Overall heat transfer coefficients, pressure drop and power demand in plate heat exchangers during the ammonia liquor cooling process

Enrique T. Tamayo, Eduardo J. Díaz, María P. Cedeño, Carlos L. Vargas, Segundo G. Peralta, and Manuel A. Falconi

Abstract: In the Ammonia Recovery process of the nickel company the pressure drop of the Ammonia liquor cooling process, by means of the plate heat exchangers, is associated to the incorrect estimate of the overall heat transfer coefficients and fluid parameters: Water and ammonia liquor outlet temperature, Water and ammonia liquor mass flow. The above increases the consumption of water, the available energy in the system and the maintenance costs. The investigation was carried out in plate heat exchangers, with the objective of determining the overall heat transfer coefficients and the behavior of pressure drop and power required for the ammonia liquor cooling process. By means of an iterative procedure was determined the equation and behavior of the overall heat transfer coefficients and their dependence with the Reynolds and Prandtl, for it was used a multifactor experimental design and measurements of the installation work parameters in function of the time. The results predict the knowledge of the overall heat transfer coefficients for the calculation of the Nusselt number with the Reynolds and Prandtl values for both fluids (water and ammonia liquor). The comparison with other investigators shows correspondence with Thonon results. To the overall heat transfer coefficient values less than 2500 W/m^2K, the outlet temperature of the ammonia liquor exceeds 40 ^OC so the maintenance of the installation is recommended in less than 27 days period. The behavior of pressure drop and power demand as a function of the Reynolds number was obtained. Values for cooling the liquor are diminished compared to the water, it is because more water is used.

Keywords*:* Overall heat transfer coefficients, Pressure drop, Plate heat exchanger

I. INTRODUCTION

The heat exchange processes between two fluids that are to different temperatures and separated by a solid wall take place in many applications in the nickel companies. The device that is used to carry out this process is denominated heat exchanger. The ammonia liquor cooling process takes place with the purpose to obtaining good ammonia and carbon dioxide absorption.

E. T. Tamayo is with, Cotopaxi Technical University, Latacunga City, Ecuador Republic (e-mail: enrique.torres@utc.edu.ec).

E. J. Díaz is with Equinoccial Technological University, Santo Domingo de los Tsáchilas City, Ecuador Republic (e-mail: eduardo.diaz@ute.edu.ec).

M. P. Cedeño is with Equinoccial Technological University, Santo Domingo de los Tsáchilas City, Ecuador Republic (e-mail: mariapaulina1980@hotmail.com).

C. L. Vargas is with, Cotopaxi Technical University, Latacunga City, Ecuador Republic (e-mail: cavafer2@hotmail.com).

S. G. Peralta is with Equinoccial Technological University, Santo Domingo de los Tsáchilas City, Ecuador Republic (e-mail: gustavopl1287@yahoo.es)

M. A. Falconi is with Equinoccial Technological University, Santo Domingo de los Tsáchilas City, Ecuador Republic (e-mail: itofalconi@hotmail.com)

The plate heat exchanger consists of a pack of corrugated metal plates with portholes for the passage of the two fluids between which heat transfer will take place. The plate pack is assembled between a fixed frame plate and a movable pressure plate and compressed by tightening bolts. The plates are fitted with a gasket which seals the inter plate channel and directs the fluids into alternate channels. The number of plates is determined by the flow rate, physical properties of the fluids, pressure drop and temperature program. The plate corrugations promote fluid turbulence and support the plates against differential pressure.

The plate heat exchangers are most efficient in comparison with the shell and tube exchangers. They achieve a high efficiency due to the great exchange surface that exists between the two fluids. The contact surface increase due to the circulate of the fluid for very narrow channels, but on the other hand they have an inlays problems and high loss of charge due to the use of ammonia liquor. The investigation was carried out in plate heat exchangers, with the objective of determining the transfer coefficients and the influence of the inlays in the efficiency loss of the installation.

To obtain the heat transfer coefficients and thermal efficiency in the heat exchanger is necessary to take in consideration different concepts related to thermodynamic, fluids dynamic and experimental considerations. These coefficients are obtained between two fluids in terms of the total thermal resistance; it includes convection and conduction resistances for plane or cylindrical surfaces [1]-[4].

The heat transfer coefficients obtained for different applications are exposed in the consulted literature [5]-[8]. The authors summarize the experimental techniques used to obtain the coefficients and their dependence on various dimensionless numbers: Nusselt, Reynolds and Prandtl. In all cases the results are applicable to the specific conditions, under which the experiments were conducted, so under different conditions are necessary experiments to determine the applicability of the results.

There have been many investigations regarding to evaluate the fouling influence on the heat exchanger efficiency. Suarez [9] established two three-dimensional numerical models, one single and another biphasic. He applied the models to the power plant condenser to assess the influence of the fouling accumulation on heat transfer surfaces. The behavior of the main parameters is analyzed and compared to traditional procedure.

Evaluation of fouling in shell and tube heat exchangers without phase change used by Bonals [5] essentially comprises an algorithm or code based on the Bell-Delaware method. From process variables determine homogeneous fouling thicknesses of both currents corresponding to each day of service. By adjusting the exponential asymptotic curve fouling of each stream is obtained. With this information is possible to estimate with greater precision the future behavior of changes in flow rates and temperatures.

In plate heat exchangers is important the work done by Varona [10]. The author analyzes the incrustation influence caused by the deposition of calcium and magnesium salts in loss capacity of a cooler must exchanger. The author makes a comparative analysis of fouling resistance of the equipment before and after cleaning and its impact on the cost of beer production.

Several research works developed in order to obtain mathematical models for the analysis of heat exchange processes [11]-[14]. They apply numerical methods for determining the basic parameters and make predictions of energy losses in the heat exchangers, and develop the finite difference method of irregular meshes with partial analytical solutions to predict the flow behavior using boundary conditions [15]-[18].

Pressure drop is defined as the difference in pressure between two points of a fluid carrying network. Pressure drop occurs when frictional forces, caused by the resistance to flow, act on a fluid as it flows through the tube. The main determinants of resistance to fluid flow are fluid velocity through the pipe and fluid viscosity. Pressure drop increases proportional to the frictional shear forces within the piping network. A piping network containing a high relative roughness rating as well as many pipe fittings and joints, tube convergence, divergence, turns, surface roughness and other physical properties will affect the pressure drop. High flow velocities and / or high fluid viscosities result in a larger pressure drop across a section of pipe or a valve or elbow. Low velocity will result in lower or no pressure drop. In this paper it is assumed that the pressure drop allowed is equal to the friction loss. Empirical correlations have been developed for the pressure drop factor as functions of the Reynolds number [19].

The analysis of previous work demonstrates the need for experimental results in estimating the overall heat transfer coefficients and pressure drop in heat exchangers, the mistakes made in the selection and evaluation are reduced and predict the dependence of the coefficients with dimensionless numbers: Nusselt, Reynolds and Prandtl.

Works consulted agree on the need to predict the behavior of pressure drop, power demand and continuous evaluation of the heat exchangers by using measurements of the fundamental parameters involved in the process of heat exchange. The power demand increase with the Reynolds number in plate heat exchangers for the cooling water and ammonia liquor.

The objective of the article is to determine the overall heat transfer coefficients, pressure drop and power demand in plate heat exchangers during the ammonia liquor cooling process.

II. METHOD DEVELOPMENT

Heat transfer coefficients

Determining the overall heat transfer coefficient in a heat exchange installation depends on several factors, the most significant are the following

- Convection heat transfer Coefficient.
- Conduction heat transfer coefficient
- Resistance inlay

Main parameters and fluid properties (temperature, pressure, velocity, viscosity, density and Prandtl number)

By using the convection heat transfer coefficients for both fluids and knowledge of fouling resistance, the overall heat transfer coefficient is obtained by the following expression [8]:

$$\frac{1}{U \cdot A} = \frac{1}{h_l \cdot A} + R_{cond} + \frac{1}{h_a \cdot A} + R_l + R_a \qquad (1)$$

The value of the global coefficient (U) depends on the convection heat transfer coefficients of hot and cold fluids (h_l, h_a) and is strongly influenced by the shape of the plates corrugations. Fouling resistances (R_l, R_a) are generated as a result of the fluid can carry contaminants, and over time these are deposited on the surfaces. Therefore a layer between the fluid and the surface grows thick and generates an additional thermal resistance with significant value for calculating the overall heat transfer coefficient.

Because the plates are constructed of stainless steel (AISI 316) whose thermal conductivity is 13.4 W / mK, for plate thickness of 0,4 mm, conduction resistance is [9]

$$R_{cond} = \frac{e}{k_m \cdot A} = \frac{4}{134000 \cdot A} \qquad (2)$$

The values of c and n are coefficients depending on the flow type and are obtained experimentally. The characteristic length of the channel, also called hydraulic diameter is calculated from the channel geometry

$$L_c = \frac{4 \cdot S_c}{P_c} = \frac{4 \cdot b \cdot W}{2 \cdot (b + W)} \qquad (3)$$

Because the distance between plates (b) is less than the plate width (W) the above equation can be expressed as follows

$$L_c \cong \frac{4 \cdot b \cdot W}{2 \cdot W} = 2 \cdot b \qquad (4)$$

The Reynolds number relates the inertial forces and viscous forces, its expression is

$$\mathrm{Re} = \frac{V \cdot L_c \cdot \rho}{\mu} \qquad (5)$$

The Prandtl number relates the viscose diffusivity and thermal diffusivity

$$\mathrm{Pr} = \frac{\mu \cdot C_p}{k} \qquad (6)$$

The Nusselt number, whose physical meaning is the dimensionless temperature gradient on the surface, is determined by the following expression

$$Nu = \frac{h \cdot L_c}{k} \qquad (7)$$

When cleaning is performed in the heat exchanger fouling and conduction resistance are practically negligible compared with both fluids by convection resistance. Conduction resistance and fouling of the plates when cleaning of the heat exchanger is performed, are negligible compared to convection for both fluids. To calculate the convection coefficients is necessary to establish its relationship with dimensionless numbers such as Reynolds, Nusselt, Prandtl. Its general form can be expressed by the following equation [15]-[16].

$$h = \frac{c \cdot \mathrm{Re}^{n} \cdot \mathrm{Pr}^{\frac{1}{3}} \cdot k}{L_c} \quad (8)$$

From equation (1) is obtained:

$$\frac{1}{U} = \frac{L_c}{c_l \cdot k_l \cdot \mathrm{Re}_l^{\,n} \cdot \mathrm{Pr}_l^{\frac{1}{3}}} + \frac{L_c}{c_a \cdot k_a \cdot \mathrm{Re}_a^{\,n} \cdot \mathrm{Pr}_a^{\frac{1}{3}}} \quad (9)$$

Multiplying both sides of the equation by the term

$$\mathrm{Re}_l^{\,n} \cdot \mathrm{Pr}_l^{\frac{1}{3}} \cdot \frac{k_l}{L_c}$$

Is obtained the following equation

$$\frac{1}{U} \cdot \frac{k_l}{L_c} \cdot \mathrm{Re}_l^{\,n} \cdot \mathrm{Pr}_l^{\frac{1}{3}} = \frac{1}{c_l} + \frac{1}{c_a} \cdot \left(\frac{k_l \cdot \mathrm{Re}_l^{\,n} \cdot \mathrm{Pr}_l^{\frac{1}{3}}}{k_a \cdot \mathrm{Re}_a^{\,n} \cdot \mathrm{Pr}_a^{\frac{1}{3}}} \right) \quad (10)$$

To calculate the value of the coefficients a, c_l, c_a applied to a procedure from which the experimental results converge, there is provided the same dependence of the Nusselt number with Reynolds for both sides of heat exchanger because has the same geometry. However different coefficients to absorb the differential effect of fouling are taken. The coefficients C_l and C_a are obtained assuming an initial value of the exponent n because equation (10) has the form of straight line equation.
Using the logarithms properties the values convergence is obtained by a new equation, after some transformation to the expression (1) is obtained:

$$Ln\left[\frac{1}{\left(\frac{1}{U} - \frac{L_c}{c_a \cdot \mathrm{Re}_a^{\,n} \cdot \mathrm{Pr}_a^{\frac{1}{3}} \cdot k_a} \right) \cdot \frac{k_l \cdot \mathrm{Pr}_l^{\frac{1}{3}}}{L_c}} \right] = Ln(c_l) + n \cdot Ln(\mathrm{Re}_l) \quad (11)$$

This new expression has the form of the line equation. The values obtained in the expression (4), are introduced into the equation (5) so that a new value of "n" is obtained. Using an iterative process may convergence calculation method.

Efficiency of the plate heat exchangers according to fouling
The influence of deposits in the heat exchangers efficiency loss is determined by the overall heat transfer coefficient based on the input and output parameters [9, 16].

$$U = \frac{m_l \cdot C_{pl} \cdot (T_{el} - T_{sl})}{A \cdot \left[\frac{(T_{el} - T_{sa}) - (T_{sl} - T_{ea})}{\ln\left(\frac{T_{el} - T_{sa}}{T_{sl} - T_{ea}} \right)} \right]} \quad (12)$$

The fouling factor (R_d) is obtained by comparing the value of the global heat transfer coefficient obtained experimentally when the equipment is clean, with experimental values of equation (6) versus time [16].

$$R_d = \frac{U_{máx} - U}{U_{máx} \cdot U} \quad (13)$$

Efficiency in heat exchangers is typically defined a comparison between the real and ideal best performances.

$$\eta = \left(\frac{T_{el} - T_{sl}}{T_{el} - T_{ea}} \right) \cdot 100 \quad (14)$$

Pressure drop and Power demand in the heat exchanger
In the mechanical design of any plate heat exchanger, the pressure drop is critical because it determines the power and energy consumption in the pump motors that drive fluid and therefore influences the investment, operating cost and the maintenance of the pumping system.
The expression to calculate this component is

$$\Delta P = \frac{f \cdot m^2 \cdot L}{b \cdot \rho \cdot A^2} \quad (15)$$

The friction factor can be calculated from tables or the Shah and Focke equation, having the form

$$f = C \cdot \mathrm{Re}^{m} \quad (16)$$

The values of the coefficients C and m depend on the Reynolds number and is chosen from the literature (18). From the definition, ΔP and f increase when the characteristic length decrease. The pressure drop increase when the distance between the plates decrease.
Power demand needed for fluid movement through the plate heat exchanger is obtained from the pressure loss inside the heat exchangers.

$$N = \frac{\Delta P \cdot m}{1000 \cdot \rho} \quad (17)$$

Experimental technique
Experiments to determine the heat transfer coefficients were made by fixing three variables: The outlet temperature of the water, the water mass flow and the mass flow of liquor. The levels of each variable were obtained from the parameters of the ammonia liquor cooling process. The plate heat exchanger used in the experiment is installed in the productive process itself, it possible to ensure the geometric similarity. The heat exchange area is 589 m^2 and the plates used are of Chevron type.

Table 1 Selected experimental design matrix

Number of experiments	Water outlet temperature (^oC)	Water mass flow (kg/s)	Liquor mass flow (kg/s)
375	40	320	220
	42	325	225
	44	330	230
	46	335	235
	48	340	240

The number of experimental runs is obtained by a multifactorial design, according to levels of the variables has a number of 125; but in order to check the validity of the experiments and reduce errors of observation, at all levels 3 replicates are carried out, which concluded with a total of 375 experimental runs. In table 1 summarizes the experimental design is shown.

The influence of deposits in the loss of efficiency of plate heat exchangers for ammonia liquor cooling process was determined by five experimental runs a duration of 30 days each. Before each experiment are made the system cleanliness through disarmament and the use of appropriate chemicals products. The plates should be washed with soap and water and a brush.

In case of slight scaling these are removed by washing the surface with acetic acid. If the fouling is severe concentrated hydrochloric acid (37 %) is used. Finally the plates are rinsed with water, once dried are placed on the mounting stage. It circulates hot water all equipment to remove debris that are still in the pipeline. After all the cleaning process the team is prepared to carry out reliable testing. Measurements of the different parameters were performed by thermocouples and flow meters connected to the input and output devices, both the ammonia liquor and water.

The ammonia liquor is obtained from the absorption of NH_3 and CO_2 gases resulting from distillation and waste liquor. It is a colorless liquid; the average density is 1 g/cm^3 at a temperature of 35 ^{0}C. The chemical composition shown in table 2.

Table 2 Chemical composition of the ammonia liquor

Ni	<0,005 %
NH3	14 %
CO2	7 %
H2O	79 %
Suspended solids	20 ppm

III. RESULTS AND DISCUSSION

The values (equation 4 and 5) are determined by an iterative process using the professional software Mathcad 15. Obtaining coefficients starts by setting a value of "n" in equation (4) and through the "slope" function is obtained the line slope. With the "intercept" function is obtained the origin value. Once the results are known can be determined $c_l \ y \ c_a$. The above coefficients are introduced in the equation (5), the process is repeated until the value of "n" converges. The program ends when the error in estimating the value of "n" is less than 10^{-6}. The values of the coefficients obtained are as follows: n=0,718; $c_a = 0,2983$; $c_l = 0,2817$.

Using equation (4) and the value of the coefficients is possible to determine the overall heat transfer coefficient when working by other fluids with similar characteristics in nickel companies. The correct estimation of the coefficient prevents errors in the design of heating systems and the capacity loss in the heat exchange process. Analysis of the overall coefficient and its dependence on the convection heat transfer coefficients to the water and ammonia liquor is expressed through the Nusselt number and the coefficients: n, c_a, c_l.

Result of the water Nusselt number

$$Nu_a = 0,2983 \cdot \mathrm{Re}_a^{0,718} \mathrm{Pr}_a^{\frac{1}{3}} \quad (9)$$

Result of the ammonia liquor Nusselt number

$$Nu_l = 0,2817 \cdot \mathrm{Re}_l^{0,718} \mathrm{Pr}_l^{\frac{1}{3}} \quad (10)$$

Figure (1) shows the behavior of the Nusselt number as a function of Reynolds for fluids involved in the heat exchange process (ammonia liquor and water). Increased Nusselt values with increasing Reynolds number is observed, it is associated with increased turbulence exchanger favoring heat transfer between two fluids. Nusselt values of water are higher than those obtained with ammonia liquor; this is due to the presence of gaseous components in the liquor (Table 2) to reduce the convection heat transfer coefficient.

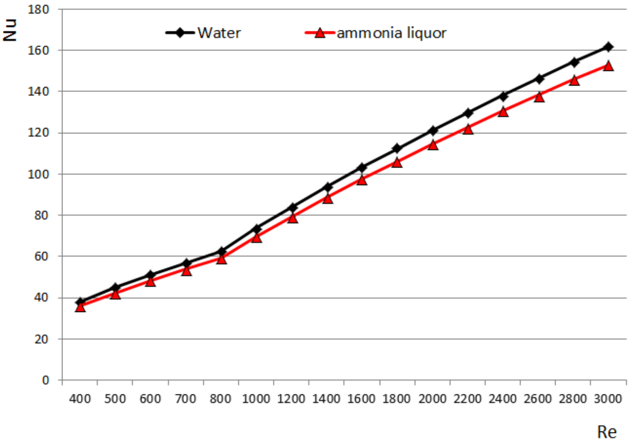

Fig. 1 Behavior of the Nusselt number as a function of Reynolds to water and ammonia liquor

In figure (2) the behavior of the Nusselt number as a function of Reynolds in plate heat exchangers exposed for several investigators and obtained in this paper indicated with the name "Torres" in graphics. The correlation of Thonon presents a similar behavior obtained in this research, but their values are lower. The results obtained by Buonopane and Maslow differ from the values obtained for the ammonia liquor cooling process.

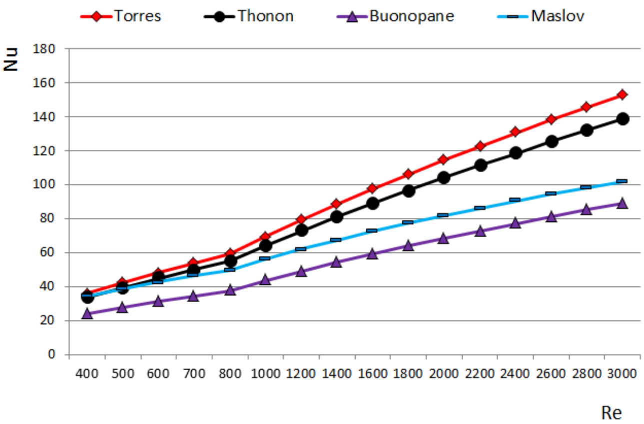

Fig. 2 Behavior of the Nusselt number as a function of Reynolds in plate heat exchangers

Results of the efficiency loss in the installation

The behavior of the fouling factor for each day of service is shown in Figure (3). The values increase achieving results that exceed 0,00025 m^{2}K/W. The fouling factor increases after cleaning, it must be associated with the existence of embedded particles in the plates causing loss of capacity and efficiency of the ammonia liquor cooling process. The results obtained in this research recommend selecting high values of the factor (near 0,0002 m^{2}K/W) to ensure the rational design of the installations.

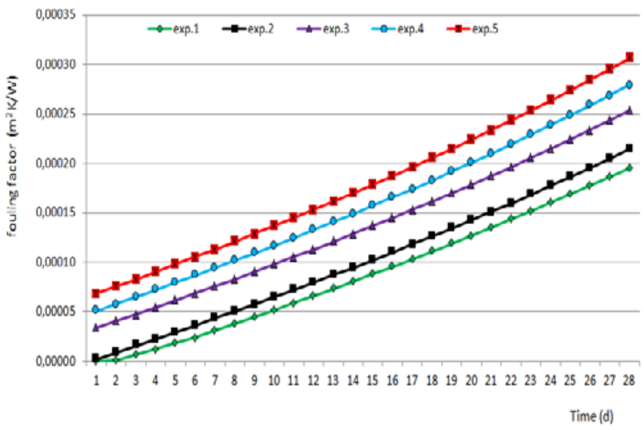

Fig. 3 Behavior of the fouling factor versus time

The behavior of the overall heat transfer coefficient versus time (Figure 4) is obtained from the knowledge of the convection heat transfer coefficients and the fouling factor. The values show decreasing trend with increasing time to the fluids analyzed, results exceeding 6000 W/m^2K when the heat exchanger is free of fouling. The coefficient is reduced when increases the time. To values less than 2500 W/m^2K, the outlet temperature of the ammonia liquor exceeds 40 ^oC so the maintenance of the installation is recommended in less than 27 days period. The above analysis involves using overall heat transfer coefficients close to 4500 W/m^2K which guarantee a safety factor in the design and operation of the equipment.

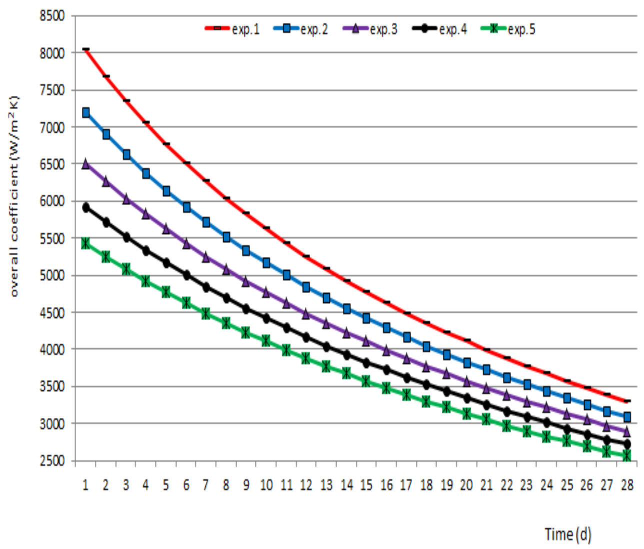

Fig. 4 Behavior overall heat transfer coefficient versus time

In figure (5) is shown the behavior of efficiency versus time. The exponential behavior is obtained from the process variables. With this information it is possible more accurate in efficiency estimating to changes in flow rates and temperatures.

The results show tendencies to reduction in efficiency with increasing time of installation work. Process requirements set maintain outlet temperature of the ammonia liquor below 30 ^oC, this is achieved when the thermal efficiency is over 70 %. The average time for the cleaning of the equipment is 27 days of continuous operation. The results obtained are applicable only for the investigated fluid (ammonia liquor). For other fluids it is necessary to develop experimental research.

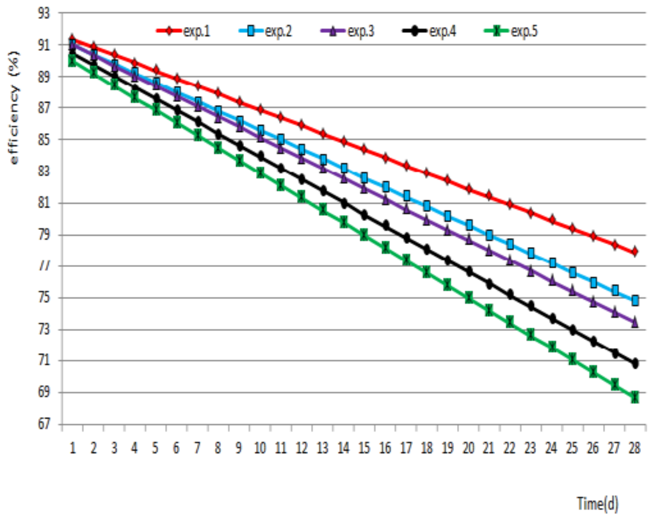

Fig. 5 Behavior of heat exchanger efficiency versus time

Results of the pressure loss and Power demand in the heat exchanger

Figure (6) shows the behavior of pressure drop and power demand as a function of the Reynolds number for the cooling water. Parameters increase with the Reynolds number, it is associated with increased the fluid velocity inside the channels between plates. The maximum values achieved are:

- Pressure drop: 2300 Pa
- Power demand: 450 W

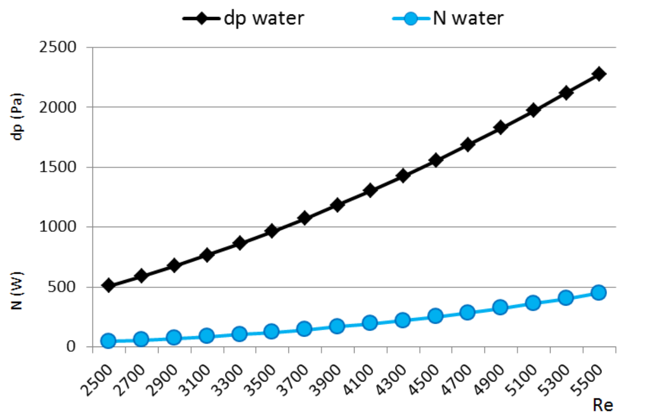

Fig. 6 Behavior of pressure loss and power required for the cooling water

In Figure (7) the behavior of pressure drop and power demand depending on the Reynolds number for the ammonia liquor is shown. Values are diminished compared to the water; it is because more water is used for cooling the liquor, the flow rate (water mass flow / liquor mass flow) is greater than 1.4. The maximum values achieved are:

- Pressure drop: 2000 Pa
- Power demand: 150 W

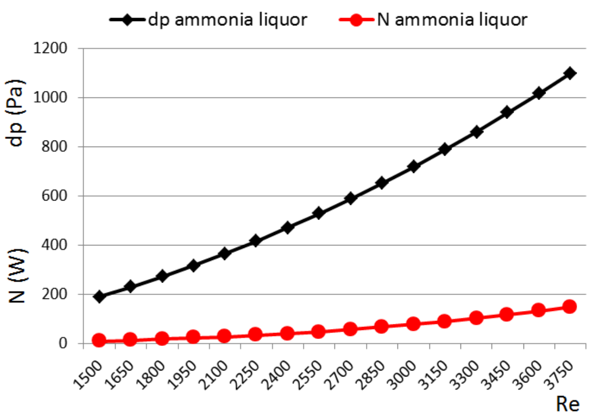

Fig. 7 Behavior of pressure drop and power required for the ammonia liquor

IV. CONCLUSION

The heat transfer coefficients values for fluids involved in the heat exchange process (ammonia liquor and water) are as follows: n=0,718; C_a=0,2983; C_l= 0,2817. They allow the calculation of the Nusselt number and the overall heat transfer coefficient for ammonia liquor cooling process.

The performance of the Nusselt number as a function of Reynolds in plate heat exchangers found in this paper presents a similar behavior of Thonon correlation, but their values are lower. The results obtained by Buonopane and Maslow differ from the values found for the ammonia liquor cooling process.

To the overall heat transfer coefficients values less than 2500 W/m^{2}K, the outlet temperature of the ammonia liquor exceeds 40 ^{o}C so the maintenance of the installation is recommended in less than 27 days period. The above analysis involves using overall heat transfer coefficients close to 4500 W/m^{2}K which guarantee a safety factor in the design and operation of the equipment.

The behavior of pressure loss and power demand as a function of the Reynolds number for the cooling water and ammonia liquor increase with the Reynolds number. Values for cooling the liquor are diminished compared to the water; it is because more water is used. The flow rate is greater than 1.4.

Nomenclature:

U - overall heat transfer coefficient, W/m^{2}K

A - heat transfer area, m^2

h_a, h_l - convection heat transfer coefficient to water an liquor, W/m^{2}K.

R_a, R_l - fouling thermal resistance to water and liquor, m^{2}K/W.

e – plates thickness, mm

k_m, k_a, k_l - plates thermal conductivity, water and liquor, W/m K

Cp_a, Cp_l - heat capacity of water and liquor, J/kg K

$\mathrm{Re}_a, \mathrm{Re}_l$ - Reynolds number for water and liquor

$\mathrm{Pr}_a\ y\ \mathrm{Pr}_l$ - Prandtl number for water and liquor

L_c - channel characteristics length, m

b - plate width, m

T_{ea}, T_{sa} - inlet and outlet water temperature, K

T_{el}, T_{sl} - inlet and outlet liquor temperature, K

m_a, m_l - mass flow of water and liquor, kg/s

N - Power demand in the plate heat exchanger, W

ΔP - pressure loss in the plate heat exchanger, Pa

ρ - density of water and liquor, kg/m^3

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Enrique Torres Tamayo (M'2015). He was born in Cuba, Year 1966, graduate of Mechanical Engineer (1993) and Electromechanical Master (1999) in the Metallurgical Mining Higher Institute of Cuba, Doctor in Technical Sciences (PhD) in the Cuban Sciences Academy (2003).
He worked in Mechanical Engineering Department at Metallurgical Mining Higher Institute of Cuba from 1993 to 2014, currently working in the Electromechanical Engineering Department, Cotopaxi Technical University, Latacunga City, Ecuador. He is expert in termal –fluids, having developed investigations related with heat transfer in industrial processes, transport of two-phase and single-phase fluids; modelling and simulation of thermal processes and transportation of fluids with the employment of finite elements method.