LIMITATIONS ON WATER COOLING OF ROTORS AND STATORS IN INTERMITTENT DUTY MACHINES

By:

C. Hearn
J. Hahne
R. Hebner

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Center for Electromechanics
The University of Texas at Austin
PRC, Mail Code R7000
Austin, TX 78712
(512) 471-4496

Limitations on water cooling of rotors and stators in intermittent duty machines

Clay S. Hearn, Jonathan J. Hahne, and Robert E. Hebner
The University of Texas at Austin, Austin, Texas, USA

Abstract: This investigation focuses on charge transfer and standoff considerations for water coolant, where the water is in intimate contact with energized conductors. The flow rates of interest are up to 5 m/s. The emphasis is on the behavior of the coolant in intermittent duty machines in which the conductors are energized for periods of 10^{-5} to 10^{-3} s. As the water is routed through copper coolant tubes, the primary contaminant produced is copper.

Introduction

Water cooling at high voltage and/or current is established technology for electric utilities for rotors and stators in power generators [1,2]. Water cooling is also used successfully in coils for accelerators and magnetic confinement systems [3]. In addition, water has been used as coolant, dielectric [25], and electrical insulation in short pulse (i.e. >100 ns) accelerators [4]. These applications are all either much longer or much shorter than the expected characteristic time for charge decay, τ , where

$$\tau = \epsilon / \sigma \quad (1)$$

In (1), σ is the conductivity of the fluid and ϵ is the permittivity. For the pure water used in existing systems, the conductivity is about 5×10^{-4} S/m [1,3] and the relative permittivity of water is 80. This leads to

$$\tau \approx 10^{-6} \text{ s} \quad (2)$$

Under pulsed conditions, however, the conductivity may be as much as four orders of magnitude smaller, leading to a characteristic time of 10^{-2} s. At the maximum flow rates tested, the transport distance during the characteristic time for charge decay ranges from 5 μ m to 5 cm.

A second factor in machines that see intermittent duty is that one may wish to cool the windings at a higher rate than in a steady-state machine. Thus, this work explores flow rates that are up to about five times greater than the rates used in earlier work [1-3].

Copper tubing is used as the test conductor because copper has high thermal conductivity so it is typically the material of choice for these applications. It has been discovered in practice that copper has an important limitation [2]. Fouling of the lines has occasionally been a problem in long-term, continuous operation.

This problem is addressed either by routine maintenance if the thermal properties are of paramount importance or by using stainless steel instead of copper when the fouling problems are a serious concern and there are sufficient thermal margins in the design to permit the use of stainless steel.

Because the primary contaminant in the cooling system is expected to be copper [5], it is likely that the charge transport from stainless tubes will be less than from copper tubes. So this work should place an upper bound on the charge transport problem in practical machines. The information produced in this study is expected to assist a machine designer to assess the trade-offs in a particular design between thermal conductivity and dielectric effects.

This paper reports on the first phase of the study. It addresses the change in electrical conductivity due to flow when the system is all at ground potential. The second phase is expected to generate data when the coil is raised to a constant high potential while the remainder of the system is grounded. The final phase will address the effects of transient high voltage excursions.

Generation of Electrical Charge

The fundamental operating concept guiding this research is for the water to flow through copper tubes in intimate physical and electrical contact with the conductors in either the rotor or the stator. Since the conductors are at different potentials, each tube has a short section of electrically insulating material before the water from all parts of the machine is mixed in a manifold and flows to a heat exchanger.

The minimum length of the insulating section is determined by the need for voltage standoff in the air surrounding it. In addition, there is conduction in the water and the tube must be long enough to make that resistance sufficiently high to maintain the electrical integrity of the machine. There are three important mechanisms for the production of charge: bulk dissociation, streaming electrification, and transient charge redistribution.

Bulk Dissociation

In water, there is an equilibrium level of bulk dissociation:

where, in pure water:

$$[\text{H}]^+ / [\text{H}_2\text{O}] \approx [\text{OH}]^- / [\text{H}_2\text{O}] \approx 10^{-7} \quad (4)$$

In this work, the brackets [] are used to indicate the concentration of the product inside of the bracket. Impurities, for example Cu atoms removed from the walls of the tube, can interact, e.g. via charge exchange, with the dissociation products and perturb the approximate equilibrium as well as affect the mobility of the carriers and thus the conductivity of the water [6].

Flow Electrification

Flow electrification, or streaming electrification, is the term describing the multitude of interactions that can lead to charge transfer to a flowing liquid. A good description of flow electrification was given in [7]:

“...it is the process by which charge associated with the Debye layer, which is inherently present at a liquid solid interface, is sheared away by the motion of the fluid. The electrochemistry of this layer is only partially understood ... being the result of a complex interplay of electrostatic and diffusive forces with dependencies on the physical and chemical nature of the materials, the fluid flow characteristics, the applied electric field, and the geometric configuration.”

If this were not complex enough, the charge in a flowing fluid can also be affected by charging of small particles entrained in the fluid and by desorption of material from the tube wall.

Transient Charge Distribution

When a transient charge occurs, the electric field redistributes in the metal and in the surrounding air in times short compared to a nanosecond. However, the intrinsic charge relaxation time in the liquid, determined by the permittivity and conductivity of the water [8], is in the μs to ms range. During that time, fluid flow can also affect the net transport of charge.

Each of these three processes has been found to be important in cryogenic fluids and in hydrocarbons [6-12]. Although the effects are expected to be less pronounced in water than in these other fluids, primarily due to the shorter characteristic relaxation time, some experimental investigation is needed as the complexity of the possible contributing processes makes modeling efforts unavailable.

Experimental Approach

The test system is designed to be used to investigate the effect of flow rate, the effects of a steady voltage on the

current carried in the flowing water, and the effects of transient voltages on the current carried in the flowing water. The basic apparatus for the studies of flow, with no voltage excitation of the coil, is shown in Figure 1.

The important instrumentation includes inline conductivity probes and flow and pressure transducers. To supplement the inline measurements, samples were periodically drawn for offline measurements of copper concentration.

Tests were conducted in four different coil configurations:

1. Shunt: The coil was removed and replaced by a stainless steel shunt to produce control data for the remainder of the system other than the coil.
2. Coil A: A typical coil “racetrack” geometry with six parallel coolant tubes with a total length of 15.2 m
3. Coil B: A coil of the same length bent around a rectangular form (40 x 38 cm) with a nominal 5 cm bend radius.
4. Coil C: A coil 15.2 m coil bent around a rectangular form (40 x 36.5 cm) with a nominal 1.3 cm bend radius.

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Figure 1. Schematic diagram of flow test system.

Coils B and C each had approximately 175 bends. The bend radii were selected to be typical of those required for cooling in rotating machines. These two coils were selected to explore whether bend radius would influence the production of copper.

Results and Discussion

The first set of experiments investigated whether the ion filter affected the measured conductivity. At a flow of 4.6 m/s, with coil A, the measured conductivity was about a factor of 5 lower with the ion filter in the circuit than when it was shunted. This result supports the presumption that the water flow produces impurities that can be removed by an ion filter.

With this base information, the ion filter was removed from the system and data was taken to correlate the change in conductivity to changes in copper concentration.

The experimental results from a set of eight-hour runs are summarized in Table 1. These results reinforce the results obtained by adding and removing the ion filter by showing that the copper coil always provides a greater rate of conductivity increase than does the circuit with a stainless steel shunt. This data would be consistent with a significant influence on the conductivity by the release of Cu from the tubing due to water flow.

The results from the different coil geometries, while showing the expected trends, also suggest that more complex processes contribute to the final result. In all three coils, the highest flow rate resulted in a higher conductivity than the lowest flow rate. In addition, after about the first 15 minutes of operation, these runs of up to eight hours produced very linear increases in conductivity with time. This a constant rate of production of conducting contaminants. It is clear, however, that the conductivity increase rate is not a linear function of the flow rate.

Table 1. Flow rate and conductivity correlations

	Flow rate m/s	Conductivity increase rate S/cm/hr
Shunt	4.6	0.02
Coil A	1.5	0.049
	3.0	0.047
	4.6	0.055
Coil B	1.5	0.048
	3.0	0.091
	4.6	0.128
Coil C	1.5	0.052
	3.0	0.072
	4.6	0.072

To explore further the influence of copper, water samples were drawn during the tests. The copper concentration was measured and correlated with the conductivity measurements. The results are summarized in Figure 2.

The linear fit to the data yields a slope of 2.9 S/cm² and an intercept of 0.2 S/cm. If we assume the increasing portion of the conductivity is due to the increase with time with copper ion concentration, we have

$$\sigma = q_i [Cu^i] + \sigma ([Cu^i] = 0) \quad (5)$$

For a singly charged ion, the derivative of the conductivity with respect to copper ion concentration should provide a measure of the mobility. Using the slope of the linear fit in Figure 1 as the numerical value of the derivative yields a value of $\mu = 6 \times 10^{-4} \text{ cm}^2/\text{Vs}$. Published values [13] of the mobility of metallic ions in aqueous solutions state:

$$\frac{10^{-4} \text{ cm}^2}{\text{Vs}} < \mu < \frac{10^{-3} \text{ cm}^2}{\text{Vs}} \quad (6)$$

So the data in Figure 2 also yield data consistent with the assumption that the dominant contributor to the electrical conductivity under flow conditions is the concentration of copper ions transported from the copper walls of the coolant tube. Although these results do not rigorously differentiate between a dominant ion and the linear superposition of production of different ions with a product of concentration and mobility similar to that of copper, the latter hypothesis is less likely.

Figure 2. The measurements of conductivity and copper concentration are well correlated.

Conclusions

Measurements of the electrical conductivity and copper concentration in a model cooling system for pulsed rotating machines has shown that

1. The conductivity increases with time.
2. Flow rate influences the rate of increase but it appears that other factors also have an effect.
3. The conductivity can be lowered using an ion filter.
4. The conductivity increase is linearly related to the copper concentration in the water.
5. The slope of the graph of conductivity vs. copper concentration implies a mobility value that is consistent with the expected value for copper in water.

These results provide the technical base needed to support further studies to determine the influence of coil voltage on the dielectric behavior. This preliminary analysis and data suggest it will be possible to design versatile cooling systems for pulsed rotating machines in the microsecond to millisecond time frame, but electrical testing will be needed to confirm this expectation

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Author address: Robert Hebner, Center for Electro-mechanics, The University of Texas at Austin, 1 University Station, MC R7000, Austin, TX, USA 78712, Email: r.hebner@mail.utexas.edu