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Constructal design of gas-cooled electric power generators, self-pumping and atmospheric circulation

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ABSTRACT

Rotating electric machines generate heat volumetrically, and are cooled by forced convection aided by the self-pumping effect. In this paper we focus on the fundamental relationship between the internal flow architecture of the gas cooled winding and its thermal performance, which is represented by the nearly uniform distribution of peak temperature throughout the winding volume. We show that the cooling passages can be sized such that the volumetric cooling is most effective. From this finding follows the number of passages and their distribution through the heat generating volume. The principle is developed analytically, and it is then validated based on numerical simulations of the cooling architecture. The paper also reports the thermodynamics basis of the self-pumping effect, and its natural occurrence as free convection in general, which includes atmospheric circulation.

1. Introduction

In this paper we take a look from above at the improvements that can be made in the performance of cooling architecture of synchronous electric power generators for steam power plants. The focus is on fundamentals. The approach is based on constructal design [1,2] which is the philosophy that improvements in global performance are achievable through continuing changes in the geometry of the architecture of the flow system, to facilitate flow. For this purpose, the flow architecture must be free to morph, and the better and better flow architectures must be pursued relentlessly.

What designers view as "optimal" is the time direction in which the architectural changes are happening. The direction is natural, and is exhibited by the evolutionary designs of manmade systems (the evolution of technology) and, even more visibly, by the flow architectures of nature [2]. The natural evolutionary character of technology was illustrated recently by the evolution of aircraft [3].

Here we focus on the evolutionary design of gas-cooled synchronous generators powered by steam turbines in modern power plants [4–6]. The synchronous generator is a solid structure that generates heat volumetrically, and is cooled by a gas that flows through multi-scale channels embedded in the structure. The design of the structure (sizes, materials, shapes, connections) is the result of trade-offs between several key objectives: mechanical strength, stiffness, electromechanical power conversion, heat transfer (cooling) and fluid flow [7,8].

Traditionally these objectives were pursued separately, and the features that satisfied one objective served as constraints in the pursuit of features that satisfy the other objectives. More recently, computational design is making possible the search for features that satisfy several objectives simultaneously. Electric machines of all kinds are evolving toward compactness, which means higher power density. In this direction, the generation of heating per-unit volume increases, and so do the peak temperatures that threaten the mechanical integrity and electrical performance of the machine. Effective volumetric cooling is of paramount importance in the future of electric machines.

In this paper we address the fundamentals of the volumetric cooling of the machine structure. The approach is based on constructal design, which is the view that the heat and fluid flow structure morphs freely as we search for a higher heat transfer density, lower peak temperatures, and a more uniform distribution of the allowable temperature level throughout the machine volume. Key are the continuous changes in the geometry of the solid, in the direction of greater compactness.

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Nomenclature

c_P	specific heat, J kg^{-1} K^{-1}
d_a	length, m
D	diameter, m
H	height, m
k	thermal conductivity, W m^{-1} K^{-1}
L	length, m
L_r	rotor length, m
L_t	spacing between bars, m
L_c	core length, m
$\dot{m}$	mass flow rate, kg s^{-1}
n	number of core packages
q, $\dot{Q}$	heat current, W
$\tilde{q}$	dimensionless heat current, Eq. (24)
r	outer radius of bars, m
R	radius, m
Re_H	Reynolds number, Eq. (5)
S	spacing, m
T	temperature, K
T_{max}	peak temperature, K
T_0	inlet temperature, K
V	fluid velocity, m s^{-1}
W	width, m
$\dot{W}$	pumping power, W

Greek letters

δ	boundary layer thickness, m
ΔP	pressure drop, Pa
μ	viscosity, kg s^{-1} m^{-1}
ν	kinematic viscosity, m^2 s^{-1}

Subscripts

b	bar
c	core
out	outlet
r	radial
r	rotor
x	axial

2. Configuration

The cooling gas enters the volume of the generator as a single stream. The channels distribute this stream throughout the volume such that the coolant bathes the smallest features of the heat generating structure. Finally, the warmed up coolant is reconstituted as a single stream and is led to an external system to be cooled before being reused (Fig. 1).

Heat is generated non-uniformly in three dimensions. The stator structure generates and conducts heat longitudinally along the bars and radially along the laminations. The stator structure is hierarchical: laminations are stacked into packages that are swept by coolant, and packages are grouped into sections that are permeated by coolant that flows in a particular radial direction, toward the axis, or away from the axis. Heat is also convected radially along the cooling channels. The key feature to be discovered is the channel spacing, or the number of packages in one section (Fig. 2).

In current designs, the rotor winding has the highest heat generation density. Its heat and fluid flow structure (Figs. 3 and 4) is similar to the stator structure. Heat is generated and conducted longitudinally in the electrical conductors of the magnetic field winding. Heat is intercepted by the coolant and convected radially through radial spacings. The flow of coolant through the rotor is always outward, toward the relative motion gap between rotor and stator.

In summary, the flow of heat is in steady-state, from the cylindrical volume of the machine to the stream of coolant that flows through the volume. The coolant flows through multiple channels: it is distributed non uniformly and hierarchically though few large and many small channels. A fan drives the flow of coolant. In the rotor, the flow is augmented (aided) by the self-pumping effect that emerges when the coolant is heated by the solid structure. Self-pumping is another name for natural convection (or chimney flow) through radial channels. The pressure difference generated by this effect is given in Section 4.

The cross sectional shapes of the rotor and stator volumes with heat generation and radial flow are annular. In each annulus, the radial thickness is not much larger than the inner radius. Consequently, the annular space can be modeled as a two-dimensional space, as shown in Fig. 5. The radial dimension of this space (H) is the radial length traveled by the coolant. The axial dimension of this space (L) is the distance between two consecutive cooling channels. The channel spacing (S) and the solid thickness (L) may vary.

In the rotor (r) and the stator (s) the conduction through the spaces filled with solid (the windings) is anisotropic. In the rotor, the axial thermal conductivity (k_{rx}) is greater than the radial conductivity (k_{rr}). In the laminations of the stator, the opposite is true: the radial conductivity (k_{sr}) is greater than the axial conductivity (k_{sx}).

The anisotropy of the stator is complicated further by the thermal conductivity of the stator bars (k_{bx}), which is greater than k_{sr} and k_{sx}. The fluid flow through the stator is also complicated by the fact that the channel flows may be oriented in counterflow, unlike the parallel flows through the rotor winding.

3. Parallel flow

Consider one of the heat generating volumes (in the rotor, or the stator, Fig. 6), and treat it as a two-dimensional volume of longitudinal length L_r (the rotor length), transversal flow length H, and third dimension πD, where D is the diameter of the relative motion gap. The total heat generation rate removed from this volume is q. The total mass flow rate of fluid that bathes this volume is $\dot{m}$.

There are n radial slits of flow length H and spacing S, where $n = L_r/L$, and L is the axial dimension of each heat generating section k_x, cf. Fig. 6. The coolant is an ideal gas. It enters the slit at the temperature T_0, and exits at the temperature T_{out}, which is to be determined. The maximum allowable temperature (T_{max}) occurs at hot spots located in the exit plane, midway between two consecutive exits. The objective is to configure the flow such that ($T_{max} - T_0$) and the fan (pump) power are small when q and $\dot{m}$ are specified. In the limit of small S and large n, the flow through the volume resembles Poiseuille flow through parallel-plates channels (Fig. 7, left). In this limit, T_{out} approaches T_{max}, and the entire plane with the outlets is isothermal, at T_{max}. The coolant ($\dot{m}$) enters the volume at T_0, and exits at T_{max}, therefore $q = \dot{m}c_P(T_{max} - T_0)$. The performance is indicated by the ratio

$$\frac{T_{max} - T_0}{q} = \frac{1}{\dot{m}c_P} \quad (1)$$