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COOLING SYSTEMS FOR ELECTRICAL MACHINED COOLED WITH SEAWATER

Alcides Fediuk Junior
Rafael Fernando Junckes
WEG Equipamentos Elétricos S.A. – Energy Division, Department of Development and Technological Innovation – Avenida Prefeito Waldemar Grubba, 3300, Vila Lalau – Jaraguá do Sul-SC, Brazil, 89256-900.
alcidesf@weg.net
rafaelfj@weg.net

Abstract. *This article presents an analysis of the cooling system for water jacket electrical machined using seawater as a refrigerant. In this system, the water circulates through channels inside the machine transferring the heat generated by the active part to the external environment.*

Water-cooled electrical machined have been developed for use in space-constrained installations, with a compact design is commonly used in boats. The use of seawater as refrigerant in this case is an interesting alternative, eliminating the use of cooling towers and treatment of water in the boat. Therefore, it is possible to reduce the water storage, increase the space available and reducing the investments considerably. However, the use of seawater for cooling is always critical, due to the problems related to increase of corrosion and incrustation. This work will present the study of two protection alternatives that will reduce the effects of corrosion and incrustation in a cooling system of electrical machined cooled with seawater. For this, two prototypes were prepared and those submitted to the test that simulates the operation condition of the water jacket electrical machined. After the test, the samples were analyzed to understand the effects of corrosion and incrustation in the different protection alternatives.

Keywords: *Electric machine, Cooling system, Corrosion, Incrustation, Seawater*

1. INTRODUCTION

The objective of this work is to study two corrosion protection systems applied in a water jacket refrigeration system with the use of seawater as refrigerant.

This cooling system consists in removal the internal heat generated by the active part of a rotating electric machine by means of the circulation of water into the spiral channels of the frame, this system must have good corrosion resistance and good thermal conductivity, thus guaranteeing a good cooling performance of the equipment.

For the study were designed and manufactured two similar prototypes changing only the corrosion protection system used, in one of them was used aluminum coating applied by thermal sprinkling and in the other was used anode of sacrifice. Laboratory tests were performed simulating the operating conditions of the equipment in both prototypes.

After the tests, samples were collected from the carcasses for metallographic analysis and comparison, in order to determine which corrosion protection system is the most effective for the application.

2. WATER JACKET REFRIGERATION SYSTEM

The water water jacket refrigeration system is mainly used because it has high thermal performance and has a compact structure; it usually can operate in an “open system with recirculation of water that uses cooling towers to dissipate heat from water or closed system without recirculation of water, where the water is immediately discharged after the absorption of heat. This method is generally used in equipment and industries near the sea using seawater (Peabody, 2001)”.

The main problem in using seawater as refrigerant is due to the high corrosion rate presented in materials commonly used in the industry for the manufacture of such equipment, often making the production process unfeasible.

In order to reduce the rate of corrosion on metal parts in contact with seawater it is possible to employ corrosion protection systems, if it maintained a good heat exchange efficiency.

3. COATINGS AND TYPES OF PROTECTION EMPLOYED

There are a multitude options of coatings for corrosion protection, the systems adopted here, were chosen through technical criteria with reduced costs and easier application. The coating cannot reduce the thermal exchange of the system and the surface should not generate high friction increasing in the system load loss.

3.1 Coating by electric arc spraying

It is a group of processes through which layers of metallic or non-metallic materials are deposited on a previously prepared surface. These materials are fused by a heat source generated in the nozzle of a gun and then are sprayed and accelerated against the substrate, reaching it in the molten or semi-molten state. When they collide against the substrate, they are flattened and adhered well, as each other, generating a typical "lamellar" structure.

It is very important to observe the conditions that the component will receive the coating, it is necessary to understand the work environment that the equipment will works and to know which requests are involved for the region to be coated, this factors will determine the need for some special tests. For the example: Thermal barrier coating requires testing to measure the thermal conductivity of the coating. Or a coating with the purpose of electrical insulation determines tests to measure its electrical conductivity and so on.

The main characteristic desired for a coating using electric arc spraying process is its adhesion. Also it is common the analysis of the transversal microstructure with the objective to verify the formed microstructure, porosities, interface coating-substrate and micro-hardness.

3.1.1 Validation of electric arc spraying protection

To evaluate the coating, a sample was prepared where the objective was to analyze the condition of this coating with different surface finishes, the coating was initially applied throughout the part. The component was then divided into 4 parts and different types of finishes were applied, as shown in Fig. 01 the first part was finished in the raw state, the next part was submitted to the machining process, the third part went through the rectification process the last part was process of polishing. The analysis of the finishing conditions is important for this application because as bigger the roughness of the surface where the water circulates as greater the loss of load of the system due to the friction.

After applying the different surface finishes the sample was submitted to thermal cycling and salt spray tests respectively. The objective is to evaluate if the sample in different types of surface finish will show cracks in the coating layer and to evaluate the type of corrosion that each surface development with these tests, the Fig. 02 shows the state of the sample after the tests were completed.

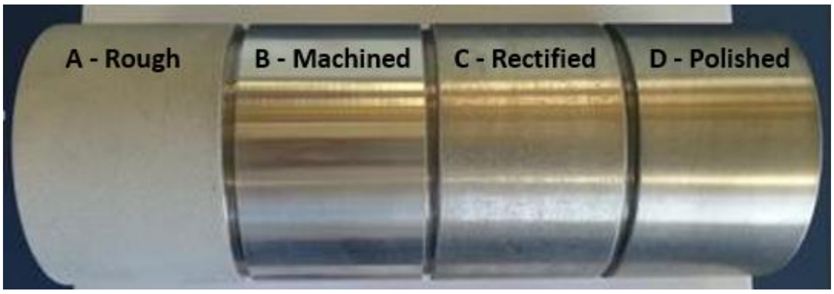

Figure 1. Sample coated with different types of surface finish

After 720 hours of tests with saline mist, the following results are obtained, according to Table 01,

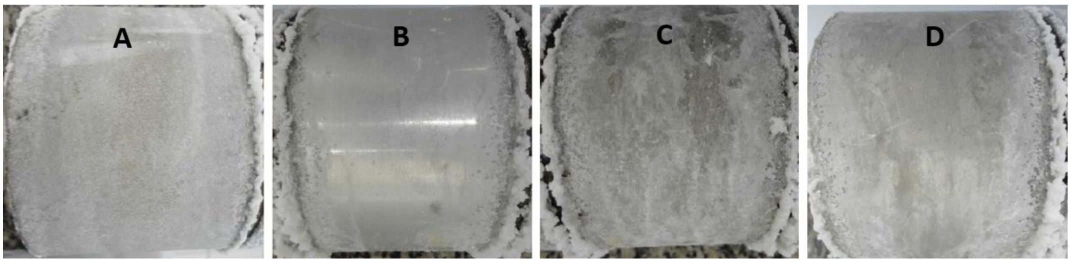

Figure 2. Results of saline mist tests for each type of finished surface.

Table 1. Data from the experiments with saline mist and thermal cycling for sample

Section	Oxidation	Results for 720 hours
Rough - A	White	Ri 4 – Surface smearing
	Red	Ri 0
Machined - B	Branca	Ri 2 – Surface with a matte appearance, that is, loss of the gloss of the metal
	Red	Ri 0
Retified - C	White	Ri 5 - Dark spots at high intensity covering the entire surface
	Red	Ri 0
Polished - D	White	Ri 5 - Dark spots at considerable intensity covering the entire surface
	Red	Ri 0

According to ISO 4628-3 the degree of oxidation of the surface Ri shows in percentage the amount of the analyzed area that underwent oxidation where Ri 2 identifies that 0.5% of the surface showed oxidation.

According to the Tab. 1, the region of machining finished surface was the region that developed the least corrosion and another region with less corrosion developed was the region with surface rough.

All samples developed only the type of white corrosion and no part of the sample showed red type corrosion, which could indicate that the steel was undergoing a corrosion process.

As the surface that developed the smallest area of corrosion of the white type was the machined surface where it was expected that the surface with rough surface state would develop less corrosion.

Comparing the size of the area of corrosion developed on both surfaces, the difference between the two surfaces is very small, it was decided to use the rough finished surface in the prototype for seawater tests. A sealant has been applied to the coating to reduce surface roughness and thus there is no need to add the machining process to the coating and thereby eliminate additional costs.

3.2 Protection against corrosion with sacrificial anodes

"Cathodic Protection is a technique used to control the corrosion of a metal surface, making it the cathode of an electrochemical cell (Gentil, 2014)". In a simple way, this method of protection connects the metal to be protected to a metal of sacrifice that is more easily corrodible to act as anode. The metal of sacrifice is then corroded in place of the metal to be protected. The materials normally used to act as anode are zinc, magnesium alloys and aluminum alloys, for naval area, zinc is the most indicated. It is important that the material of the anode is as pure as possible, especially free of iron and copper, which greatly increases the cathodic reaction of hydrogen on the metal.

For this type of protection it is important to evaluate the amount and distribution of the anodes, depending on the ambient they are immersed, they can be more or less conductive. It is important to remember that in this type of system it is necessary to evaluate the anode condition from time to time, verifying if there is necessary replacement, thus ensuring the protection of the system over the years.

3.2.1 Validation using sacrificial anodes protection.

In this test it was decided to couple to the sacrificial anode system with zinc in the form of a pin and it was added to the refrigeration circuit, being in contact with the water flow in the system.
To validated this method of protection is to verify the existence of material loss on the zinc pin, in Fig. 03 the pin situation can be observed in two moments, in the middle of the test and after concluded.

Figure 3. Anode of sacrifice in the middle of test a) and after full test b)

3.3 Thermal validation of the types of protection employed.

To simulate the thermal exchange during the tests with both prototypes, heating resistors were set up to cause thermal exchange with the refrigeration circuit and thereby validate if the coatings or corrosion protection methods do not interfere with the thermal exchange of the system, Fig. 04 shows the prototype in detail.

4. DESCRIPTION OF PROTOTYPE.

4.1 Parts and components.

Two small-scale prototypes of a water jacket refrigeration system were created that will use corrosion protection systems, this system has a serpentine-like system, the inner tube has a helical shaped channel where the coolant circulates, the Fig. 04 shows the prototype in detail. The main components of the tests were developed in cast iron, with silicon orings sealing system. To prevent damage to water inlet and outlet coupling threads, 316 stainless steel adapters were fitted with silicone sealing rings.

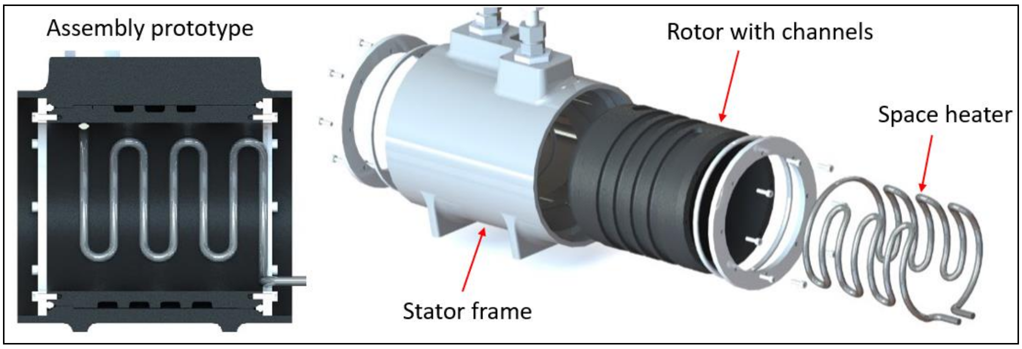

Figure 4. Detail of prototype design in cut and exploded view

4.2 Description of test operation.

The test with the corrosion protection systems has the objective of achieving a validation of the protection of the refrigeration circuit with seawater, the prototypes created are referred to as a serpentine system of water around the source that is generating the heat. The type of test circuit is closed and have a pump capable of working with seawater, a tank with one thousand liters of synthetic seawater, flexible hoses, stainless steel connection and temperature meters, flow and pressure. The Fig. 05 shows complete system where the prototypes are arranged in parallel to the water pumping system where both prototypes receive the fluid with the same characteristics, and the systems are coupled with equal heating resistors.

The monitoring system of the prototype will be done through a flow, pressure and temperature meter, coupled at strategic points, which allow evaluating the thermal exchange of the system, generated loss of load and the flow variation.

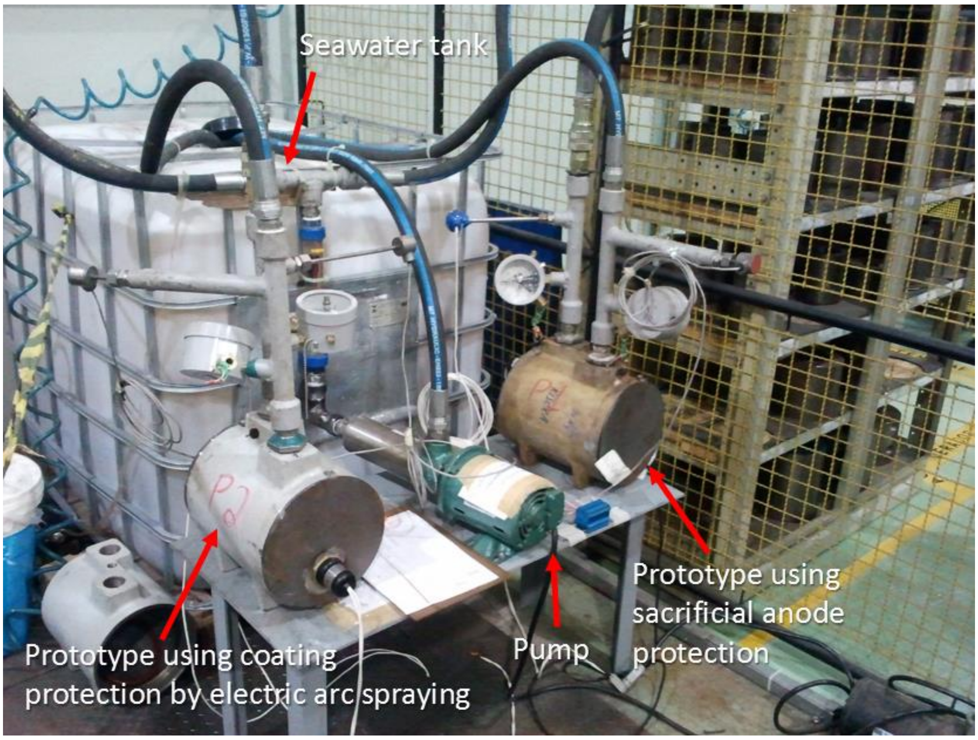

Figure 5. Assembly set for testing with different with two protection systems

5. ANALYSIS OF RESULTS.

The criterion to finalize the tests was related to the variations outside the acceptable parameters of the system, the parameters used for analysis were the variation of pressure, temperature and flow.

The prototypes were disassembled and with visual analysis it can be verified that the main problem to increase the loss of load is due to the increase of the incrustation found mainly in the region of exit of water of the all spiral, with this visual analysis the impression that the corrosion does not was so intense.

Metallographic analysis of the components of the system and analysis of the composition of the water were done to achieve higher quality results.

5.1 Metallographic Analysis

The objective of the metallographic analysis is to verify the constitution, structure and texture of the samples to relate the results obtained with the mechanical, physical and chemical properties. The Fig. 06 shows the spiral tube with coating and Fig. 07 is presented the metallographic analysis of this spiral tube.

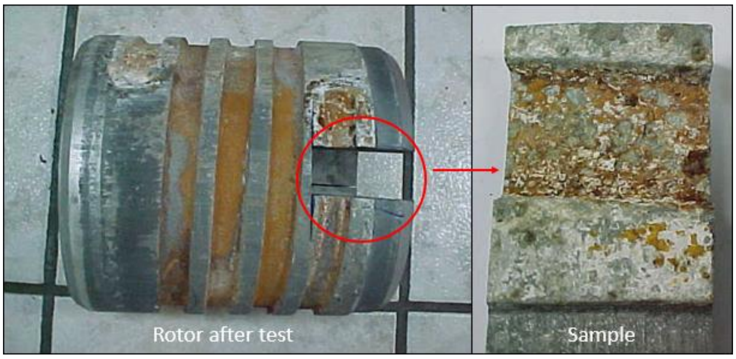

Figure 6. Spiral tube with aluminum coating by arc electric spray

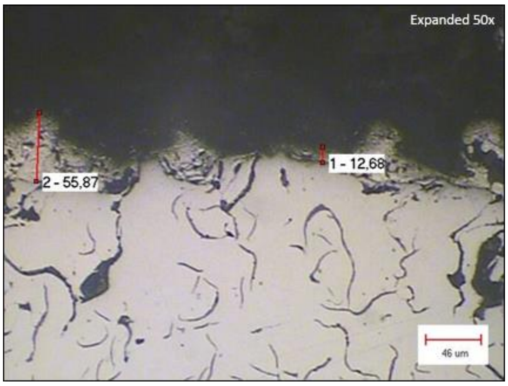

Figure 7. Metallographic analysis of spiral tube with aluminum coating by arc electric spray

For the prototype with anode of sacrifice is shown in Fig. 08 and Fig. 09 shows the metallographic analysis of this tube. These components presented the most critical results from the point of view of oxidation.

Figure 8. Spiral tube without coating and cathodic protection.

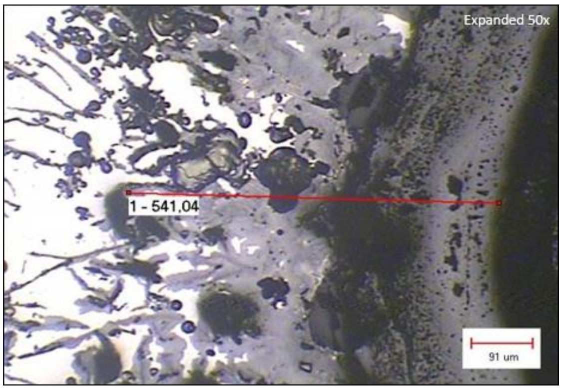

Figure 9. Metallographic analysis of spiral tube without coating and cathodic protection.

Both prototypes showed corrosion and oxidation, the coated prototype presented a lesser amount of corrosion of the material to be protected, as can be seen in the images. The expected objective for the coated condition was to avoid corrosion of the material to be protected and to exhibit oxidation only in the coating layer, but with the results of the analyzes it is possible to observe that the same occurred although at a much lower rate when compared to the system with anode of sacrifice. The reason for the interruption of the tests was due to the increased pressure loss and not because of corrosion, but it is necessary to take into account the corrosion rate presented in this time interval.

5.2 Analysis of test residues.

Evaluating the composition of the coolant is important to understand the composition of the suspended particles in the water. In the evaluation it was found that the refrigerant composition is composed primarily of iron oxides and other inorganic compounds such as oxides of Ca and Mg in the saline water, in Tab. 03, is described the composition of the waste found in the water.

"The corrosive action of seawater can be determined initially by its salinity. This salinity is practically constant in oceans but may vary in inland seas, as can be seen in Tab. 2 (Gentil, 2014)".

Table 2. Salinity in oceans and seas

	Salinity, %
Pacific Ocean	3,54
Atlantic Ocean	3,49
Mediterranean Sea	3,7-3,9
Red Sea	>4,1
Baltic Sea (Gulf of Finland)	0,2-0,5
Caspian Sea	1,0-1,5
Caspian Sea (Karabaguz Gulf)	16,4

To determine the salt concentration for the tests, the salt concentration data were used equal to the values recorded for the oceans in Tab. 2.

Table 3 shows the data of the composition of the water used in the tests, it is possible to perceive a large percentage of iron oxide concentration present. The carbon content found in the residue may indicate that the iron oxide found has its origin in the cast iron components.

The concentration of zinc in the water composition shows that a reduction of the zinc pin used for the cathodic protection occurred.

Table 3. Data from analysis of water composition used in the tests

Analysis of residues		**Analysis of the composition of water**	
Elements	**Result (%)**	**Elements**	**Result (mg/l)**
Ca	0,689	Ca	356
Mg	0,724	Mg	1116
Fe	35,33	Fe	0,160
P	0,055	P	0,043
Mn	0,027	Si	1,24
Cr	0,010	Chlorides	14160
Ni	0,006		
Si	0,470		
Zn	1,200		
Na	1,340		
K	0,064		
C	0,655		

Based on the results found it is possible to affirm that the increase of these incrustations is mainly due to the presence of the chlorides, the main one responsible for the deposits of material in the walls of the exchanger.

5.3 Analysis of the thermal, flow and pressure results.

According to the monitoring of the parameters during the tests were registered the values of temperature, flow and pressure of the system, the data were recorded daily and recorded in Tab. 04.

"The verification of these parameters is important to monitor the System and can change the corrosion speed, for example, "the seawater circulation velocity is important, as its increase in general increases the corrosion rate and removes layers of corrosion products that, adhering to the metallic material, can delay the corrosive process (Gentil, 2014)".

Table 4. Temperature and flow data of the prototypes during the tests.

	Prototype 1		Prototype 2			
Date	T_e [°C]	T_s [°C]	T_e[°C]	T_s [°C]	T_a[°C]	V [l/min]
29/04	33,8	34,3	-	-	-	-
30/04	34,3	34,3	-	-	23,3	-
02/05	35,1	35,6	-	-	30,3	-
06/05	37,2	37,4	-	-	28,2	-
07/05	36,9	37,3	-	-	29,5	-

	Prototype 1		Prototype 2			
Date	T_e [°C]	T_s [°C]	T_e[°C]	T_s [°C]	T_a[°C]	V [l/min]
09/05	39,0	39,6	-	-	29,8	-
12/05	33,4	34,0	-	-	26,0	-
15/05	36,3	36,4	-	-	29,4	-
22/05	36,4	36,7	-	-	27,3	-
02/06	42,6	41,9	42,1	41,6	24,6	24
03/06	40,0	40,0	39,1	39,8	23,0	24
04/06	39,3	38,5	37,9	37,9	22,6	24
10/06	39,7	40,4	39,7	40,5	21,1	30
16/06	41,6	42,12	42,12	42,12	23,0	30
20/06	36,1	36,9	36,4	36,7	17,0	30
25/06	40,82	41,34	41,08	41,34	22,0	30
27/06	40,82	41,34	41,08	41,08	21,0	30
30/06	39,52	40,04	40,04	40,08	22,0	30
03/07	37,18	37,7	37,7	37,7	19,0	30
09/07	37,7	38,48	38,22	38,22	18,0	30
21/07	36,4	36,92	36,4	36,66	22,0	30
23/07	39,78	40,04	39,78	40,3	22,0	30
13/08	-	-	37,18	37,44	17,0	30

With the collected data, it was observed there were no heat transfer problems between the coated prototype and the water, this was a critical point analyzed because the doubt about the coating thermal insulation characteristics.

Based on the data presented temperatures of both prototypes can be seen that at no time the temperature measured prototypes reached very high values compared to previous measurements, which would signal that the operation of the prototypes was having unwanted changes.

The measured flow data show that no significant flow variations were obtained, indicating that the incrustation did not affect the system flow during the test period.

The pressure values gradually increased as the time as the channels were getting larger layers of fouling. At the beginning of the test, the system pressure had values close to zero bar, in the final period, days before the test was finished, the pressure was around 2.3 bar, which shows that the test should be finalized in order to prevent damage to the water pumping system.

6. CONCLUSION

Based on the analysis performed and evaluating the parts after the tests it is possible to observe that the corrosion is not as impacting as the level of incrustations presented, although the two phenomena are directly connected.

The incrustation evaluated soon after the disassembly of the prototypes was a more critical problem than the corrosion, the speed that this phenomenon occurs is much greater than the evolution of the corrosion rate. As an initial objective was to develop a system to prevent corrosion and the same was not achieved, then the condition of working with systems that can coexist with corrosion can be evaluated, since it is possible to define how severe this phenomenon occurs.

However, it may be concluded that any cooling system with seawater should occur processes of corrosion and incrustation.

This systems must be able to operate with both processes exist, the refrigeration system must predict the loss of mass by corrosion and the system must allow the cleaning of the incrustation deposits from time to time. The ideal in such a case is to combine both solutions, “protection using a combined system, coating and cathodic protection has been widely used because of the good results achieved. (Gentil, 2014)”.

7. REFERENCES

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8. RESPONSIBILITY NOTICE