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Implementation of a Nickel-Electroless Coating in Heat Exchanger Pipes Considering the Problem of the Environmental Conditions of the Cooling Water Without Recirculation to Increase the Effectiveness Under Uncertainty

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Abstract. Hydroelectric power plants use a cooling system with tube heat exchangers for the generators, the cooling water is taken from the rivers, which are contaminated, having a direct consequence in pipes of the exchangers forming oxides, localized corrosion, incrustations, and pitting, reducing the efficiency of the equipment [1], being important to carry out studies to minimize this effect [2]. Various solutions have been proposed working even with more aggressive media such as sea water [3] or permanganic acid [4] and the effect of erosion and corrosion on nickel copper alloy pipes, [5] material commonly used in the exchangers. One solution is the change of material to minimize this effect, without affecting heat transfer. Studies have been carried out to observe this effect before and after being subjected to an oxidation process [7] and with materials that are less susceptible, such as 316L stainless steel [8] or titanium [9], implying a redesign for the loss of heat transfer. Different coatings have been tested for problems such as electroless nickel coating [13], how it influences, its thickness and the solutions to which it can be subjected, even comparing its behavior with stainless steel.

Keywords. Heat exchangers, Corrosion effects, Pattern Recognition and Decision Support System.

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1 Introduction

The generating station of Angostura, in Venustiano Carranza, Chiapas, Mexico, has a hydroelectric plant with five generators of 180MW each. Due to its design, to maintain its operating temperature, an air recirculation system is used, in which cold air circulates through the poles of the rotor and the winding of the stator, then the hot air is extracted and made pass through tube heat exchangers (air-water), which are mounted in each of the stator windows to continue its cooling cycle.

Each generator has 24 heat exchangers, which perform the cooling of the air through the circulation water that passes through the pipe, in a crossflow system where the working fluids do not mix. The water from the cooling system is taken from the Grijalva riverbed, it passes through the equipment and is poured back into it, not having a water recirculation [14], Fig. 1.

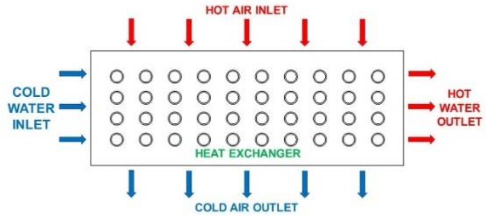


Fig. 1. Diagram of operation of the heat exchanger

The exchanger is composed of 90/10 cupro-nickel alloy tubes and A-36 steel structure. The water used in the cooling system is highly contaminated mainly by hydrogen sulfide, causing the heat exchangers and the mate-rials that make it up to be susceptible to erosion, incrustations, and localized corrosion Fig. 2, having an in-crease in the temperature of the generator damaging the winding thereof.

Fig. 2. Exchanger mirror with the presence of corrosion and incrustations

1.1 Bat Algorithm

Bats are fascinating animals and their advanced capability of echolocation have attracted attention of re-searchers from different fields. Echolocation works as a type of sonar: bats, mainly micro-bats, emit a loud and short pulse of sound, wait it hits into an object and, after a fraction of time, the echo returns to their ears. Based on the behavior of the bats, Yang has developed a new and interesting meta-heuristic optimization technique called Bat Algorithm. Such technique has been developed to behave as a band of bats tracking prey/foods using their capability of echolocation. To model this algorithm, Yang has idealized some rules, as follows:

1) All bats use echolocation to sense distance.

2) A bat bi fly randomly with velocity vi at position xi with a fixed frequency $f$min, varying wavelength λ and loudness A0 to search for prey. They can automatically adjust the wavelength (or frequency) of their emit-ted pulses and adjust the rate of pulse emission $r \in [0, 1]$, depending on the proximity of their target.

3) Yang assume that the loudness varies from a large (positive) $A0$ to a minimum constant value $Amin$. Algorithm 1 presents the Bat Algorithm (adapted from):

Objective function $f(x)$, $x = (x1, ..., xn)$.

Initialize the bat population xi and vi, $i = 1, 2, ..., m$.

Define pulse frequency fi at xi, $\forall i = 1, 2, . . . , m$.

Initialize pulse rates ri and the loudness Ai, $i = 1, 2, . . , m$.

1. While $t < T$

2. For each bat bi, do

3. Generate new solutions through Equations,

4. (2) and (3).

5. If $rand > ri$, then

6. Select a solution among the best solutions.

7. Generate a local solution around the

8. best solution.

9. If $rand < Ai$ and $f(xi) < f(\hat{x})$, then

10. Accept the new solutions.

11. Increase ri and reduce Ai.

12. Rank the bats and find the current *best* $\hat{x}$.

Firstly, the initial position xi, velocity vi and frequency fi are initialized for each bat bi. For each time step t, being T the maximum number of iterations, the movement of the virtual bats is given by updating their velocity and position using equations:

$$fi = f\min + (f\min - f\max)\beta, \quad \textbf{(1)}$$

$$vji\,(t) = vji\,(t-1) + [\hat{x}j - xji\,(t-1)]fi \quad \textbf{(2)}$$

$$xji\,(t) = xji\,(t-1) + vji\,(t) \quad \textbf{(3)}$$

where β is a randomly generated number within the interval [0, 1]. Recall that $xji\,(t)$ is the value of decision variable j for bat i at time step t. The result of fi (1) is used to control the pace and range of the movement of the bats. The variable $\hat{x}j$ represents the current global best location (solution) for decision variable j, which is achieved comparing all the solutions provided by the m bats. Primarily, one solution is selected among the cur-rent best solutions, and then the random walk is applied to generate a new solution for each bat that accepts the condition in Line 5 of Algorithm 1:

$$xnew = xold + \epsilon A(t) \quad \textbf{(4)}$$

in which $A(t)$ stands for the average loudness of all the bats at time t, and $\epsilon \in [-1, 1]$ attempts to the direction and strength of the random walk. For each iteration of the algorithm, the loudness Ai and the emission pulse rate ri are updated, as follows:

$$Ai(t+1) = \alpha Ai(t) \quad \textbf{(5)}$$

$$ri(t+1) = ri(0)[1 - exp(-\gamma t)] \quad \textbf{(6)}$$

where α and γ are ad-hoc constants. At the first step of the algorithm, the emission rate $ri(0)$ and the loudness $Ai(0)$ are often randomly chosen. Generally, $Ai(0) \in [1, 2]$ and $ri(0) \in [0, 1]$ [2].

2 Characterization of the problem.

2.1 Test tube

The pipes used in the heat exchangers are made of cupro-nickel 70/30 and 90/10, which contain copper (Cu) and nickel (Ni) [15], the nickel is to protect the pipe [16]. The exchanger is composed of 4 rows of 10 tubes each row in aligned form. The use of pipes of different materials for their analysis and observe their behavior is implemented. The copper (Cu) material was used as main pipe for the material used in the industry. The tanks or mirrors of the exchanger are made of a structural steel like 1018 steel pipe [17]. Some solutions that have been proposed are the replacement of pipes with a material that is more resistant to these media, such as alloys of stainless steels, due to the percentage of nickel (Ni) and chromium (Cr) in their composition as they have good corrosion resistance in general [18], good strength (hardness) and weldability but low thermal conductivity. We chose stainless steel 316L pipe [19], (1) copper (Cu), (2) stainless-steel 316L and (3) 1018 steel [20] Fig. 3.

Fig. 3. Test pipelines

2.2 Piping Analysis

The behavior in the beaker was observed and after seven days (168 hrs.). When removing the test tubes were observed. The stainless-steel pipe don´t showed changes, the copper pipe has areas with a little oxidation, but not uniform, and the 1018 steel pipe showed oxidation, but not uniformly. After observing, the tubes that would not be used in the test were given a methanol bath and dried for 15 minutes to remove all traces of moisture. Subsequently, the specimens were weighed again Table 1, and the test tubes Table 2.

Table 1. Weight of test tube

Test tube	Clean (gr)	Rusty (gr)	Difference (gr)
cupper	2.99	2.82	0.17
1018 steel	2.52	0.69	1.83
stainless-steel *316L*	2.62	2.62	0

Table 2. Weight of test tubes

Test Tubes	Clean (gr)	Rusty (gr)	Difference (gr)
cupper	171	171	0
1018 steel	146	141	5
stainless-steel *316L*	220	220	0

With the weight of the specimens and the tubes we could only observe in the steel tube a reduction of 3.5% and in the copper and stainless 316L no change. The corrosion rate of the test pieces was obtained for the different materials and compared with:

- For Copper:

$$^{mm}/_{year} = 87.6\left(\frac{W}{At\rho}\right) = 87.7\left(\frac{0.17g}{(0.3676cm^2)*(168h)*\left(8.96\,^{g}/_{cm^3}\right)}\right) = 0.0269 \quad \textbf{(1)}$$

0.0269 mm / year comparing = Excellent

- For 1018 Steel:

$$^{mm}/_{year} = 87.6\left(\frac{W}{At\rho}\right) = 87.7\left(\frac{1.83g}{(0.3676cm^2)*(168h)*\left(7.87\,^{g}/_{cm^3}\right)}\right) = 0.3299 \quad \textbf{(2)}$$

0.3299 mm / year comparing = Good

- For Stainless Steel 316L:

$$^{mm}/_{año} = 87.6\left(\frac{W}{At\rho}\right) = 87.7\left(\frac{0.0g}{(0.4009cm^2)*(168h)*\left(8.0\,^{g}/_{cm^3}\right)}\right) = 0.0 \quad \textbf{(3)}$$

0.0 mm / year comparing = None

2.3 2nd Oxidation in the Test Pipe

In the hydroelectric plant use the river water for the cooling of the heat exchangers, but unfortunately, the water contains polluting residues mainly hydrogen sulfide (H_2S), damaging the pipeline and the tanks. Under normal conditions, hydrogen sulfide is a flammable colorless gas, it is characterized by having a repulsive odor, like rotten egg, although it can be smelled at low levels. Care must be taken because it is considered a broad-spectrum poison. The characteristic that most affects us is that it is corrosive to all metals in the electrochemical series.

2.4 Test Tube with Coating

The use of an electroless nickel coating is proposed for your corrosion resistance, it has the lowest corrosion factor in alkaline environments. It contains a surface hardness of up to 500-650 Vickers (44 to 62 °Rockwell C), protecting it against wear. These characteristics makes it an ideal coating for the problem. The test pipes to be coated is copper and 1018 steel, which are the main materials used in the exchanger for industrial use prone to oxidation Fig. 4.

Fig. 4. Copper and 1018 steel tube with coating

3 Proposal Methodology
3.1 Acquisition of Temperatures

With the work fluids ready, we use T-thermocouples (copper-constantan) to temperature measures. To know the temperatures of the hot fluid (air), a thermocouple was placed at the fan outlet, as a reference to which air enters the duct. Three thermocouples were placed passing the electrical resistances, in a distributed way to the height and width, to know the average temperature reached at the desired operating temperature and on which the pipe is affected. Seven thermocouples were placed at the exit of the exchanger, in a distributed way to the height and width, to know the average of the air at the exit and see how much it increases or decreases. To know the temperatures of the cooling fluid (water), a thermocouple is placed at the water inlet in the upper tank and at the outlet of the exchanger, and thus to know the received energy. To know the temperature of the pipeline, six pipes distributed in the exchanger were chosen to monitor their behavior, in each of them three thermo-couples were distributed, one in the upper part, in the central one and the lower one.

Using a 32-channel National Instrument data acquisition and with the Labview program as a graphical inter-face, a configuration is made to obtain the voltage differential of each thermocouple and convert it to a temperature in degrees Celsius Fig. 5.

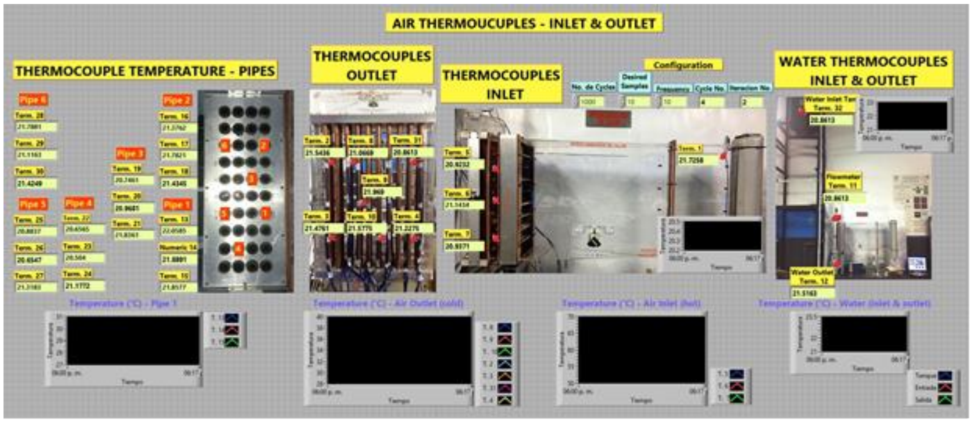


Fig. 5. Configuration of the Labview graphic interface

3.2 Test piping - with nickel-electroless coating

A uniform nickel-electroless (nickel-phosphorus alloy, Ni-P) coating of 5 microns' thickness was applied over the copper and 1018 steel materials, as a viable solution to reduce the problem to the corrosion and avoid deterioration in chemical means. This type of coating was applied because it has a low corrosion factor in alkaline environments compared to high-cost alloys and stainless steel 316L, Fig. 6.

Fig. 6. Copper and 1018 steel pipe with Ni-P coating

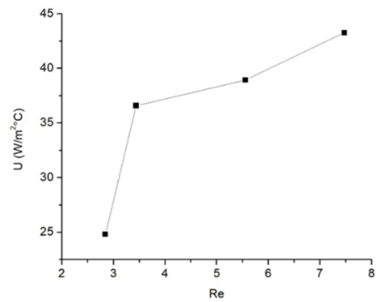
Experimental tests are carried out by varying the nine flows gradually and the behavior is obtained, such as its different temperatures and the volumetric flow in each one of them.

3.3 Multiple Matching

The multiple matching is a series of many evaluations according to different combinations of optimal values associated with the components and a batch of 50 runs under different scenarios. In the evaluation phase thermos mechanical specifications with more similarities will be given a preference, and then these aspects will be selected to compete. Components must be ranked according to their customers' preferences after tournaments end once the final list of multiple matching is evaluated. The hybrid algorithm will be scheduled to set the timing for the comparison of different similarities using a round of multiple matching analyses based in the optimization assigned to a component. Then, components that qualify for selection in a model will be chosen on the following prioritized basis. Given the organization for each component and the matches for each round in the algorithm, components are assigned to state their participation for its evaluation in each of the series. To ensure an active participation in the future, a minimum of twenty-five comparatives are recommended for the four included rating lists and before the main rating list. When a component does not accept to participate into a Multiple Matching series, then the selection process uses the average rating plus number of games played during the rating period. The algorithm repeats this process until reaching the required qualifiers of the Multiple Matching series.

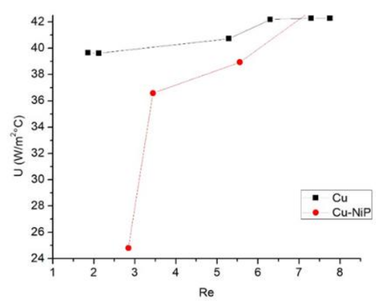
4 Experimentation and Results
4.1 Temperatures

The programming in MATLAB is used to perform the calculations where all the variables obtained for each of the flows and the mentioned equations are integrated to be able to establish their behavior in a general way in a graph represented with the variation of the number of Reynolds vs the Global Heat Transfer Coefficient.
To observe its behavior, the behavior is placed with the coating for the copper pipe, with its linear trend line Graph 1. It is observed that the copper pipe with the coating continues to show an upward normal trend as the water flow increases.



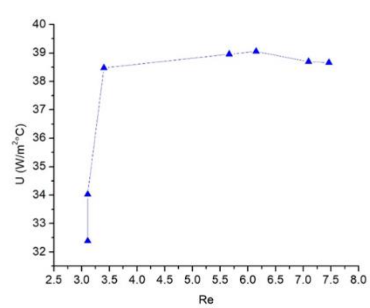
Graph 1. Copper pipe with Ni-P coating

The behavior is observed, and the comparison of the pipe is placed in normal state and with the coating for the copper pipe Graph 2. It is observed that, in both conditions, the same behavior occurs in an ascending manner, the increase in volumetric flow is proportional to the increase in heat transfer.



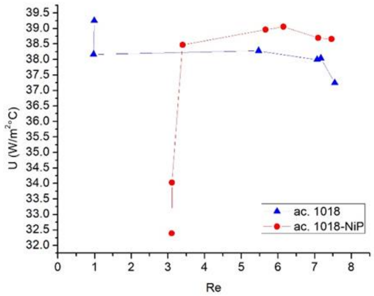
Graph 2. Copper pipe under normal state and with Ni-P coating

Comparing the ideal conditions with the pipe with the coating, we observe that it behaves very similar with a low volumetric flow, but as the flow increases, the transfer increases proportionally in both pipes, but with the coating in a better range with a difference of 2% until almost coincide. To be able to have an analysis in the same way in the part of the tanks and mirrors of the exchangers its behavior is observed, and it is placed with the coating for the pipe 1018 steel Graph 3.



Graph 3. 1018 steel pipe with Ni-P coating

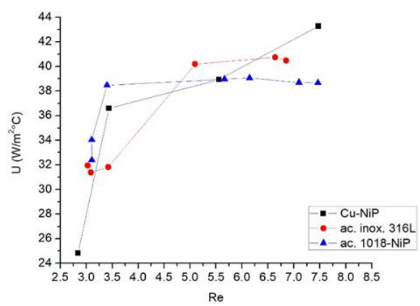
The behavior is observed, and the comparison of the pipe is placed in normal state and with the coating for the pipe 1018 steel Graph 4.
In the 1018 steel tubes had an inverse behavior, since under normal state they have a descending behavior and with the ascending coating due to the increase of the volumetric flow with the heat trans-fer.



Graph 4. Behavior of 1018 pipe steel under nor-mal conditions and with the Ni-P coating

Comparing the ideal conditions with the pipe with the coating, we observe a better behavior but with the coating in a range greater than 4%, noting that said coating helps to protect it from corrosion but does not greatly affect its thermal conductivity. otherwise, it helps, although it is not essentially the use of this material, for being what constitutes the tanks and mirrors of the exchangers has the benefit of the coating for the prevention of corrosion and proliferation of the same.

The number of Reynolds is plotted vs the Global Heat Transfer Coefficient to observe the behavior of the copper with coating against the 1018 steel with coating and the stainless-steel 316L, to have it as a comparison, this material being one of the most used for this problem but implying a high cost for the material and the redesign of the exchanger due to its low thermal conductivity Graph 5.



Graph 5. Copper and 1018 pipe steel with Ni-P coating against stainless-steel 316L

With these pipes we have two different ways to prevent corrosion, and they show the same behavior, the in-crease in volumetric flow is proportional to the increase in heat transfer, only that copper is the only one that works better from medium laminar flows. to high. Stainless-steel is very resistant to corrosion against various chemical agents, but it has low thermal conductivity that is observed in the graph that despite increasing the volumetric flow the heat transfer is a difference of 7% in its highest flow with respect to copper. As we observed previously, although the coated copper presents a lower heat transfer against copper under ideal conditions, even so, it has a greater transfer than that of the stainless-steel 316L and even higher of the 1018 steel.

4.2 Bat Algorithm Multiple Matching Model

To obtain the most efficient arrangement of components, we developed a cluster for storing the data of each of the representative individuals for each component. It consisted in implementing components with our hybrid algorithm, with 500 issues and 200 époques. The stop condition is reached after 50 iterations; this allowed generating the best selection of each component at Model. An optimal value is evaluated using Multiple Matching Model as in. The vector of weights employed for the fitness function is Wi= [0.6,0.7,0.8,0.5,0.6,0.9,0.8,0.7,0.6,0.9], which respectively represents the importance of each component. Then, the hybrid algorithm will select the specific value of each component based on the attribute's similarity. Each attribute is represented by a discrete value from 0 to 7, where 0 means absence and 7 the highest value of the attribute. The experiment design consists of an orthogonal array test with interactions amongst variables com-ponents; these variables are studied within a location range (1 to 400) specific to a coordinates x and y. The orthogonal array is L-N (2**7), in other words, 7 times the N executions. The value of N is defined by the com-bination of the 7 possible values of the variables, also the values in the location range. In Table 3 we list some possible scenarios as the result of combining the values of the attributes. The results permit us to analyze the effect of all the possible combinations of values.

Table 3. The orthogonal array test.

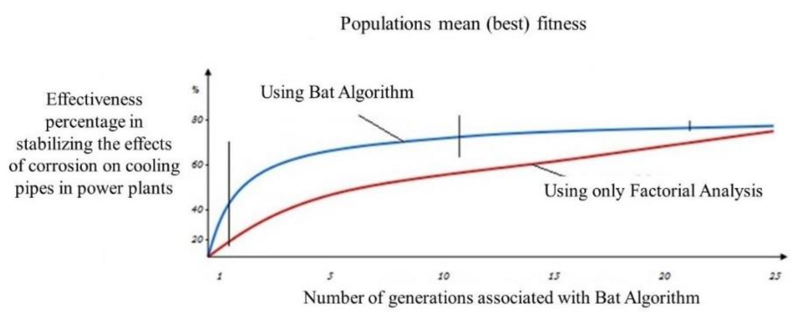
V_1 Air Speed	Te_1 Air Inlet Temp.	Ts_1 Air Outlet Temp.	fv_2 Water Flow	Te_2 Water Inlet Temp.	Ts_2 Water Outlet Temp.	D_{ext} External Diameter	L Pipe Length	N Pipe Numbers	K_{cooper} Conductivity
4	1	2	2	3	5	3	5	2	2
3	1	2	2	3	3	4	4	7	4
2	1	3	2	4	1	2	2	5	5
5	1	3	2	5	4	5	5	4	3

Main effect and Interaction Effect

The effect of a factor is defined as the observed change in the response variable due to a change in level of such factor. In particular, the main effects are changes in the average of the response variable are due to the individual action of each factor. In mathematical terms, the main effect of a factor two difference between the levels is obtained when the factor was in the second level, for example, for the data of Table 3, the main effects mean response are given by:

$$Effect\ A = \frac{41+45}{2} - \frac{28+63}{2} = -2.5 \quad \textbf{(4)}$$

$$Effect\ B = \frac{63+45}{2} - \frac{28+41}{2} = 19.5 \quad \textbf{(5)}$$



Graph 6. Comparison of appropriate bio-inspired tuning our algorithm to properly reduce the effects of corrosion

5 Conclusions

A coating is applied with the help of an external supplier, of nickel-electroless (Ni-P), it has a good adhesion due to its shape application by completely uniform autocatalytic chemical reduction both outside and inside, in addition to presenting greater hardness and resistance to abrasion and wear.

The comparison of the behavior in the test pipes with nickel-phosphorus coating is performed, obtaining a difference in its copper coefficient heat transfer against 1018 steel of the maximum 4.1%. Comparing its coefficient heat transfer of copper under normal operating conditions against coated copper, a difference of 3.7% maximum was obtained, observing that the transfer of heat energy decreases in a small proportion due to the thickness of the coating layer. microns in the material. Comparing its copper coefficient heat transfer with coating against stainless steel 316L, a difference of 5.9% was obtained, observing a greater difference than without the coating, but keeping copper with a heat energy transfer better than stainless steel 316L.

To be able to carry out a good planning and organization of experimental work, techniques such as the design of experiments are used, which turns out to be a useful tool in the characterization and understanding of the processes, but when you want to maximize the results, it can be more complex iterative. Through a metaheuristic-tic optimization with the bat algorithm technique, the experimental work is planned and organized and the behavior generated by the oxidation in the test pipe is observed in more detail, obtaining the appropriate associated values for the reduction of this factor, obtaining that the air velocity, the water inlet temperature and the air outlet temperature have the effect of a change factor in which the variables range from -2.5 to 19.5, where it is denoted that there are noise factors (uncontrollable) considered explicitly or implicitly, that affect our experimentation, on which the combination of levels must be found to the factors that can be controlled and have the least possible noise.

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