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On-line cleaning technique for mitigation of biofouling in heat exchangers: A case study of a hydroelectric power plant in Brazil

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ABSTRACT

An experimental methodology was developed to assess an on-line cleaning technique to mitigate biofouling in plate heat exchangers. The exchangers are used in the cooling system of the journal bearings of hydro-generators of a power plant. The cleaning technology tested consisted of a non-intrusive electronic device wrapped around the water cooling piping that generated an electric field to inhibit the growth of micro-organisms on the heat transfer surfaces. Limnology studies explained the phenomenon of biofouling formation caused by limnophilous microorganisms present in the deepest parts of the reservoir manage to survive in hostile environments under anoxic conditions. Two criteria were adopted to assess the performance of the antifouling technology: a hydrodynamic criterion based on Kakaç's pressure drop equation for plate heat exchangers and a thermal criterion (*index of fouling*) that takes into account the heat transfer effectiveness under the clean and fouled conditions of operation. The position of the antifouling device produced better results when installed in the primary cooling circuit. For the conditions studied, the cleaning technique mitigated biofouling but did not eliminate it completely. Excitation of the flow by an electric field diminishes the pressure drop and the *index of fouling* when compared to the unexcited flow condition. Control and reduction of the fouling thermal resistance is highly desired as it drastically lessens mechanical pumping costs and increases heat transfer performance.

1. Introduction

Fouling is a resistance to energy transfer between fluids in process equipment [1]. It reduces the heat recovery and restricts the fluid flow in a heat exchanger by narrowing the flow area. Biofouling occurs whenever living matter is in contact with wetted surfaces. Generally speaking, heat exchangers are liable to fouling where the unwanted deposition of micro-organisms severely deteriorates heat transfer performance. Despite precautions taken at the design stage, the formation of biofouling associated with aqueous systems is inevitable if the temperature within the heat exchanger is similar to that of the environment. The biofoulant arises by a combination of complex processes. The process generally involves the transport of dissolved particulate matter from the bulk of an aqueous medium to the surface, firm attachment, and microbial transformation and detachment generally due to fluid shear forces [2–4]. Non-aqueous fluids may also favour the growth of living matter [5].

The accumulation of biological material on the internal walls of heat exchangers cannot be understood by the traditional fouling resistance approaches (freezing fouling or liquid solidification, crystallisation or scale formation, or fouling due to corrosion) [4]. It is difficult to destroy the activity of the biofoulant without frequent off-line cleaning is far more difficult. The addition of chemicals to the process generally eliminates the biofoulant or interrupts the biofouling process but at an undesirable environmental cost.

A simplified method for monitoring the thermal efficiency of fouled heat exchangers in oil refineries – where reduction in energy consumption is mandatory – was suggested by Jerónimo et al. [6]. Based on the evaluation of the predicted effectiveness of a fouled and an unfouled heat exchanger, the actual effectiveness was computed from the measured data for four inlet and outlet temperatures of a heat exchanger unit. The predicted values were calculated as a function of the Number of Transfer Units (NTU) and of the heat capacity ratio according to changes in mass flow rate. The use of his proposed *index of fouling* provided a good estimate of the *fouling thermal resistance*, understood to be equivalent concepts. As Jerónimo's approach was slightly sensitive to changes in fluid properties, this approach was later extended by Negrão

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Nomenclature

a	general model parameters (a_1, a_2, a_3)
A	cross section area of a pipe-element of the heat exchanger
b	channel average thickness, m
C	heat capacity rate, W K^{-1}
f	fanning friction factor
L	effective plate length for heat exchange, m
D_e	equivalent diameter of channel, m
D_p	port diameter of plate, m
$\dot{m}$	fluid mass flow rate, kg s^{-1}
N	number of channels per pass
G	mass flux ($G = m/A$), kg m^{-2} s^{-1}
G_c	channel mass flux (or mass velocity), kg m^{-2} s^{-1}
G_p	port mass flux (or mass velocity), kg m^{-2} s^{-1}
g	acceleration of gravity, m s^{-1}
P	number of passes
V	fluid velocity, m/s
Re	Reynolds Number ($R_e = G_c D_e/\mu$)
T	fluid (hot or cold) temperature
w	effective plate width for heat exchange, m
μ	fluid viscosity, Pa s
ρ	fluid density, kg m^{-3}
β	diameter ratio (nozzle factor)
ε	effectiveness of the heat exchanger
ϕ	plate area enlargement factor

Subscripts

c	clean condition (after mechanical cleaning)
f	fouled condition (when the temperature of the journal bearing exceeds 85 °C)
o	refers to the hot fluid side (oil)
w	refers to the cold fluid side (water)
i	measured at the inlet of the exchanger
e	measured at the outlet of the exchanger
min	minimum value

et al. [7] to supervise a whole train of heat exchangers. Other authors refer to the friction factor – usually modelled as a semi-empirical correlation of the pressure drop – as a key parameter to study the effects of biofouling on heat transfer performance [8–10]. Wallhäußer et al. [11] reviewed different fouling methods to detect and model fouled heat exchangers. They concluded that it is not easy to find a suitable method to monitor fouling in closed systems. Mohanty and Singru [12] uses the C-factor (the ratio between the flow velocity and the square root of the pressure drop) as a tool for investigating the performance of fouled heat exchangers. According to the authors, the C-factor proved to be an effective technique for detecting the fouling and degradation in heat transfer efficiency. In China, Zhang et al. [13] investigated fouling in plate heat exchangers. Sophisticated scanning electron microscope to study the complex structures of fouling and the Von-Karman analysis were used to build a semi-empirical fouling model. Prediction of fouling factors agreed well with experimental data. Genić et al. [14] measured the thermal performance of heat exchangers with parallel helical tubes in district heating in Serbia. The group of researchers from the University of Belgrade developed a correlation based on the hydraulic diameter [15] to calculate the shell-side heat transfer coefficient. The authors found that the values of fouling resistances were slightly smaller than the usual ones encountered in shell-and-tube exchangers with straight tubes.

A variety of off-line and on-line cleaning techniques to restore heat exchanger efficiency are discussed in the literature [16]. On-line cleaning techniques have a clear advantage over off-line cleaning techniques, as they do not require partial or complete shutdown of the process for cleaning, which is critical in power plants. The choice between the two is often dictated by of operating conditions or construction limitations (e.g. devices used in some on-line cleaning techniques may obstruct the inner passages of the exchanger). The decision to use one or the other also depends on several factors such as cost, safety of maintenance staff, use of biocides, and the impossibility to interrupt the operation of the heat exchanger. However, no cleaning technique can guarantee that the biofoulant will no longer adhere to the surface. In general, maintenance personnel are left with no option other than to dismantle the heat exchanger at scheduled stops to clean it. An alternative to ensure system network performance is to make use of a spare heat exchanger installed in a bypass circuit to replace the biofouled exchanger. Operational costs of maintenance have an outrageous economic impact; the expenditures of the US process industry to overcome fouling related problems exceed 5 billion USD per year just to overcome fouling related problems [17].

On-line cleaning techniques use one of several types of procedures (mechanical cleaning, surface modification, chemical injection, magnetic and electronic anti-fouling devices [18]). A variety of engineering concepts, techniques and state of the art technology are commonly used (e.g.: Mechanical cleaning [19,20]; Surface modification [21]; Chemical cleaning [22,23]; Magnetic cleaning [24–26]; Electronic cleaning [27–33]).

Overall heat transfer is quite sensitive to biofilm formation, that compromises heat exchanger performance. This is particularly severe in heat exchangers of the cooling system of turbines and generators of hydroelectric power plants. These heat exchangers often need to be dismantled for cleaning from time to time and such an operation requires a plant shutdown, resulting in loss of electricity generation, hours of hard work and, ultimately, loss of revenue. Efficiency loss due to fouling is then restored by judicious maintenance programmes.

The existing methods for assessing the performance of non-intrusive cleaning techniques are usually based on performance degradation and are unable to predict future scenarios. An advanced prognostic approach capable of forecasting operating conditions would be highly desirable to manage the life cycle of the cooling system.

This paper reports an experimental methodology to assess a non-intrusive electronic anti-fouling technology to mitigate biofouling in plate heat exchangers used to cool the journal bearings of generators of a hydroelectric power plant.

2. Biofouling in the Fontes Nova hydroelectric plant

Conceived and built at the beginning of the twentieth century, the hydroelectric complex of Fontes Nova is one of the oldest in Brazil. The complex consists of five main reservoirs (Santa Cecília, Vigário, Santana, Tocos and Lajes); five power plants (Fontes Nova: 132 MW, Pereira Passos: 100 MW, Nilo Peçanha (built under the ground): 380 MW, Ilha dos Pombos: 183 MW, Santa Branca: 57 MW) and two pumping stations (Santa Cecilia: 35 MW, 160 m^3/s and Vigário: 91 MW, 190 m^3/s). These pumping stations raise water from the Paraiba do Sul and Piraí rivers to the Lajes and Vigário reservoirs. Lajes, the largest of the reservoirs, stores one half billion cubic metres of fresh water. As a result of this ingenious arrangement, water from different sources becomes available to generate electricity for the city of Rio de Janeiro at a total height (hydrostatic head) of 312 m.

Over the years, biofouling has been a matter of concern at Fontes Nova Power Plant. The cause of biofilm formation on the heat transfer surfaces of plate heat exchangers – employed to cool the bearings of the three Francis turbines (44 MW each) – was not elucidated. At first, it was believed that the sludgy water from Vigário reservoir was responsible. In fact, the water, which was full of debris and sediments, acts as an abrasive material while in contact with the plates of the heat exchangers, and helps to remove scaling deposits. The untainted waters of the Lajes Reservoir – a lake surrounded by stretches of tropical rain forest that assures good water quality – was not believed to be responsible for biofouling of the exchangers. Further tests were carried out to resolve the apparent controversy. Oddly enough, the biological analysis [34] did reveal that the water of Lajes was the cause of the biofouling.

The water of Lajes has been extensively studied [35]. To understand the nature of fouling, chemical and physicochemical (plasma emission spectrometry) methods allowed for the identification of chemical elements and infrared spectrometry identified chemical bonding. A biological analysis using optical microscopy detected the presence of microorganisms including filamentous cyanobacteria and bacilariofic eas algae. The living matter was similar to the activated silts usually found in biological treatment plants. The results confirmed aggregates of bacterial growth. Biological material in the inner passages of the exchanger may promote other fouling mechanisms.

Independent limnology studies, based on internationally recognised standard procedures [36], carried out on the vertical column structure of the Lajes Reservoir [37,38], confirmed that the water column dynamics is of fundamental importance to explain the nature of the fouling. Despite the small seasonal shifts typical of tropical climates and long periods of stratification, water mixing may not necessarily occur in the deepest parts of the reservoir during the warm season. Surprisingly, limnophilous microorganisms managed to survive under conditions of anoxia in the resulting nutrient-rich, poor quality water. Recent studies conducted at the University of Sheffield [39] on the mechanism of oxygen sensing by bacteria has showed that bacteria manage to survive in these hostile environments by switching on specific genes.

As the waters of the reservoirs flow through the turbine blades of the hydro-generators, the bacteria encounter an aerated environment and thrive in huge colonies. The colonising bacteria, which are fed by a continuous supply of nutrients from the water flow, quickly adsorb onto the internal surfaces of the exchangers and the biofilm begins to develop.

Comprehensive chemical and bacteriological analyses of water samples and scaling deposits directly collected from the inner passages of the heat exchangers revealed the presence of fungi hyphae. Infrared and plasma emission spectrometry detected the presence of cyanobacteria colonies, chlorophilic algae and amorph among the debris (shown in Fig. 1).

Fig. 2 illustrates a schematic of the counter current plate heat exchanger manufactured by Alfa Laval (model M6-MFG, 28 effective plates) featuring the flows of hot (oil) and cold (water) fluids and the colonies of microorganisms adsorbed onto the surfaces of the vertical plates of the heat exchanger forming a biofilm.

In the cooling system of the journal bearings of the turbines, lubricating oil and water enter at the opposite ends of the counter flow heat exchanger (schematically shown in Fig. 2a). The lubricating oil is cooled from 50 °C to 38 °C and returns to the turbines bearings while the water is heated from 20 °C to 22 °C and discharged to the river downstream of the plant. The water fulfils the heat exchange requirements (abundance, quality and temperature) at virtually no cost but biofouls the heat exchanger (Fig. 2b).

The uncontrolled growth of microorganisms quickly biofouls the heat exchangers to an undesirable situation compromising fluid flow and heat transfer performance. Biofouling is a serious problem and as little as parts per million can trigger the formation of the biofilm. The exchangers may even become totally blocked; forcing maintenance teams to shutdown the line and dismantle the fouled exchangers, previously cleaned by mechanical means.

The economic benefit that results from the implementation of a new cleaning technique can be assessed in different ways. A practical one is to evaluate the cost of the energy not generated due to an undesirable shutdown of the turbine for maintenance. In the case studied (Francis Turbine of 44 MW), the economic impact of a single day of maintenance would amount in 180,000 USD taking into account the energy priced at the Brazilian spot Market. In reality, the resulting economic impact may be higher as maintenance stops may keep the plant off for a few days.

3. Assessment of the antifouling technology

Implementation of real time measurement of pressure, temperature and mass flow rate and knowledge of the fluid flow properties are essential to assess antifouling technologies. Darcy–Weisbach formula is convenient to model the pressure drop ΔP induced by the cooling fluid (density ρ) as it flows (at a mass flow rate $\dot{m}$; mass flux G) through a pipe-element (diameter d; cross section area A; length L; friction factor f) of a heat exchanger subject to fouling deposits.

$$\Delta P = f\frac{L}{d}\frac{G^2}{2\rho} \tag{1}$$

where:

$$G = \frac{\dot{m}}{A} = \frac{4}{\pi}\frac{\dot{m}}{d^2} \tag{2}$$

Applying Eq. (1) to the "clean" and "fouled" conditions of pipe-element of the heat exchanger one obtains:

$$\frac{\frac{\Delta P}{\Delta P_c}}{\left(\frac{\dot{m}}{\dot{m}_c}\right)^2} = \frac{\frac{\Delta P\Delta}{\dot{m}^2}}{\left(\frac{\Delta P}{\dot{m}^2}\right)_c} = \frac{\frac{f}{f_c}}{\left(\frac{d}{d_c}\right)^5} \tag{3}$$

To guarantee that the desired mass flow rate m will be supplied, the pump must be properly specified by combining the system curve and the manufacturer's pump curve that describes the relation between flow rate and head loss for the actual pump. Fig. 3a depicts a typical situation where the centrifugal pump curve system changed during operating conditions due to the scaling de posits. Fig. 3b explains why the ratio $\Delta P/\dot{m}^2$ that appears in Eq. (3) increases with fouling. These curves clearly show, for different pipe diameters, that the fouling has a detrimental effect worsening the pump operating conditions. As a result the system deviates from its best efficiency point.

Based on this line of thought a comprehensive analysis that includes a modified efficiency method will unfold in two criteria – hydrodynamic and thermal experimental – to assess the effectiveness of the cleaning technology.

3.1. Experimental set-up

The experimental set-up consisted of vertical plate heat exchangers instrumented with temperature and differential pressure transmitters; a module for data acquisition (DAQ) and the electronic antifouling device used to excite the flow. A web-based

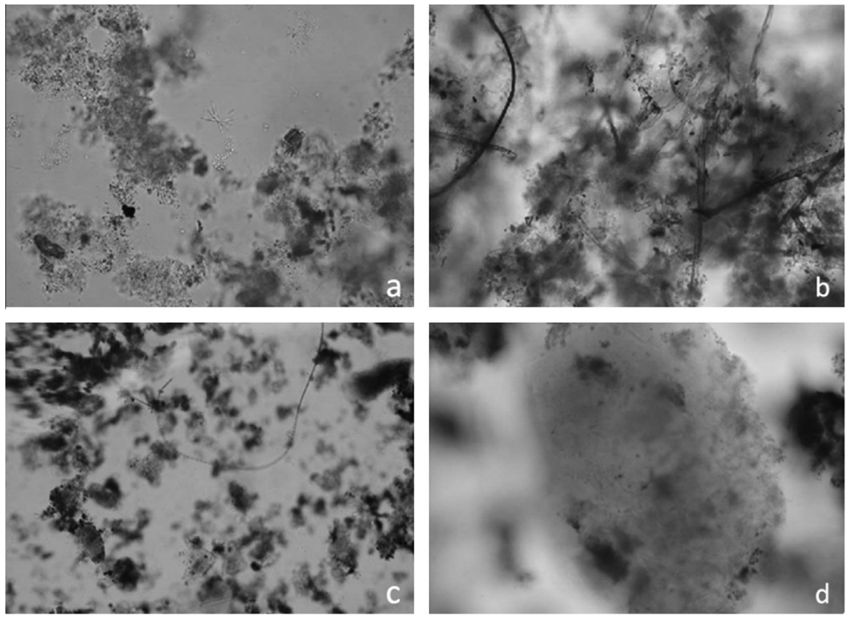

Fig. 1. Bacterial water analysis. (a) General aspect of the collected material with the presence of organic and inorganic flakes and filamentous cyanobacteria (200× zoom). (b) Evidence of the presence of microorganisms: fungi hyphae among the debris. (c) Cyanobacteria colonies, chlorophilic algae and amorph debris. (d) Details of the biological aggregate that constitutes predominant flakes in the analysed material (600× zoom).

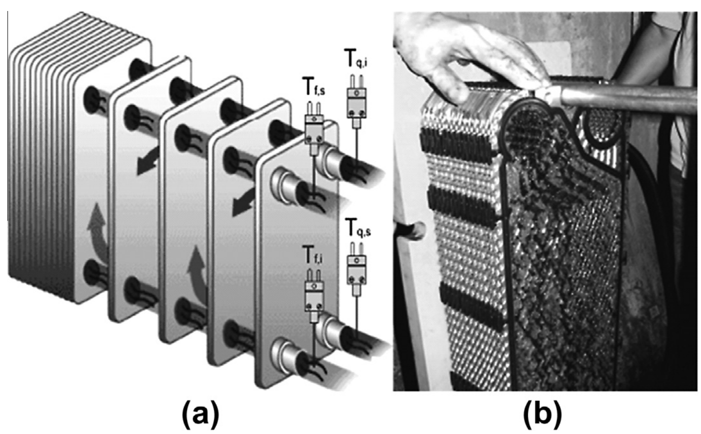

Fig. 2. Biofouling formation in a heat exchanger ((a) overall schematic of a counter current heat exchanger and (b) fouled plates of the Alfa Laval exchanger, after exposed to the flow).

protocol allowed real time data (pressure drop, temperatures and mass flow rate) to be measured locally and transmitted (sampling time of 120 s) to the university laboratory, where the data were remotely processed. Experiments were planned to cause the least interference possible in the operating routine of the power plant.

3.1.1. Measuring system

Fig. 4 illustrates a pictorial view of the Fontes Nova Power Plant featuring the cooling system of the journal bearings of the turbines and the remote data acquisition/transmitter web-based system. The picture focuses on one of the heat exchangers instrumented to study the effectiveness of the antifouling device installed in two different positions: in the primary cooling circuit (EAF position #1) and in an adjacent water circuit (EAF position #2) used to supply cooling water to auxiliary components. The measuring system is described next.

Fig. 5a and b depicts details of the real time measuring system that is installed in the heat exchangers: (i) the differential pressure transmitter for measuring mass flow rates (Honeywell, model FDW, calibrated in the range 0–25 psid for the transmission of electronic signals varying from 4 to 20 mA); (ii) a plumbing connection, that allows for the safe pressurization and depressurization of the transmitter and (iii) measuring stations for temperature and pressure data acquisition. The cooling water and oil temperatures were measured with sheathed PT-100 thermo-resistance (manufactured by Ecil-Lab Measurement System Ltd.) calibrated vis-à-vis the International ITS-90 Temperature Scale (0.2%). The pressure drop was measured by a differential pressure transducer (Honeywell model FDW), calibrated in the range 0–50 psid whose accuracy was obtained through a best-fit-straight-line method in relationship to its calibration curve.

3.1.2. Measurement of flow rate and associated uncertainty

The mass flow rate is an essential parameter to assess hydrodynamics and heat transfer performance. [40,41], installed in the primary cooling circuit that feeds the heat exchanger, is an inexpensive and reliable method for measuring flow rate. Easily in-

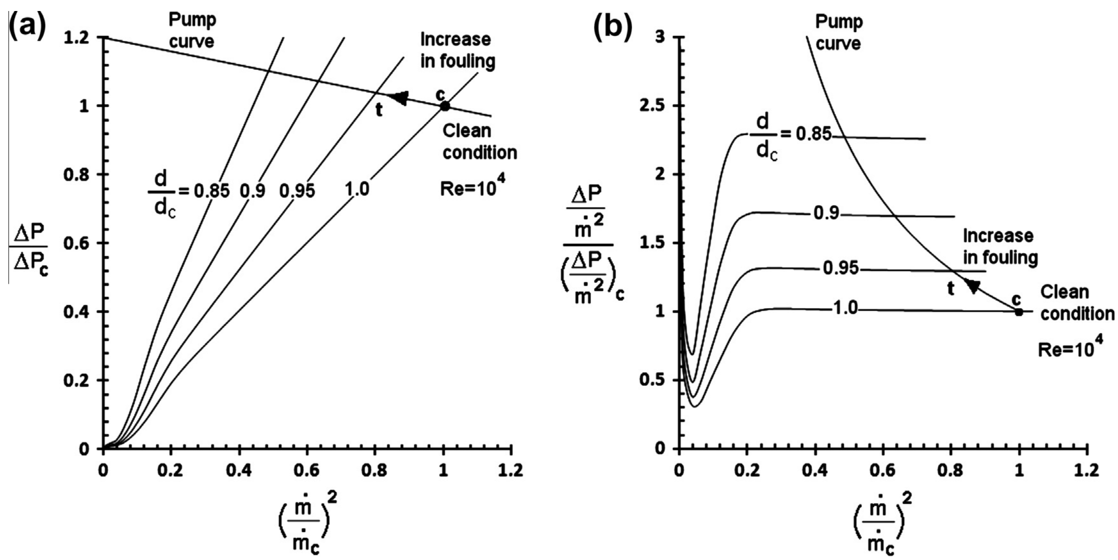

Fig. 3. The system operating curve and pump performance curve. (a and b) The system curve and pump performance curves scaled on the parameters used in Eq. (3); i.e.: pressure drop vs. mass flow rate (fouled values normalised on clean values).

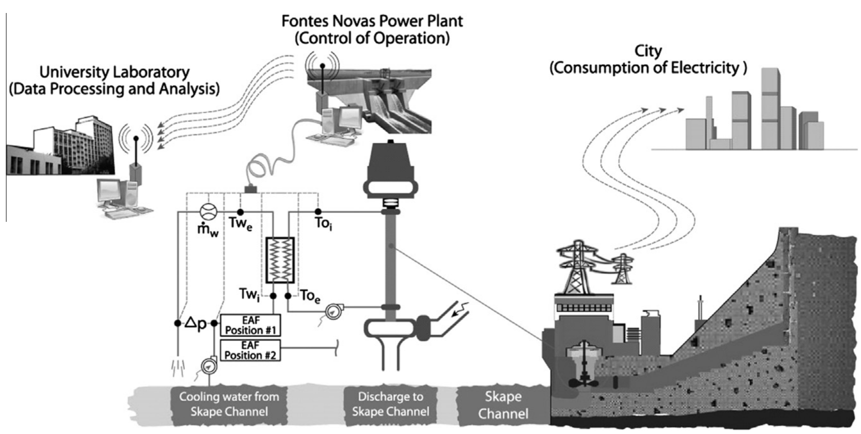

Fig. 4. Schematic picture of the cooling system of the journal bearings of the turbines and the remote data acquisition/transmitter web-based system. (EAF-1: antifouling device installed in the primary cooling circuit that feeds the heat exchanger; EAF-2: antifouling device installed in an adjacent water circuit).

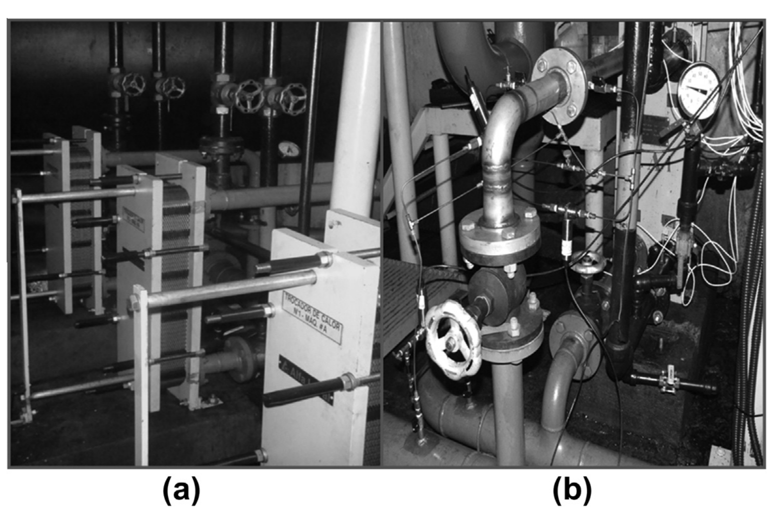

Fig. 5. The Alfa Laval plate heat exchangers; 5a before instrumented and 5b after installation of the real time measuring system.

Table 1
Measurement uncertainty associated with measurement of mass flow rate.

		Sensitivity coefficient	Sensitivity value, S	Uncertainty, U_{95} (%)	$(S \cdot U_{95})^2$
C	Discharge coefficient	1	1	2	4
d	Diameter of orifice	$\frac{2}{1-\beta^4}$	2.133	0.07	0.022
D	Pipe diameter	$\frac{2\beta^4}{1-\beta^4}$	0.134	0.9	0.015
ΔP	Differential pressure	$\frac{1}{2}$	0.5	0.1	0.0025
ρ_1	Density of the fluid	$\frac{1}{2}$	0.5	0.3	0.0225
Sum of the squares $\sum(S \cdot U_{95})^2$					4.06
Uncertainty associated with $\dot{m}^2 = \sqrt{\sum(S \cdot U_{95})^2}$					2%

stalled, these nozzles yield accurate results despite the undesirable pressure drop that increases pumping costs.

Table 1 summarises the measurement routine used in the calculation of the measurement uncertainties associated the mass flow rate, for a 95% confidence level.

In spite of the concern to keep the measurement uncertainties at an acceptable level, Table 1 confirms that the accuracy of the mass flow measurements in this work are limited to the dominant relative uncertainty associated with the discharge coefficient (specified in the standard ASME MFC-3M [35]).

3.1.3. Measurement device and effect of fouling formation on its accuracy

Conventional standard ultrasonic measurement techniques did not work in severe biofouled flows, either because the transmitter/receptor sensing elements of the ultrasonic measurement device become contaminated (the transit time signal may drop up to 70% after a few weeks of operation) or because the ultrasonic device may not operate properly when subject to the local magnetic field induced by the operation of the hydro generators.

Fig. 6 depicts the two-phase testing scheme: (i) selection of the optimum β diameter ratio of the nozzle to be used as the sensing element (nozzle) of the flow measuring system and (ii) quantification of the undesirable effect of the fouling formation on its surfaces; i.e., to verify the impact of the fouling on the accuracy of the measurement of mass flow rate.

During a preliminary period, three nozzles (β = 0.50; 0.60 and 0.75) that were manufactured in compliance with the ASME standard [35,40] were tested in the cold-water circuit vis-à-vis the output of a calibrated reference measuring standard. This 70-day first round of experiments revealed that: (i) fouling grew mildly on the surfaces of the nozzle; (ii) out of the three nozzles tested, β = 0.50 produced the highest amplitude signal within ±10% of the true value of the flow rate and (iii) for the β = 0.50 nozzle reproduced the reference mass flow rate within ±1.9%. This result was the qualification criterion for selecting the overall flow rate measuring system and validating it against experimental data. The effect of fouling formation inside the nozzle was then investigated over a longer period of time. At day 182, the nozzle was removed and the fouling was analysed. The biological analysis revealed the presence of living matter (micro-organisms) attached to its internal walls. The nozzle and pressure taps were then cleaned and put back in place. At day 392 (i.e.: 210 days after the nozzle was cleaned), a set of flow measurements was carried out for three different situations: the nozzle and pressure taps biofouled ($\dot{m}$ = 2.98 kg/s); the pressure taps cleaned ($\dot{m}$ = 3.00 kg/s) and the nozzle and pressure taps cleaned ($\dot{m}$ = 2.89 kg/s). Inspection of the thick biofilm that formed and the physics of the phenomenon explained these results. Unplugging the pressure taps accounts for the 0.7% increase in the response of the pressure transducer signal. In addition, the formation of scale at the throat of the nozzle accelerates the flow. An artificial increase in the fluid velocity reduces the pressure drop across the nozzle leading to a 3.7% error in the mass flow rate. Compared to the accuracy of the measuring system operating under normal conditions (±2%), this error may be too high, but it is left to the discretion of the maintenance team to clean the nozzle earlier if this level of error cannot be tolerated.

3.1.4. The antifouling device

The cleaning device tested – Hydropath Technology, model S160, input/output power: 65 W/45 W and frequency ranging from 50 to 500 kHz, [28] – was installed in the water circuit of a vertical

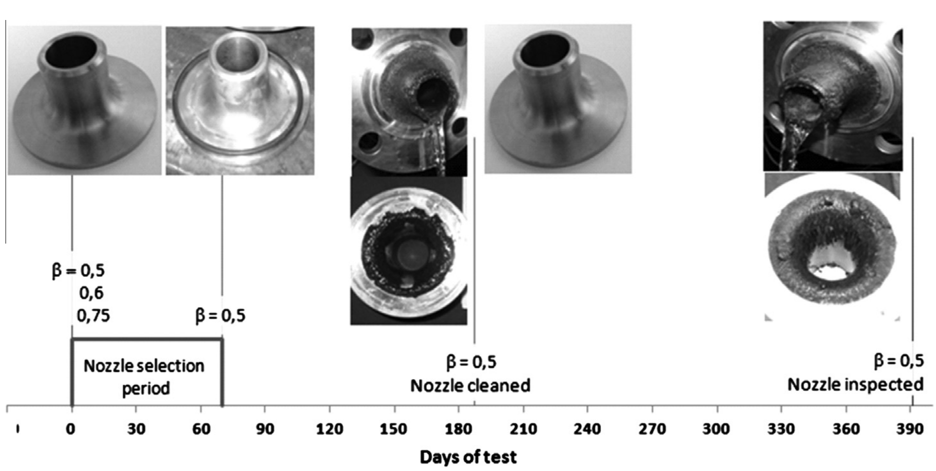

Fig. 6. Sensitivity of the flow measuring device to biofouling formation.

plate heat exchangers. A succession of radio frequency signals that excited the flow was generated by a step-up transformer. It generated a series of exponentially decaying sine waves (amplitude diminishing from a maximum value to zero) to mitigate the undesirable effects of *limescale*, algae, bacteria and flocculating material. The biofilm thus detaches from the surfaces.

3.2. Experimental procedures

After the measuring system was validated, a new set of experiments was implemented to evaluate the performance of the antifouling electronic device. Assessment was based on two experimental criteria (hydrodynamic and thermal). One of the heat exchangers was instrumented to measure and monitor hydrodynamic and thermal parameters (flow rate, temperature and pressure drop) in the absence and presence of the external electric field. A stand-by exchanger (also instrumented) was kept in place should the tested exchanger fail. For each set of experiments, the instrumented exchanger was always cleaned to ensure similar initial operating conditions.

To settle controversial views [28] regarding the reach of the electric antifouling device, experiments were carried out with the device at two positions in the cooling system: (i) wrapped around the piping of the primary cooling circuit that feeds the heat exchanger and (ii) installed in an adjacent water circuit also subject to fouling (EAF-1 and EAF-2 in Fig. 4). For each position of the antifouling device, experiments were repeated in the presence and absence of an applied electric field. These experiments are discussed in the following two sections.

3.2.1. Hydrodynamic criterion

The pressure drop ΔP of a vertical plate heat exchanger (applicable to the hot or cold sides) can be calculated by Kakaç's equation [42]:

$$\Delta P = \left(\frac{2f(L+D_p)PG_c^2}{\rho_m D_e}\right) + 1.4\left(P\frac{G_p^2}{2\rho_m}\right) + \rho_m g(L+D_p) \tag{4}$$

where:

$$G_c = \frac{\dot{m}}{Nbw}; \quad G_p = \frac{4\dot{m}}{\pi D_p^2}; \quad R_e = \frac{G_c D_e}{\mu}$$

$$D_e = \frac{4bw}{2(b+w\phi)} \approx \frac{2b}{\phi}; \; f = a_1 + \frac{a_2}{Re^{a_3}}$$

While the Darcy–Weisbach phenomenological formula is often used to express the hydrodynamic performance, the pressure drop normalised on the square of the fluid mass flow rate was found to be a convenient criterion [29,30] to evaluate performance degradation of the heat exchangers. The resulting ratio describes somehow the increase of the biofilm thickness. An experimental parameter was developed based on Eq. (4) and was written for a situation where the water (cold fluid) inlet and outlet pressure taps are installed at the same height to compensate for the hydrostatic term that vanishes. Thus,

$$\frac{\Delta P}{\dot{m}^2} = \left(\frac{2f(L+D_p)P}{N^2b^2w^2\rho_m D_e}\right) + 1.4\left(P\frac{8}{\pi^2 D_p^4\rho_m}\right) \tag{5}$$

Eq. (5) holds for any condition of operation of the heat exchanger. Compared to the fouled condition, the ratio $\Delta P/\dot{m}^2$ yields a smaller value when the exchanger is unfouled (clean). As the exchanger becomes fouled, the ratio $\Delta P/\dot{m}^2$ increases as the inner passages of the exchanger become partially obstructed increasing the pressure drop (ΔP) and decreasing the mass flow rate ($\dot{m}$). Inspection of the right hand side of Eq. (5) confirms the same trend as the friction factor increases with roughness as the equivalent channel diameter (D_e) decreases with fouling (assuming that the fluid properties and exchanger geometric parameters remain unchanged). Eq. (5) can be directly evaluated from experimental data of ΔP and $\dot{m}$. This is a more convenient evaluation of the ratio $\Delta P/\dot{m}^2$; f and D_e are not straightforward to measure experimentally, as they require *in situ* measurements of local thickness of scaling deposits. Deviations from the minor value assigned to the ratio $\Delta P/\dot{m}^2$ indicate the "degree of fouling".

3.2.2. Thermal criterion

For a compact counter flow heat exchanger Kays and London [1] defines heat transfer effectiveness ε as the ratio of the actual heat transfer rate to the (thermodynamically limited) maximum possible heat transfer rate, as it would be realised only in a counter flow heat exchanger of infinite heat transfer area.

$$\varepsilon = \frac{q}{q_{max}} = \frac{C_o(T_{oi} - T_{oe})}{C_{min}(T_{oi} - T_{wi})} = \frac{C_w(T_{we} - T_{wi})}{C_{min}(T_{oi} - T_{wi})} \tag{6}$$

For the current situation where C_{min} – the smaller heat capacity rate between C_w and C_o – corresponds to C_o, then the exchanger heat transfer effectiveness ε can be calculated by Eq. (7):

$$\varepsilon = \frac{T_{oi} - T_{oe}}{T_{oi} - T_{wi}} \tag{7}$$

Because the temperatures of the lubricating oil (T_o) and of the cooling water (T_w) were continuously measured at the inlet and outlet ports of the counter flow heat exchangers, the heat transfer effectiveness ε was directly evaluated based on experimental data.

The performance of the antifouling device (i.e.: its capacity to clean the heat exchanger) can be assessed either by Eq. (7) or by Eq. (8), which describes the *"index of fouling"* (*IF*) proposed by Jerónimo et al. [6], a concept equivalent to the *thermal resistance* [7].

$$IF = \frac{\varepsilon_c - \varepsilon}{\varepsilon_c - \varepsilon_f} \tag{8}$$

In this equation, $IF = 0$ denotes the condition of a clean heat exchanger (unfouled) and $IF = 1$ the extreme condition when fouling reaches the maximum tolerated level (set by the maximum accepted journal bearing temperature).

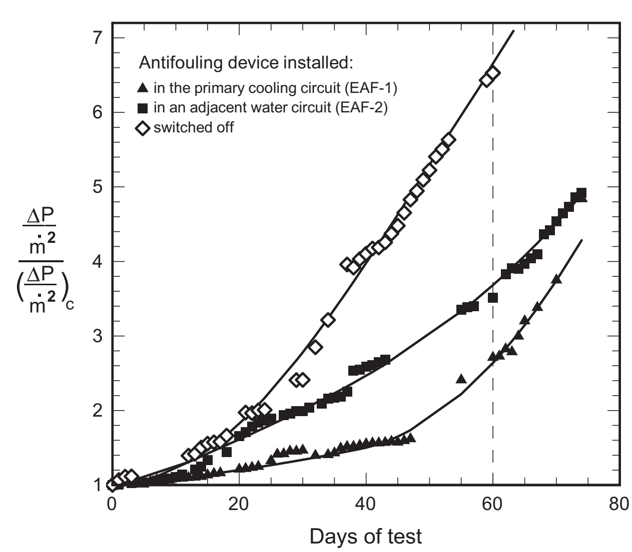

Fig. 7. Hydrodynamic criterion for assessing the antifouling device in the presence and absence of the action of the antifouling device.

4. Results and discussion

This section describes key findings of the assessment of the non-intrusive antifouling device. Both base line criteria considered – the hydrodynamic and thermal performance of the exchanger – led to similar trends expounded as follows.

Fig. 7 summarises the experiments associated with the hydrodynamic approach where values of the ratio $\Delta P/\dot{m}^2$ were calculated from experimental data acquired during repeated of about 60-day testing cycles (antifouling device switched off and switched on, the latter for two positions of the antifouling device: installed in the primary cooling water circuit and in an adjacent water circuit). The data displayed are normalised to the corresponding unfouled (clean) value of the ratio. The open data symbols denote unexcited flow (antifouling device switched off); filled triangles (▲) symbols denote data obtained with the antifouling device in position 1 (EAF-1) and filled squares (■) obtained with the device in position 2 (EAF-2) as shown in Fig. 4. As can be seen, fouling grows faster (open symbols) when the antifouling device is off, thus deviating from the clean condition.

In analogy to an electric circuit, $\Delta P/\dot{m}^2$ can be understood as a sort of index to measure the *biofouling hydrodynamic resistance*. Due to the square of the mass flow rate in the denominator, the proposed index magnifies the value of the ratio $\Delta P/\dot{m}^2$ used to measure the effect of the antifouling device acting in the flow. In the absence of the effect of the device, the *biofouling hydrodynamic resistance* grows at a high rate. As seen in Fig. 7, after 60 days of operation of the heat exchanger without the effect of the antifouling device (switched off), the *biofouling hydrodynamic resistance* reaches the value 6.6. For the same period of operation, much favourable results are obtained when the antifouled device is activated: the *hydrodynamic resistance* is drastically reduced to 2.6 when antifouling device is installed in the primary cooling circuit but reaches 3.7 when installed in an adjacent water circuit. In other words, the effect of the antifouling device is to postpone stops for maintenance.

For a 95% confidence level, Table 2 summarises the propagated uncertainties associated with the ratio $\Delta P/\dot{m}^2$, calculated from separate measurements of ΔP and $\dot{m}^2$.

Fig. 8 illustrates the evolution of the *index of fouling IF* taken as the key parameter to assess the performance of the exchanger according to the thermal criterion. This *index of fouling*, *IF*, which was calculated from experimental data collected during the testing, exhibited the same trends observed for the hydrodynamic criterion. The symbols are the same as those described previously for Fig. 7; i.e.: open data symbols denote unexcited flow; filled triangles denote the condition when the antifouling device was mounted in the primary cooling circuit that feeds the heat exchanger (EAF-1) and filled squares denote data associated with the antifouling device intentionally installed in an adjacent water cooling pipe (EAF-2).

Contrary to what manufacturers and sales representatives commonly advertise – i.e., the electronic antifouling device produces its expected effect regardless its position in the pipe network – this work has shown that the position of the device does affect its cleaning performance. Better results are always obtained when

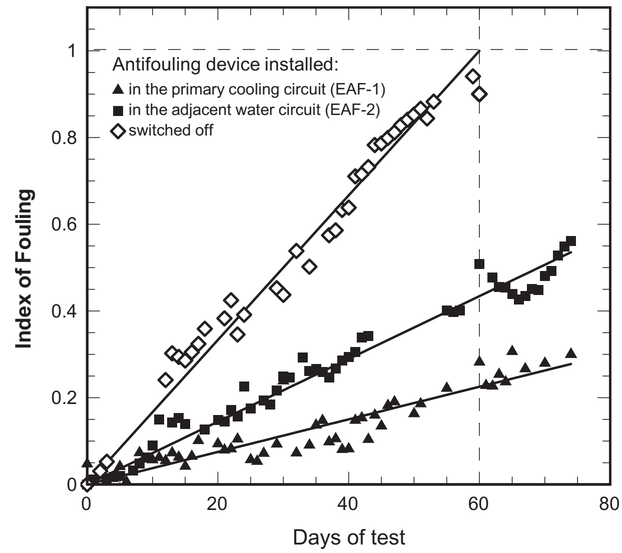

Fig. 8. Thermal criterion for assessing the antifouling device in the presence and absence of the action of the antifouling device.

the device is installed in the primary cooling circuit that feeds the heat exchanger. The effectiveness of the technology requires prior understanding of the positioning of the antifouling device and proved to impact in its performance.

As shown in Fig. 8, if the cooling flow is not exposed to the effect of the antifouling device, living matter deposited on the plates of the exchangers increases rapidly and the index of fouling reaches the value $IF = 1$, after the 60 day of operation; i.e.: the journal bearing temperature reaches its maximum tolerated value ($T \approx 85$ °C). However, if the antifouling is activated in the primary cooling circuit, at the same day 60 of operation the index of fouling reaches a much smaller value; i.e.: $IF = 0.23$. This index of fouling almost double ($IF = 0.43$) if the antifouling device is installed in an adjacent water circuit. As shown, the results obtained clearly confirm that the electronic antifouling device indeed mitigates fouling.

Extrapolation of the data shown in Fig. 8 leads to the conclusion that when the antifouling device is properly installed in the primary cooling circuit (filled triangles ▲ symbols), the journal bearing temperature would reach its extreme temperature only after 266 days of operation; i.e.: at a much later stage than the 60-days usually required when the flow is not exposed to the electronic cleaning device. Similar experiments with the antifouling device installed in an adjacent water circuit (filled squares ■ data) show that the maximum bearing temperature is reached at a much earlier stage; i.e.: at day 138. In brief, the antifouling device effectively mitigates biofouling but needs adequate positioning.

For a 95% confidence level, Table 3 summarises the propagated uncertainties associated with the *index of fouling, IF*.

Tests performed in accordance with both hydrodynamic and thermal criteria confirmed that, the antifouling device was capable of reducing the effect of the undesirable incrustation. Ultimately, the benefits are a reduction in the pressure drop across the exchan-

Table 2
Measurement uncertainty associated with the ratio $\Delta P/\dot{m}^2$.

		Sensitivity coefficient	Sensitivity value, S	Uncertainty, U_{95} (%)	$(S \cdot U_{95})^2$
ΔP	Pressure drop	1	1	0.1	0.01
$\dot{m}$	Mass flow rate	2	2	2	16
Sum of squares $\sum(S \cdot U_{95})^2$					16.01
Uncertainty associated with the ratio $\Delta P/\dot{m}^2 = \sqrt{\sum(S \cdot U_{95})^2}$					4%

Table 3
Measurement uncertainty associated with the *effectiveness of the exchanger*, ε.

		Sensitivity coefficient	Sensitivity value, S	Uncertainty, (%)	$(S \cdot U_{95})^2$
ΔT_1	Differential temperature	1	1	0.2	0.04
ΔT_2	Differential temperature	1	1	0.2	0.04
Sum of squares $\sum(S \cdot U_{95})^2$					0.08
Uncertainty associated with the effectiveness, $\varepsilon = \sqrt{\sum(S \cdot U_{95})^2}$					0.28%
Absolut uncertainty associated with the index of fouling, $\delta_{IF} = 0.02^{*}$					

* Calculated from the propagation of uncertainties associated with ε and ΔT.

ger, a gain in overall heat transfer performance and the avoidance of costly interruption for cleaning.

5. Conclusions

Scheduled maintenance for cleaning should counterbalance the overall system performance and hopefully reduce operational costs, a major concern in the highly competitive electricity market.

Experimental data confirmed that the antifouling technology tested does mitigate biofouling but not eradicate it. All in all, the technology is not a panacea as advertised by sales representatives. On the contrary, results are sensitive to the peculiarities of the environment and waters studied. Experiments also show that the position of the antifouling device in the cooling stream plays a key role in the efficiency of the cleaning method. Moreover, the hydrodynamic and thermal criteria proposed to assess the performance of the antifouling device confirmed its effectiveness: reduces the *biofouling hydrodynamic resistance* by a factor of 2.6 and the *index of fouling* by a factor 3.7. These conclusions are limited to the conditions of the environment and waters studied.

Biofouling and biofilm control on heat exchanger surfaces still lack a systematic study to quantify the effects of different variables. One should bear in mind that foulants also adhere to turbine blades and other cooling equipment of the hydro-generator. The highly complex phenomenon of biofouling needs to be fully understood before an ultimate cleaning technique can be devised to successfully remove the biofoulant in its entirety. Despite decades of research effort the ultimate solution of the problem remains elusive.

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