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HYDRODYNAMIC AND THERMAL EVALUATION OF FOULING MITIGATION IN HYDROGENERATORS HEAT EXCHANGERS

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ABSTRACT

The effectiveness of a mitigation technology for undesired formation of mineral inlay (fouling) and biological material (biofouling) in the plate heat exchangers of the bearings refrigeration system in the hydrogenerators of the power plant "Fontes Nova" (Rio de Janeiro, Brazil) was studied. These incrustations change the thermal and hydrodynamic characteristics of the system due to the increase in the pressure drop and the drastic reduction of the thermal effectivity of the heat exchangers. The technology that was object of the study "excites the flow" because of the appli-cation of an electric field generated by an electronic device. To evaluate the effectivity of the mitigation method, the plate heat exchangers was instrumented. Water quality is also studied to analyze the environmental impact and the need to explain the undesired mechanism of biofouling..

INTRODUCTION

The hydrogenerators of Power Plant Fontes Nova have a refrigeration system for the bearings that use heat exchangers. The refrigeration of the hydrogenerators bearings is given by the heat exchange that occurs in a system of vertical plate heat exchangers that uses oil (process fluid) cooled by the water of discharge of the turbines (cooling fluid) pumped in counterflow to the oil flow. The maintenance experience of the heat exchangers evidences the formation of undesired inlay in its internal walls. Those inlays compromise drastically the hydrodynamic/thermal performance and jeopardize its operation.

In its actual configuration, power plant Fontes Nova, property of Light Energy, is fed by water that comes from Lajes Reservoir and Paraíba do Sul River. It has an installed capacity of 132 MW (average), nominal drop of 310 m, operates 3 Francis turbines of 44 MW each one, normal maximum water level of 415 m, height in which stores a volume of 445 million cubic meters approximately, for flow regularization. That dammed water constitutes a strategic reserve to supply almost all the potable water that supplies the metropolitan region of Rio de Janeiro. The bearings of each one of the three turbines (coupled to its respective generator) are cooled by a system of heat exchangers that constitute object of the present study.

Specialized technical literature mentions mechanic and chemical alternatives for mitigation and control of deposits formation in the heat transfer surfaces. For biological material (biofouling) removal, mechanical and chemical methods or a combination of both are used and inevitably result in technical stops for maintenance that use aggressive cleaning methods. These techniques consist in (a) thermal shock treatments [3], (b) high speed pulsed water flow in short periods of time [6], (c) on-line cleaning with abrasive spheres [6] among others. Chemical methods employ toxic products (biocides) in the cooling water that act against microorganisms and are used in closed circuits, normally causing undesirable environmental impacts. To reduce the quantity of required biocide, a combination of this and mechanical cleaning methods is used. The application of electric fields technology denotes an advanced stage of development that started with the application of magnetic fields, which was not effective. The first commercial device that used magnetic fields to avoid deposits formation was patented in Belgium in 1945[1]. Initially, intrusive permanent magnets were used but interfered directly in the flow; after that, other developments were tested in a non intrusive way forming a ring [2] presenting non satisfactory results. A wide revision of literature made by [2] shows that this technology for treatment still presents controversial questions, low effectiveness and which phenomenon is not well understood yet.

This study researches the effect of an electric field inducted by an electronic device “excite the flow” with the purpose of mitigating incrustations formation. The electric field used to excite the flow is obtained from a variable magnetic field generated by the electronic device.

Previous to the present study [7] used a similar system, but to evaluate the effect of the electric field to mitigate the corrosion in a cooling water system. Using the by-pass of the main circuit, metallic test pieces susceptible to corrosion were assembled in a metallic base structure connected to the duct wall and "not protected" test pieces assembled in a plastic base structure. Mass loss experiments made in the by-pass circuit indicated average corrosion rates of 1,91 mpy (mils per year penetration) in the test pieces submitted to protection and higher than 30% rates (~2,53 mpy) when the measures of the test pieces not protected exposed for 150 days to the electric field. The investigation concluded that the exposition reduces the corrosion process. Though, for different purposes, these positive signals motivated the present research of studying the effect of the external excitation of the flow caused by an electric field as a technological alternative to mitigate the undesirable biofouling in the heat exchangers.

From a technical and economic point of view, the undesirable effects of biofouling are accumulated in the hydraulic network and in the heat exchangers and compromise the hydrodynamic (increase of pressure drop due to friction and blocking) and thermal efficiency (effectivity of the heat exchangers) of the system. Those adverse effects increase the pressure drop (and, consequently increases the costs of pumping) and reduce the thermal effectivity of the heat exchangers. Solid deposits caused by the existence of pollutants in the cooling water impact in operational costs (pumping power) and maintenance (frequent stops in the hydrogenerators) for cleaning and clearing.

Deposits formation (organic and inorganic) reduces heat exchange mechanisms associated to critical components in the hydrogenerators, compromises the integrity of the sensors that are part of the measurement system and have a negative impact in the control and security devices of the global system.

This problem, compromising the integrity of the facilities, jeopardizes health, environment and security and impacts economically due to the reduction of the time for generation.

From an economic point of view, the study evaluates the resulting impacts of the stops made for the maintenance of the refrigeration system that could be avoided (or reduced) and that inevitably cause the interruption of the generation system operation. This means, an interruption in the electric energy supply implies high maintenance costs and interruption in the generation.

In addition to the mitigation mechanisms for inlays, the study also researched their chemical and biological nature, which is discussed in a specific section of this paper based in chemical and biological analysis of the inlays and the feed water of the Power Plant. With respect to the environmental impact, the analysis confirmed the presence (undesirable) of pollutants and microorganisms in the cooling water sources and generation that block the heat exchangers elements and return to the rivers as pollutants.

The measurement system developed and used was tested in the accredited Fluid Characterization laboratory of the PUC-Rio. Once it was validated, this system was used to monitor and collect data from the cooling system (oil cooled by water) that feeds the hydrogenerators bearings. This way, the study evaluates an innovative technology for controlled electric fields induction in a refrigeration system in order to mitigate the undesirable process of accelerated microorganisms growth observed in the heat exchangers canals of complex geometry.

EXPERIMENTAL DEVICE

Figure 1 illustrates the typical system of three heat exchangers (oil-water) for the hydrogenerators bearings cooling in Power Plant Fontes Nova. These heat exchangers were instrumented to compose the experimental model conceived, which has the following complementary systems: flow measurement subsystem, temperature, differential pressure and acquisition, transmission and processing subsystem, schematically illustrated in Figure 1.

The device for flow excitation by electric field (FEEF) is showed in Figure 1.

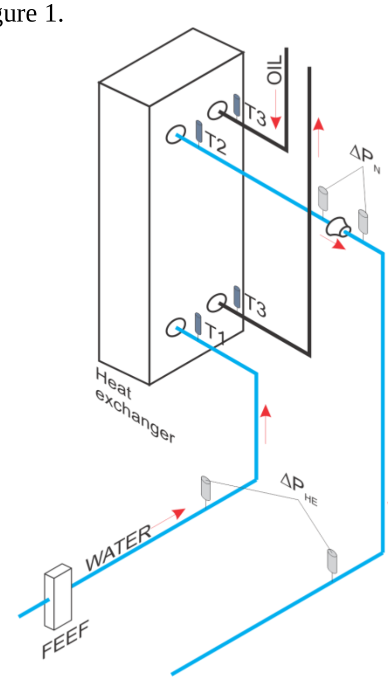


Figure 1 Experimental Model Scheme. *T* is PT-100 temperature signal; *ΔP* is the differential pressure signal.

Figure 2 illustrates the standard nozzle (ISO) specifically developed to measure water flow parameters in the heat exchangers (water–oil) instrumented to monitor and measure flow, temperature and differential pressure.

Figure 3 illustrates global details of the measurement system installed in the heat exchangers (a), the control and automation system (b), the flow excitation by electric field system, FEES (c) and the standard nozzle (d).

The nozzle was built according to ISO Standard 5167-3:2003 [8] and coupled to a differential pressure transmitter Honeywell Model FDW, which transforms the differential pressure signal to mass flow. Temperature was measured with PT-100 sensors according to Figure 1.

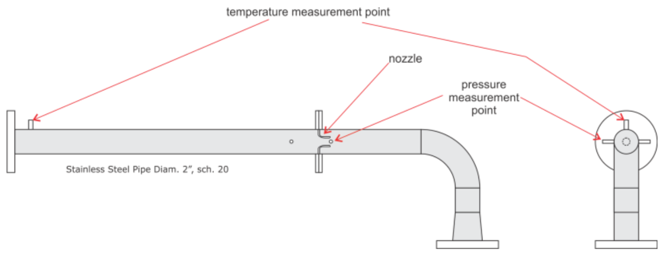
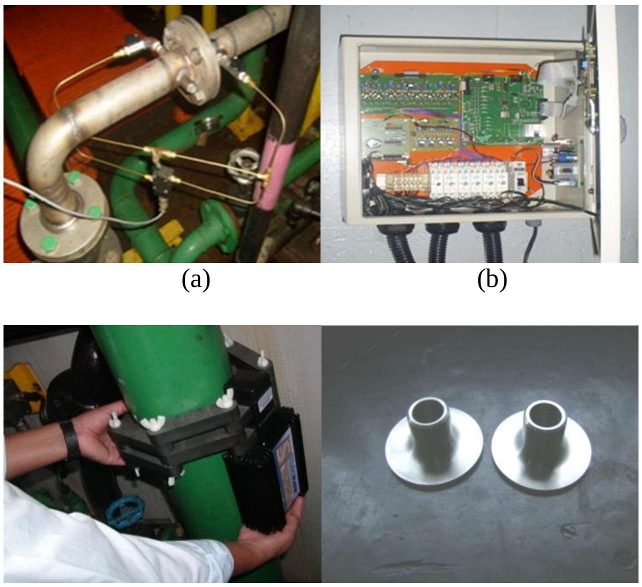


Figure 2 Experimental device for flow measurement.



(a) (b)

(c) (d)

Figure 3 Details of the measurement system used in the power plant.

Table 1 shows the studied uncertainties.

Table 1 Measurement parameters and associated uncertainties

Magnitude	Uncertainty
Fluid temperature	0.1 ºC
Differential pressure	0.3%
Mass flow	3%
Exchanged Heat	4 %
Global heat exchange coefficient	$= f\left(\Delta T_1; \Delta T_2; \delta\Delta T_1; \delta\Delta T_2\right)$

The data acquisition, transmission and processing system includes the following components: signals acquisition board; signals transmitter; signals receptor and a storage unit. Initially, the data is stored in the acquisition board and after that, for each time interval, the transmitter sends the signals to a storage unit with a sampling rate of 120 s.

The device for flow excitation by electric field (FEEF) generates a variable electric field close to the cooling water circuit pipes. The electric field is inducted by electromagnetic energy generated by a transformer with ferrite core that creates a sine wave of variable periodic amplitude from 200 kHz to 300 kHz. The study involved testing the hypothesis that affirms that inlays and material in suspension will be displaced after the operation of the system for long regimes (~ 1500 hours) of operation.

EXPERIMENTAL PROCEDURE

The following items were analyzed: (i) evaluation of hydrodynamic and thermal performance of the heat exchangers and (ii) chemical and biological analysis of the feed water of the power plant.

Figures 4 and 5 illustrate the severity of the problem caused by the inlays in the heat exchangers reducing drastically their hydrodynamic and thermal effectiveness.

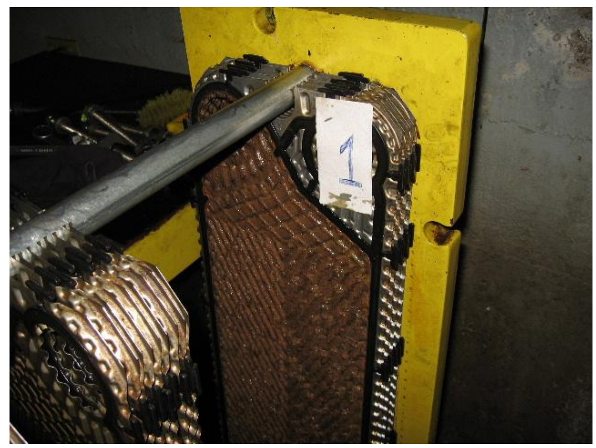


Figure 4 Inlay in the heat exchangers plates.

Figure 5 Inlay in the cooling water circuit ducts.

Studied Parameters

The experiments were planned to cause the minimum interference in the routine operation of power plant Fontes Nova; its operation didn't suffer interruptions during the research.

The thermal and hydrodynamic parameters were measured in the presence and absence of the electric field during a controlled period of time. The results presented here are the ones of heat exchanger 2 (Fig. 1).

RESULTS

Evaluation of the hydrodynamic performance

The pressure drop variation was evaluated in the heat exchangers. It is calculated in function of the following geometric and hydrodynamic parameters:

$$\Delta P = f \frac{L}{D_H} \frac{G^2 v}{2} \tag{1}$$

In this expression, G is the mass flow ($G = \dot{m} / A$), v is the fluid specific volume, f is the friction factor. It was considered that the friction factor in flat plates heat exchangers has the same hydrodynamic behaviour of tube heat exchangers [4], so it's reasonable to make a hydrodynamic analogy between these flows.

In the expression above, D_H denotes the hydraulic diameter and *A* the normal total area for the flow, then,

$$D_H = 2b \qquad A = b \cdot B \tag{2}$$

Being b the width of the plate and *B* the space between plates.

From (1) and (2):

$$\frac{\Delta P}{\dot{m}^2} = f \frac{L}{2 D_H A^2} v \tag{3}$$

Figure 7 resumes the collected data in the absence and presence of the electric field used to excite the flow. Based on the measurements, it was possible to calculate the value of the ratio (3) for both situations, in the absence and presence of electric field.

As shown in Figure 7, the further this quotient goes from a Constant value (horizontal line in the graph), the bigger the inlay degree will be. The data from the measurements confirms that the condition of excited flow caused by the electric field corresponds to a condition of lower inlay than that one without the action of the referred electric field.

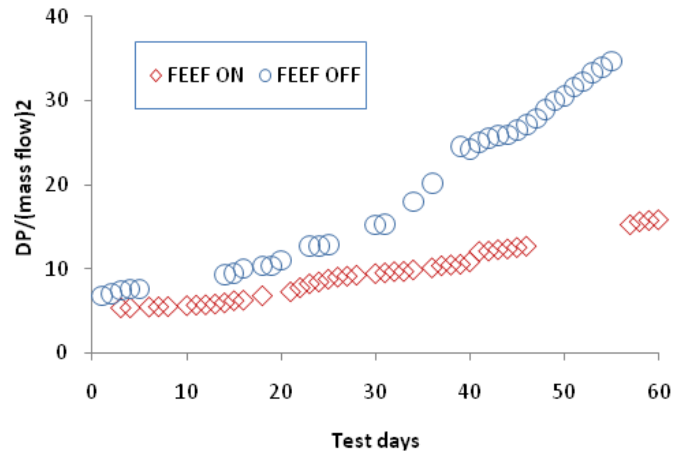


Figure 7 Ratio between the pressure drop *ΔP* and the square of the cooling water flow.

Evaluation of the thermal performance

We can define the global heat exchange coefficient as:

$$U = \frac{Q}{A \cdot LMTD} \tag{4}$$

We define the LMTD for countercurrent flow arrangement (Fig 1):

$$LMTD = \frac{(T_3 - T_2) - (T_4 - T_1)}{\ln\left[\frac{(T_3 - T_2)}{(T_4 - T_1)}\right]} \tag{5}$$

In Figure 9 we can observe that the global heat exchange coefficient (U) shows better results when the water flow is under the effect of FEEF. Nevertheless, in both cases U decreases with the time, these results indicate that the FEEF mitigates but doesn't nullify the biofouling effects,

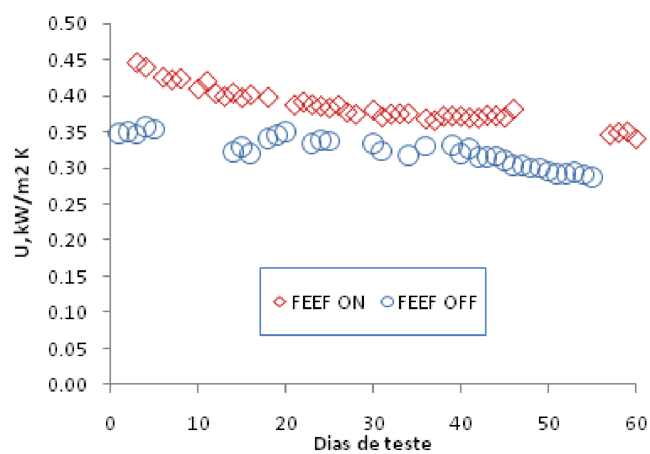


Figure 9 Thermal performance of the heat exchanger with and without the effect of the FEEF.

CHEMICAL AND BIOLOGICAL WATER ANALYSIS

The results of the optical microscopy made in the Analitical Chemistry laboratories of the *Universidade Federal Fluminense* (UFF) and the *Núcleo de Estudos Liminológicos do Instituto de Biociências da Universidade Federal do Estado do Rio de Janeiro* (UNIRio) show the result of the analysis of the collected material with the presence of organic and inorganic flakes.

Figure 10, particularly, illustrates filamentous cianobacteria (200x zoom). Other analysis made (figures 11 and 12) confirm aggregates of bacterial growth, with filamentous algae (cianobacteria) and bacilarioficeous algae.

Figure 13 details with 600x zoom, an aggregate that characterizes predominant flakes in the analyzed material, confirming the presence of biological material in the water that feeds power plant Fontes Nova.

Detailed results of the research about the detected microorganisms are documented in the reports of the project development submitted to Light [5]. The chemical analysis made by Infrared Spectrometry techniques and plasma emission Spectrometry, besides showing clearly the presence of metallic oxides (expected results), showed the presence of organic material. These are indicators of microorganisms that can explain biofouling phenomenon in the internal elements of the hydrogenerators heat exchangers.

A preliminary diagnosis of the analysis made takes us to the conclusion that though the Paraíba River water is rich in solid residues, apparently those impurities don't cause the blocking of the heat, unlike, the induct cleaning by mechanical abrasion. The water that comes from the Lajes Reservoir – though visually crystalline – has the presence of microorganisms that grow in fast reproduction colonies. Those blockings cause damage and severe pressure drops in the refrigeration system, taking it almost to a total blocking. As a result, the thermal and hydrodynamic efficiency of the heat exchangers are strongly affected.

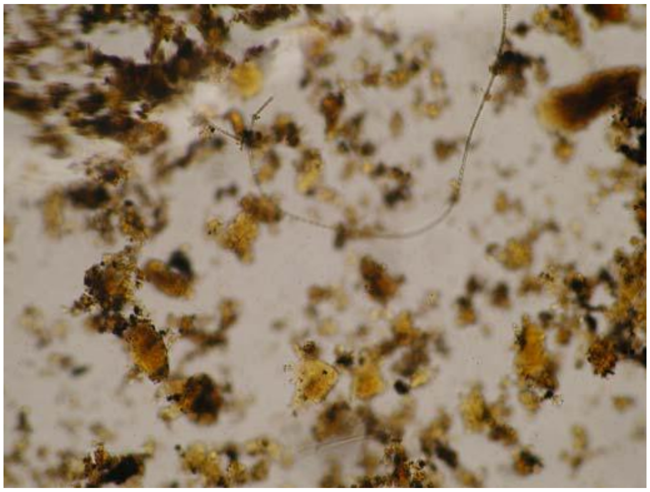


Figure 10 General aspect of the collected material with the presence of organic and inorganic flakes and filamentous cianobacteria (200x zoom).

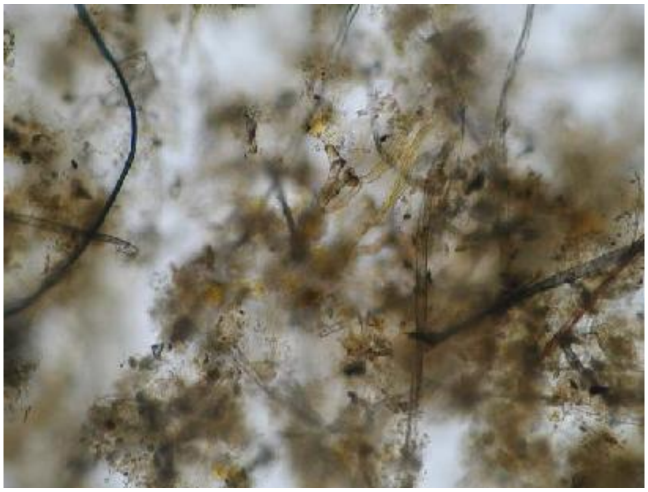


Figure 11 Evidence of the presence of microorganisms: fungi hyphae among the debris.

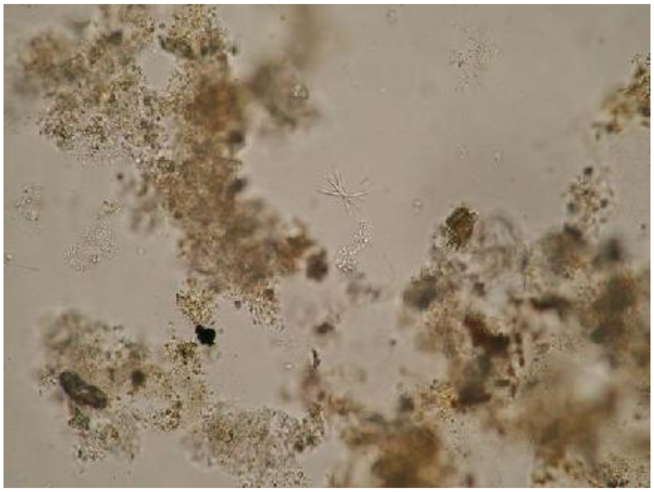


Figure 12 Cianobacteria colonies, clorophilic algae and amorph debris.

Figure 13 Details of the biological aggregate that constitutes predominant flakes in the analyzed material (600x zoom).

CONCLUSIONS AND RECOMMENDATIONS

The study that was carried confirmed the need for the implementation of an automated measurement system, able to produce measurements in real time with accuracy levels that allow the testing of the hypothesis. The developed measurement system showed itself effective to evaluate the role of the electric field in the flow as inhibitor of the biofouling mechanism. Based on the obtained results, it’s possible to affirm that, for the water that feeds Fontes Nova, the electric field reduced (but did not eliminate) the inlay formed in the internal passages of the heat exchangers. This means, it contributes to the mitigation of the biofouling mechanism in the heat exchangers of the refrigeration system for the hydrogenerators bearings.

The water analysis confirmed that cultures of microorganisms proliferate and that constitutes the main reason for the blocking of the internal canals of the heat exchangers.

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REFERENCES

[1] T. Vemeiren, "Magnetic treatment of liquids for scale and corrosion prevention," *Corros. Technol*, vol. 5, pp. 215-219, 1958.

[2] J. Baker and S. Judd, "Magnetic amelioration of scale formation," *Water Res.*, vol. 30 (2), pp. 247-260, 1996.

[3] A. D. Mercer, Corrosion in Seawater Systems (Ellis Horwood Series in Corrosion and Its Prevention), vol. I. Ellis Horwood Ltd, 1990, pp. 53-64.

[4] H. Martin, Heat Exchangers. New York: Hemisphere Publishing Corporation, 1988, p. 205, ISBN 1-56032-119-9.

[5] M.N., Frota, E.M. Ticona, J.M.Ticona, J.J. Milon, S.L. Braga, Relatório Final Relatório Final Consolidado do P P&D OKE 06-07 (Aneel-Light Energia), Tecnologia de Tratamento de água de Refrigeração da Usina Fontes Nova, Projeto desenvolvido pelao Programa de Pós-Graduação em Metrologia para Qualidade e Inovação da PUC-Rio. Documento interno da LIGHT. Dezembro de 2009.

[6] Y. G. Mussalli and J. Tsou, "Advances in biofouling control technologies: US and Japanesse perspectives," in *Proc. 1989 Proceedings of the American Power Conference 52*, pp. 1022-1027.

[7] R. C. Ferraz, "Avaliação de sistema alternativo de proteção contra a corrosão em circuito de água de refrigeração," Dissertação de mestrado, COPPE, UFRJ, 2007.

[8] *Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full – Part 3: Nozzles and Venturi nozzles*, ISO 5167-3:2003, 18 de março, 2003.