On-line cleaning technique for mitigation of biofouling in heat exchangers: assessment of performance

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Abstract

Experimental work has been undertaken to assess an on-line cleaning technique to mitigate biofouling in plate heat exchangers used in the cooling system of journal bearings of hydro-generators the Fontes Nova power plant in Brazil. Limnology studies explained the phenomenon of biofouling formation caused by limnophilous micro-organisms present in the deepest parts of the reservoir that manage to survive in hostile environments under condition of anoxia. The cleaning technology tested consists of a non-intrusive electronic device, wrapped round the water cooling piping exposing the flow to an electric field capable to inhibit the growth of micro-organisms on heat transfer surfaces. Experiments were carried out in the presence and absence of the electric field. 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, based on the exchanger heat transfer effectiveness. The position of the antifouling device in the cooling flow did affect the performance of the cleaning technique. It produces better results when the device was installed in line with the flow. For the conditions studied, the cleaning technique did not eliminate biofouling completely but contributed to alleviate it. The excitation of the flow produced a reduction in pressure drop while maintaining higher values of the exchanger heat transfer effectiveness as compared to the correspondent value achieved when the device was switched off for a like testing condition. Control and reduction of the fouling thermal resistance drastically reduces mechanical pumping costs and increases heat transfer performance.

Keywords: on-line cleaning technique, assessment of antifouling technique, biofouling, mitigation, plate heat exchangers.

1. Introduction

Fouling is a resistance to energy transfer between fluids in process equipment [1]. It reduces the heat recovery and restricts fluid flow in the 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 not too different from that of the environment. The biofoulant arises, according to Characklis [2, 3, 4], through a combination of complex processes that involves the transport of dissolved and particulate matter from the bulk of an aqueous medium to the surface, firm attachment, microbial transformation and detachment, generally due to fluid shear forces. 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 approach (freezing fouling or liquid solidification, crystallization or scale formation, fouling due to corrosion) [4]. 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 interrupt 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 clean and dirty values of the effectiveness, the actual value is computed from the four inlet and outlet temperatures of a heat exchanger unit measured data. The predicted values are calculated as a function of the Number of

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Transfer Units (NTU) and of the heat capacity ratio according to changes in mass flow rate. Comparisons of his proposed index of fouling provides a good estimate of the fouling thermal resistance. Slightly sensible to changes in fluid properties, the Jerónimo's approach was later extended by Negrão 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, 9, 10].

A variety of off-line and on-line cleaning techniques to restore heat exchanger efficiency are discussed in the literature [11]. On-line have a clear advantage over off-line cleaning techniques as they do not require partial or complete shutdown of the process for cleaning (critical in power plants). The choice between the two is often dictated by conditions of operations 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 operation. None, however, can guarantee that the biofoulant will no longer adhere to the surface. More often than not, maintenance personnel are left with no option 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 exceed 5 billion USD per year just to overcome fouling related problems [12].

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.

Nomenclature:

a	general model parameters (a_1, a_2, a_3)
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
N	number of channels per pass
G_c	channel mass velocity (or mass flux), kg/m^2s
G_p	port mass velocity (or mass flux), kg/m^2s
g	acceleration of gravity, m/s^2
P	number of passes
V	fluid velocity, m/s
Re	Reynolds number
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)
ϕ	plate area enlargement factor

Subscripts:

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

2. Brief review of on-line cleaning techniques of heat exchangers

On-line cleaning techniques use one of several types of procedures: mechanical cleaning, surface modification, chemical injection, magnetic and electronic anti-fouling [13]. A variety of engineering concepts, techniques and state of the art technology are briefly discussed below:

- **Mechanical cleaning** — the use of automatic strainers, equipped with pneumatic or electrical control actuators, provides continuous debris removal from heat exchangers fluids and piping. When simplicity and costs are taking into account, back-flushing is perhaps the ideal cleaning technique. Back-flushing implies the reverse of the direction of flow through the heat exchanger to flush out build-up silt or mineral deposits. A nozzle with a back flush valve is installed in the pipes to carry the debris out of the equipment. Daily back-flushing virtually eliminates fouling and the need to open the heat exchanger for periodic manual cleaning. An alternative technique that wipes away the biofilm is the circulation of sponge or rubber balls in the cooling fluid. The balls are collected at the outlet of the exchanger by suitable strainers, drawn off and pumped back to the inlet to re-start the cleaning cycle. The balls may be abrasive or non-abrasive depending on the tenacity of the biofilm or scaling deposits attached to heat transfer surfaces [14]. Sometimes the balls are unable to negotiate tube bends or stuck in the heat exchanger passages due to partial blockage. Ice-pigging [15] is the ultimate alternative to sponge rubber balls. The "ice-pig" can cope with very complex geometries as crushed ice never gets stuck in the inner passages of the exchanger. But even if it did one would wait a while until it melts away in the cooling fluid. In terms of efficiency, savings, and environmental safety, on-line mechanical techniques are usually the best options if the cleaning process is systematically repeated before the heat exchanger is fouled. No on-line mechanical cleaning technique can, however, thoroughly eliminate the biofouling build-up.

- **Surface modification** — almost all types of materials that heat exchangers are made of can be coated on similar or dissimilar materials in order to develop anti-fouling, wear- and corrosion-resistant properties [16]. Coating plate heat exchangers surfaces with suitable polymers can occasionally inhibit microorganism growth.
- **Chemical cleaning** — chemical injection; i.e.: the continuous flow of chemical additives through heat exchanger equipment is a far better cleaning technique. Biocides can effectively be used to inhibit growth of microorganisms in cooling water systems [17, 18].The continuous injection of biocides (chlorine) does exert a controlling effect on biological fouling [19]. However, due to potential hazards to marine or fluvial life, chlorination has been a matter of severe environmental concern. Surfactant, the main constituent of chemical cleaners, is employed to reduce the surface tension of the cleaning fluid that wets, penetrates and disperses scaling deposits.
- **Magnetic cleaning** — the use of magnets as al non-intrusive alternative to chemical cleaning is still a matter of controversy. Many patents have been granted early in Europe [20] and in the U.S. [21] that uses permanent magnets or electromagnetic solenoids for the purpose of fouling control. Such magnets can only collect magnetic debris that occasionally may occlude the pipe. Lack of understanding of governing principles and the complexities involved in the physico-chemistry of fouling have led to much criticism. It is still unclear whether the magnetic cleaning works or not.
- **Electronic cleaning —** in the U.S., a very promising electronic anti-fouling cleaning technique was tested and validated by Cho et al. [22]. An oscillating electric field using a time-varying magnetic field generated from a solenoid wrapped around the feed pipe provides the necessary molecular agitation to charged mineral ions to collide and precipitate. The authors reported that "...the EAF (Electronic Anti-Fouling) technology significantly reduces new scale deposits both in an accelerated fouling test and in field test." and that "...is effective for any dissolved inorganic ions including calcium, magnesium, barium, silica, bicarbonate, sulphate etc." Details of the operating principles and fundamentals of the EAF technology can be found in Cho et al. [23], Fan et al. [24] and Fan [25]. More recently an American company developed a high voltage capacitance based technology [26] to control biofouling in industrial heat exchangers. The authors reported a partial or complete elimination of biocides depending on the conditions of the water. In Japan, a private company developed and patented an electronic anti-biofouling system [27] while in England a non-intrusive cleaning technique was designed to eliminate scaling deposits [28]. The device excites the flow by an electrical signal induced by a magnetic field generated by a ferrite ring wrapped round the pipe. The electromagnetic field generated prevents the build-up of deposits of scale. The technique is potentially useful to control the growth of algae or bacteria in water.

Overall heat transfer is quite sensitive to biofilm formation, compromising heat exchanger performance. This is particular severe in heat exchangers of the cooling system of turbines and generators of hydroelectric power plants. They need to be dismantled for cleaning from time to time. Such an operation requires a plant shutdown, which means 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. They are unable to predict future scenarios. An advanced prognostic approach capable to forecast operating conditions would be highly desirable to manage life cycle of the cooling system.

3. Mitigation of biofouling in electricity generating equipment: the case of Fontes Nova hydroelectric plant

In most hydroelectric plants the cooling of bearings of hydraulic turbines is performed by counter-flow (oil-water) plate heat exchangers. The high heat recovery and heat transfer effectiveness of counter-flow heat exchangers make them preferable to parallel-flow heat exchangers whenever design requirements permit such a choice.

3.1 The hydroelectric complex Light Rio Company

Conceived and built at the beginning of the twentieth century, the hydroelectric complex is one of the oldest in Brazil. As shown in the pictorial view in Figure 1, 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: 35MW, 160 m^3/s and Vigário: 91 MW, 190 m^3/s). These pumping stations raise water from Paraiba do Sul and Piraí rivers to Lajes and Vigário reservoirs. Lajes, the largest of them, stores half billion cubic meters 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.

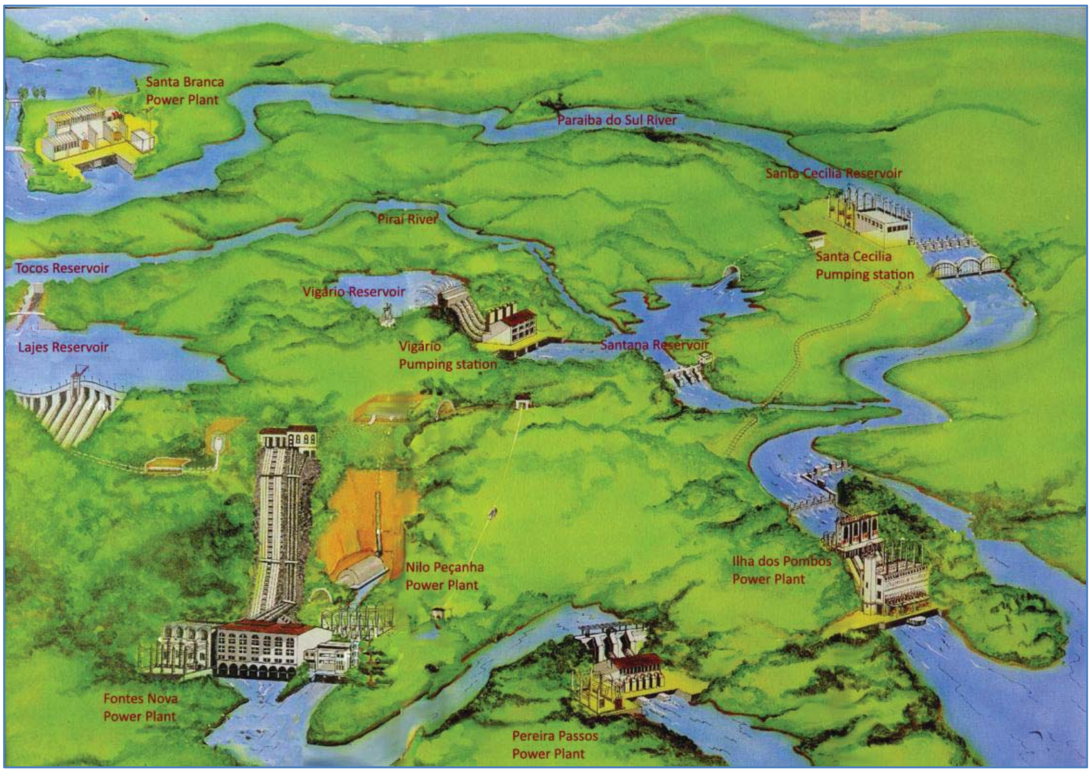

Figure 1. Pictorial view of the hydroelectric complex Light Rio Company.

3.2 The waters of Fontes Nova

Lajes and Vigário reservoirs supply water to Fontes Nova power plant that operates with three vertical axis Francis turbines (44 MW each). A set of three vertical plate counter flow (oil-water) heat exchangers are employed to cool the journal bearings of each turbine.

At first, the water from Vigário was blamed for biofilm formation. Full of debris and sediments, the water acts, in fact, as an abrasive material while in contact with the plates of heat exchangers, and helps to remove scaling deposits. The untainted waters of the Lajes Reservoir —an artificial lake surrounded by stretches of tropical rain forest that assures good water quality— could not be held responsible for biofouling the exchangers. Further tests were carried out to resolve the apparent controversy. Oddly enough, the biological analysis [29] confirmed that water of Lajes was the source of the biofouling indeed.

These waters have been extensively studied [30]. To understand the nature of fouling, chemical and physicochemical (plasma emission spectrometry) methods allowed to identify chemical elements while spectrometry in the infrared, chemical bonding. Biological analysis by optical microscopy detected the presence of microorganisms including filamentous cyanobacteria and bacilarioficeas algae. The living matter is similar to 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 of the Lajes Reservoir [31, 32] based on internationally recognized standard procedures [33] carried out on the vertical column structure of the lake confirmed that the water column dynamics is of fundamental importance to explain the nature of fouling. Despite 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, in the resulting nutrient-rich water of poor quality limnophilous microorganisms managed to survive under condition of anoxia. Recent studies conducted at the University of Sheffield [34] on the mechanism of oxygen sensing by bacteria has showed that they manage to survive in hostile environments by switching on specific genes.

As the waters of the reservoir find their way and passes through the turbine blades of the hydro-generators, they encounter an aerated environment and thrive in huge colonies. The colonizing bacteria, fed by a continuous supply of nutrients from the water flow, quickly adsorb onto the internal surfaces of the exchangers. The biofilm begins to develop.

Chemical and bacteriological analysis of samples of water and scaling deposits directly collected from the inner passages of the heat exchangers revealed the presence of fungi, hyphae while Infrared and plasma emission spectrometry detected the presence of cyanobacteria colonies, chlorophilic algae and amorph among the debris (shown in Figure 2).

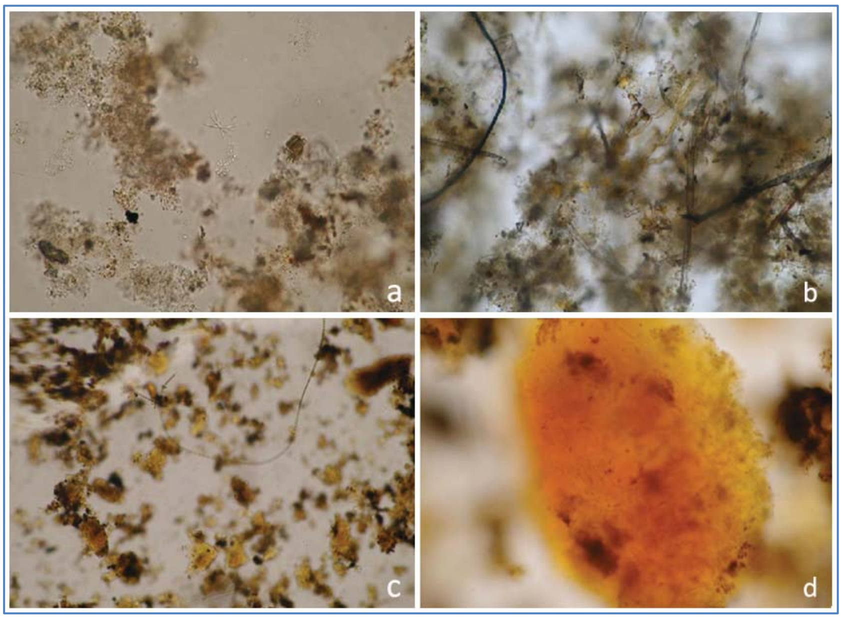

Figure 2. Bacterial water analysis. Fig. 2a General aspect of the collected material with the presence of organic and inorganic flakes and filamentous cianobacteria (200x zoom). Fig. 2.b: Evidence of the presence of microorganisms: fungi hyphae among the debris. Fig. 2c: Cianobacteria colonies, clorophilic algae and amorph debris. Fig. 2d: Details of the biological aggregate that constitutes predominant flakes in the analyzed material (600x zoom).

Figure 3 illustrates a schematic of the counter-flow heat exchanger featuring the flows of hot (oil) and cold (water) fluids and colonies of microorganism adsorbed onto the surfaces of the vertical plates of the heat exchanger forming a biofilm.

Figure 3. Biofouling formation in plate heat exchanger (2-a: overall schematic; 2-b: fouled plates after exposed to the flow).

This uncontrolled growth of microorganisms very fast biofouls the heat exchangers to an undesirable situation compromising fluid flow and heat transfer performance. Biofouling is indeed a serious operating problem where, even parts per million, can trigger the formation of the biofilm. The exchangers may even become totally blocked. Maintenance teams are forced to shut-down the line and dismantle the fouled exchangers, which used to be cleaned by mechanical means.

Figure 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.

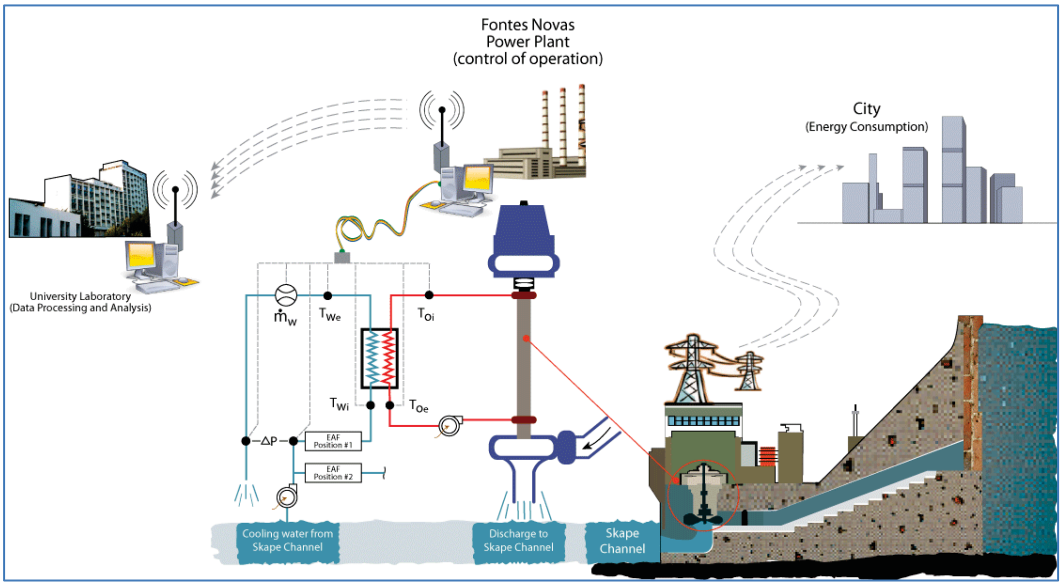

Figure 4 schematic picture of the cooling system of the journal bearings of the turbines and the remote data acquisition/transmitter web-based system. (EAF-1: antifouling device installed in line with the flow; EAF-2: antifouling device not in line with the flow).

In the cooling system of the journal bearings of the turbines, lubricating oil and water enter the opposite ends of the vertical plate heat exchangers and flow in opposite directions. Cooled from 50 ^{o}C to 38 ^{o}C, the lubricating oil returns to the turbines bearings while the water heated from 20^{o}C to 22 ^{o}C is discharged to the river downstream of the plant. The water fulfils heat exchange requirements (abundance, quality and temperature) at virtually no cost but biofouls the heat exchanger. After generating energy and properly treated it becomes the main source of potable water to the city of Rio de Janeiro.

4. Assessment of the antifouling technology

The hydrodynamic and thermal experimental procedures —the two criteria used to assess the cleaning technology— required implementation of real time measurement of mass flow rate, pressure drop and fluid flow properties.

4.1 Experimental set-up

The experimental set-up consists of temperature and differential pressure transmitters and a module for data acquisition (DAQ). A web-based protocol allows real time data (pressure, temperature and flow rate) to be measured locally and transmitted (sampling time of 120 s) to the university laboratory, where they are remotely processed. Experiments were planned to cause the least interference possible in the routine of the power plant.

4.1.1 Real time measuring system

Figure 5 depicts components of the measuring system installed in the heat exchangers: (i) the differential pressure transmitter (Honeywell, model FDW, calibrated in the range 0-25 psid for transmission of electronic signals varying from 4 to 20 mA, accuracy of 0,10%) for measuring mass flow rates; (ii) a plumbing connection, that allows a safe pressurization and depressurization of the transmitter and (iii) measuring stations for temperature and pressure data acquisition. Cooling water and oil temperatures were measured with sheathed PT-100 thermo resistance calibrated (0.2%) against the International ITS-90 Temperature Scale.

Figure 5: The instrumented (vertical plate) heat exchangers and the flow rate measuring system

Mass flow rate is an essential parameter to assess hydrodynamics and heat transfer performance. The use of ASME or ISO standard nozzles [35, 36], installed in line with the flow, is an inexpensive and reliable method for measuring flow rate. Easily installed, they yield accurate results in spite of the undesirable pressure drop that increases pumping costs.

Figure 6 depicts the two phase testing conceived (1) to select the optimum β diameter ratio of the nozzle to be used in the flow measuring system and (2) to quantify the undesirable effect of the fouling formation on the surfaces of the flow measuring device (nozzle).

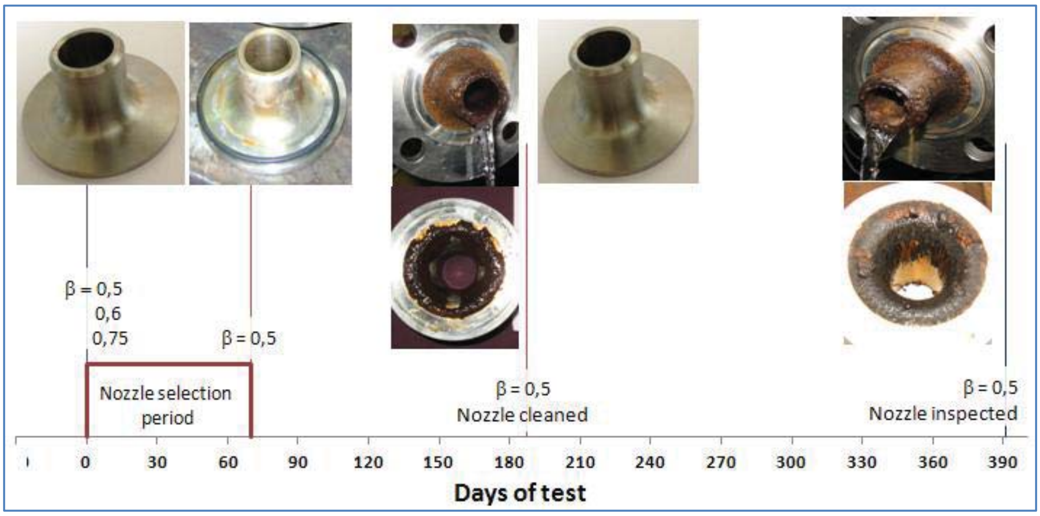

Figure 6: Sensitivity of the flow measuring device to biofouling formation

During a preliminary period, three nozzles (β = 0.50; 0.60 and 0.75), manufactured in compliance with the ASME standard [35], were tested in the cold water circuit against 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 = 0.5 produced the highest amplitude signal within ±10% of the true value of the flow rate and (iii) for the β = 0.5 nozzle reproduced the reference mass flow rate within ±2%. This was the qualification criterion for selecting and validating (against experimental data) the overall flow rate measuring system. The effect of fouling formation inside the nozzle was then investigated for a longer period of time. At day 182, the nozzle was removed and fouling analyzed. The biological analysis revealed the presence of living matter (micro-organisms) attached to its internal walls. 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: nozzle and pressure taps biofouled ($\dot{m}$=2.98 kg/s); pressure taps cleaned ($\dot{m}$=3.00 kg/s) and nozzle and pressure taps cleaned ($\dot{m}$=2.89 kg/s). Inspection of the thick biofilm formed and the physics of the phenomenon explain these results. The unplugging of pressure taps accounts for the 0.7% increase in the response of the pressure transducer signal and the formation of scale at the throat of the nozzle accelerates the flow. An artificial increase in fluid velocity reduces pressure drop across the nozzle leading to 3.7% error in the mass flow rate. Compared to the accuracy of the measuring system operating under normal conditions (±2%.) this may be too high, but it is up to the maintenance team to decide to clean the nozzle earlier if such level of error is not to be tolerated.

4.1.2 The antifouling cleaning device

The cleaning device tested —model S160, Hydropath Technology [28]— was installed in the water circuit of a vertical plate heat exchangers. A succession of radio frequency signals that excites the flow is generated by a step-up transformer. The transformer generates a series of exponentially decaying (amplitude diminishing from a maximum value to zero) sine waves (frequency ranging from 50 to 500 kHz) to mitigate the undesirable effects of limescale, algae, bacteria and flocculating material. The biofilm thus detaches from the surfaces.

4.2 Experimental Procedures

After the measuring system was validated, a new set of experiments were 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 differential pressure) in the absence and presence of the external electric field. A stand-by exchanger (also instrumented) was kept in place should the exchanger in test fail. For each set of experiments, the instrumented exchanger was always cleaned to ensure similar initial operating conditions.

Experiments were repeated for each one of the two positions (EAF-1 and EAF-2 in Figure 4) of the Electronic antifouling device to excite the cold fluid of the heat exchanger: (i) wrapped around the tube installed in line with the fluid flow and (ii) installed in an adjacent circuit in the vicinity of the exchanger. For each position of the antifouling device, experiments were repeated in the presence and absence of the applied electric field. These experiments are discussed in the following two sections.

4.2.1 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 [37]:

$$\Delta P = \left(\frac{2f(L+D_p)PG_c^2}{\rho_m D_e}\right) + 1.4\left(P\frac{{G_p}^2}{2\rho_m}\right) + \rho_m g(L+D_p) \qquad (1)$$

Where:

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

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

While the Darcy–Weisbach phenomenological formula is often used to express the hydrodynamic performance, the pressure drop normalized on the square of the fluid mass flow rate was found to be a convenient criterion [29, 30] to evaluate performance degradation of heat exchangers. The resulting ratio somehow describes the increase of the biofilm thickness. An experimental parameter was developed based on equation (1), 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,

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

Equation (2) holds for any condition of operation of the heat exchanger. As 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 gets fouled, the ratio $\Delta P/\dot{m}^2$ increases. This is because the inner passages of the exchanger become partially obstruct increasing the pressure drop (ΔP) and decreasing the mass flow rate $(\dot{m})$. Inspection of the right hand side of equation (2) confirms the same trend as the friction factor increases with roughness and the equivalent channel diameter (D_e) decreases with fouling while fluid properties and exchanger geometric parameters remain unchanged. Equation (2) can be directly evaluated from experimental data of ΔP and $\dot{m}$. This is a more convenient evaluation of the ratio $\Delta P/\dot{m}^2$ as f and D_e are not straightforwardly measured from the experimental point of view requiring *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".

4.2.2 Thermal criterion

For a compact counter flow heat exchanger Kays and London [1] shows that the heat transfer effectiveness ε compares the actual heat transfer rate to the thermodynamically limited, maximum possible heat transfer rate, as it would be realized only in a counter-flow heat exchanger of infinite heat transfer area.

$$\varepsilon = \frac{q}{q_{max}} = \frac{Co\ (Toi-Toe)}{Cmin\ (Toi-Twi)} = \frac{Cw\ (Twe-Twi)}{Cmin\ (Toi-Twi)} \qquad (3)$$

For the current situation where C_{min} —the smaller heat capacity rate of the two magnitude of C_w and C_o— corresponds to C_o then the exchanger heat transfer effectiveness ε can be calculated by Equation (4):

$$\varepsilon = \frac{T_{oi}-T_{oe}}{T_{oi}-T_{wi}} \qquad (4)$$

Because temperatures of the lubricating oil (T_o) and of 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.

5. Results and discussion

Key findings of the assessment of the non-intrusive antifouling device are discussed. Compatible conclusions were achieved for both base line criteria considered; i.e.: the hydrodynamic and thermal performance of the exchanger.

Figure 7 summarizes experiments associated with the hydrodynamic approach where values of the ratio $\Delta P/\dot{m}^2$ are calculated from experimental data acquired during two sixty-day testing cycles (antifouling device switched off and switched on). Data displayed are normalized on the correspondent unfouled (clean) value of the ratio. The open data symbols denote unexcited flow (antifouling device switched off); full triangles (▲) symbols denote data taken with the antifouling device in position 1 (EAF-1) and full squares (■) with the device in position 2 (EAF-2) as shown in Figure 4. As can be seen, fouling grows faster (open symbols) when the antifouling device is off, deviating from the unfouled condition. Differently from what is usually said by manufacturers and sales representatives, the position of the antifouling device does affect its cleaning performance. Better results are always obtained when installed in line with the flow.

In analogy to an electric circuit, $\Delta P/\dot{m}^2$ can be seen 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. After sixty days of operation, the *biofouling resistance* reaches 6,6 times the value that it would have if the antifouling device were activated. When installed in line with the flow, the effect is 3.7 times better than it would be without it. When not in line with the flow, the effect is not as good as (just 2.6 times).

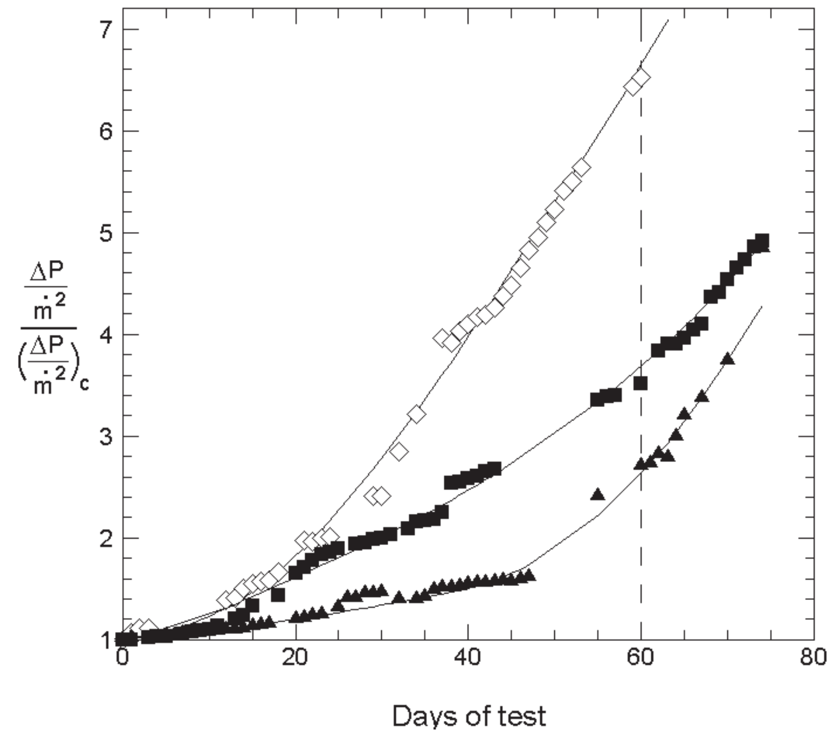

Figure 7. Hydrodynamic criterion for assessing the antifouling device. Open symbols denote data with the antifouling device switched off; ▲ denote data with the antifouling device installed in line with the flow (EAF-1) and ■ data with the device not in line with the flow (EAF-2).

Figure 8 illustrates the evolution of the heat transfer effectiveness ε taken as the key parameter to assess the performance of the exchanger. This is the basis of the thermal criterion. The effectiveness ε, calculated from experimental data during the testings, exhibited the same trend observed for the hydrodynamic criterion. Data displayed in the figure are normalized on the correspondent unfouled (clean) value of the heat transfer effectiveness. Legends are the same, open data symbols denote unexcited flow; full triangles, the calculated effectiveness when the flow was excited by the antifouling device installed in line with the cooling flow; and full squares when the antifouling device was intentionally not in line with the flow. The positioning of the antifouling device requires know-how to be installed and proved to impact on its cleaning performance.

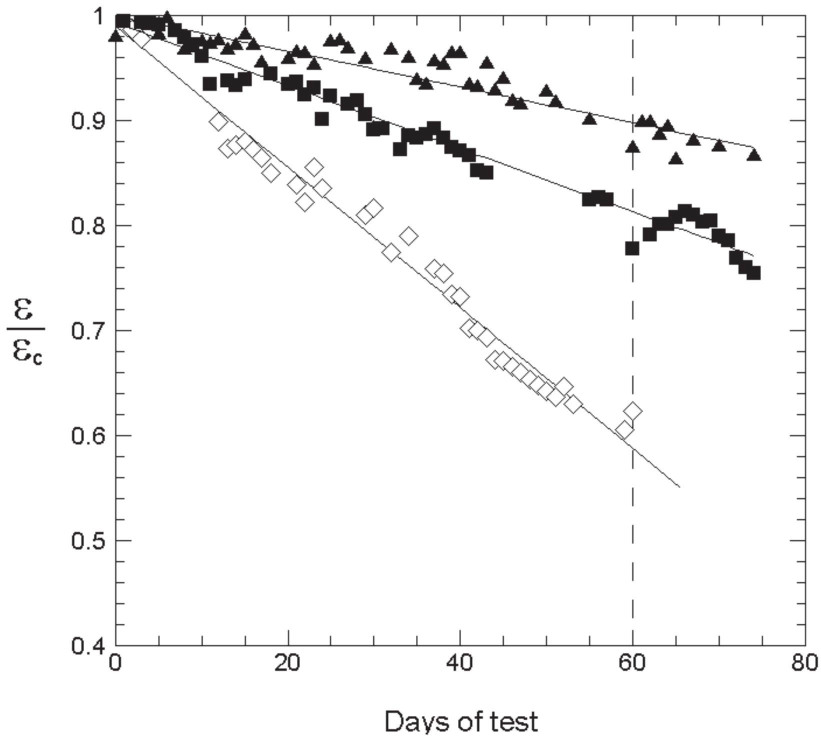

Figure 8. Thermal criterion for assessing the antifouling device. Open symbols denote data with the antifouling device switched off; ▲ denote data with the antifouling device installed in line with the flow (EAF-1) and ■ data with the device not in line with the flow (EAF-2).

If the cooling flow is not exposed to the effect of the antifouling device, the heat transfer normalized effectiveness $\varepsilon/\varepsilon_c$ degrades fast; its unfouled value drops from 1.0 to 0.6, after 60 days of operation. Similar experiments repeated for the two positions of the antifouling device showed much smaller degradation in effectiveness: from 1.0 to 0.9, when installed in-line with the flow and from 1.0 to 0.82, when installed not in line with flow.

Tests performed in accordance with both hydrodynamic and thermal criteria confirmed that, the antifouling device tested was capable to reduce the effect of the undesirable incrustation. Ultimately, the benefit is a reduction in pressure drop across the exchanger and a gain in overall heat transfer performance that avoids costly interruption in operation for cleaning.

6. Conclusions

Experimental data confirmed that the antifouling technology tested mitigates biofouling but not eradicate it completely; not a panacea as advertised by sales representatives. Specific to the local environment, results should not be generalized beyond the peculiarities of the 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.

The hydrodynamic and thermal criteria have proven to be a useful approach to assess the technology. Both yield consistent results.

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 systems of the hydro-generator. The highly complex phenomenon of biofouling needs to be fully understood before the ultimate cleaning technique is devised to remove the biofoulant entirely in a most successful manner.

Privatization of electricity utilities and market regulation —drivers for intense competition and incentives for higher operating efficiencies— has led power plants to operate more efficiently with emphasis on environmental protection. The nature of hydroelectricity production calls for a monitoring programme of heat exchangers. Scheduled maintenance for cleaning should counterbalance overall system performance and hopefully reduce operational costs, a major concern in the highly competitive electricity market.

Acknowledgements

The authors are grateful to Light Energia S.A. (a private electricity utility operating in the state of Rio de Janeiro) and the Brazilian Electricity Regulatory Agency (Aneel) for the financial support granted under its governmental regulated R&D Programme. The authors are also indebted to faculty members and technicians of the Liminology Laboratory of the Biosciences Institute of the Universidade Federal do Estado do Rio de Janeiro (UniRio) for carrying out chemical and biological analyses of the waters collected from Lajes Reservoir the period of development of the R&D project.

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