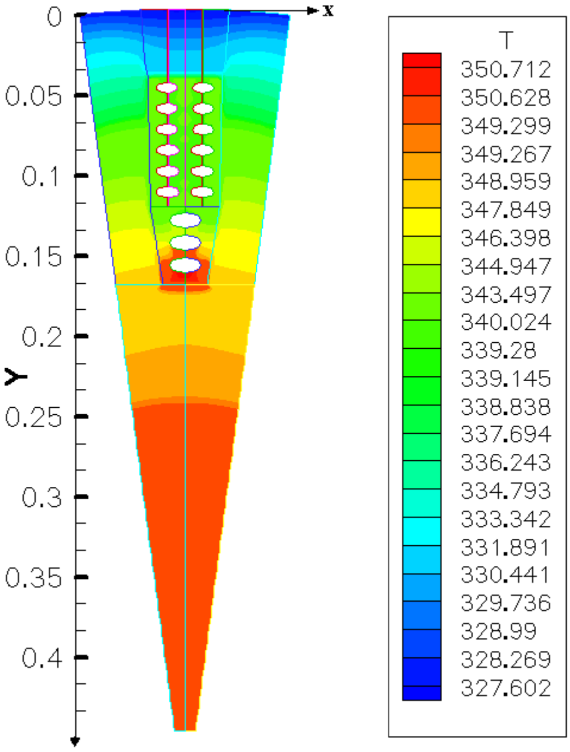

Fig. 6 Temperature distribution in sector of the rotor a generator, which is cooled by air

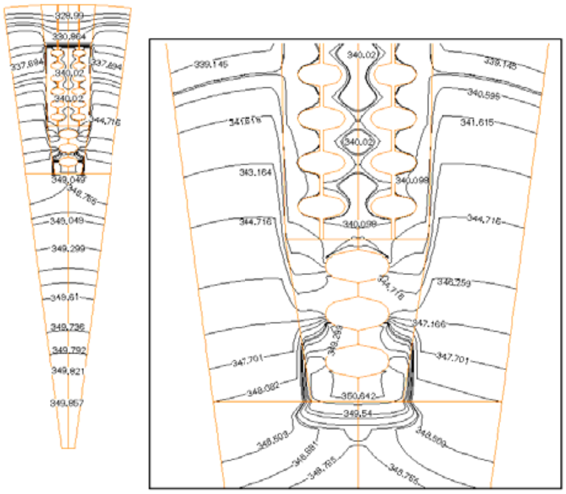

Fig. 7 Isotherm lines in sector of the rotor a generator, which is cooled by air

Table IV Convection coefficients of common coolants

| Coolant fluid | Air | Water | Hydrogen |
|---|---|---|---|
| h$_{(W/m^2\,{}^\circ k)}$, Convection coefficient for flow between rotor and stator, equation (7) | 371.4 | 7730.7 | 107.25 |

Maximum temperature of insulation for the mentioned coolants is presented in Fig. 8, which is occurred in the distance part just in the boundary of insulation and copper. From economical point of view air is the most inexpensive and water is the most expensive medium, not only because of their cooling cost, but also because of the required special precautions and auxiliary equipment. Air is in general insufficient above a generator power of 200 MVA (50Hz), and is therefore replaced by hydrogen. This also becomes inadequate for higher powers so the stator winding is cooled by water.

## VIII. CONCLUSION

The thermal design of a generator must be so that the highest temperature of insulation undergoes the critical temperature. In the present work, temperature distribution in a sector of rotor a generator is analyzed by using control volume scheme. Since, there are some electrical limitations in selecting insulation materials; the effect of different common coolants was investigated with respect to constant velocity and inlet temperature. As can be seen the best coolant is water with respect to its maximum temperature in insulation.

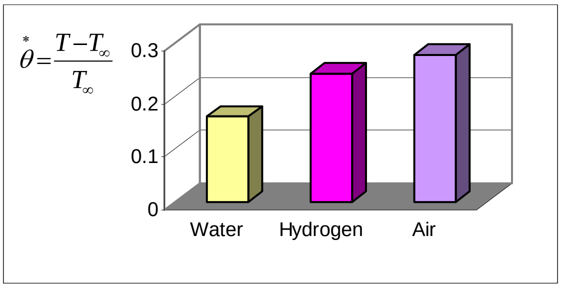

Fig. 8 Effect of coolant on maximum temperature of insulation of $\theta_{MAX}$

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