Analysis of pressure influence over heat transfer coefficient on air cooled condenser

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ABSTRACT. *In this work, the Breshnetzov's method is used to elaborate a model that is suitable to predict the pressure influence over heat transfer coefficient in air cooled condenser systems (ACC). Independent variables combination generate two not homogeneous expressions, Allow concluded that in ACC pressure is inversely proportional to heat transfer coefficient in a potency 0.7 and then for each kPa of increment in the back pressure of steam turbine, the heat transfer coefficient decrease an 0.95 %. In 714 execute proofs in the expressions developed validity status with Chato's equation, was verified that the mean deviation is around 3.52% in 92,36 % of execute proofs.*

RÉSUMÉ. *Dans ce travail, la méthode de Breshnetzov est utilisée pour élaborer un modèle approprié pour prédire l'influence de la pression sur le coefficient de transfert de chaleur dans les systèmes à condenseur à refroidissement par air (ACC). Une combinaison de variables indépendantes génère deux expressions non homogènes. En conclusion, la pression dans ACC est inversement proportionnelle au coefficient de transfert de chaleur dans une puissance de 0,7, puis pour chaque kPa d'augmentation de la contre-pression d' une turbine à vapeur, le coefficient de transfert de chaleur diminue de 0,95%. En 714 preuves d'exécution dans les expressions développées statut de validité avec l'équation de Chato, il a été vérifié que l'écart moyen était d'environ 3,52% dans 92,36% des preuves d'exécution.*

KEYWORDS: *breshnetzov's method, heat transfer coefficient, independent variables.*

MOTS-CLÉS: *méthode de breshnetzov, coefficient de transfert de chaleur, variables indépendantes.*

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1. Introduction

It is a generalized criterion currently in most of the available and known literature, to establish that in the operation of the Air Cooled Condenser systems (ACC) the work pressures higher than 30 kPa are inadmissible from the technical economic point of view (Boyko and Kruzhilin, 1967). It was recently stated in (Kim and Mudawar, 2013), that the maximum permissible value of working pressure is of the order of 25 kPa. In practice, it has been proven that the operation of ACC systems at this level of pressures generates considerable decreases in performance and accentuated power losses (Zhang *et al.*, 2015). These limit pressure values are established based on criteria and experiences accumulated in the operation of this type of technology, but in the available and known literature there is no scientific criterion that supports it.

Cuba is not exempt from the global water crisis facing humanity today and the optimal use of this vital resource is necessary. A pillar for such purpose is the use of dry condensation technology, since with its use, 160 m^3/h of water is dispensed as an average for each 50 MW of power generated. However, in this type of installation the pressure of the working agent is a function of the wind speed and the dry bulb temperature, for this reason in many cases these facilities are operated at exhausted steam pressures up to 2.2 times higher to that obtained with its wet equivalent of a pass.

The existing and currently known equations and analysis methods do not allow the direct influence of pressure in the thermal evaluation of dry condensation systems. This limitation is the cause that motivates to the author and his collaborators to deepen in the subject, to determine what would be the most adequate range of operation of pressures and analytically determine the cause of this problem. For this, the starting point is the use of statistical analysis methods that go to the convergence of functions that can be approximated by continuous asymptotes. Of the methods available in the available literature, Breshnetzov was selected, a cross-string method little known in the current literature, but with high precision in the results obtained, especially when it is necessary to correlate several independent variables (Shah, 1979; Tandon *et al.*, 1995).

2. Methods and validation

2.1. Introductory elements of analysis

Recently, the author and his collaborators in an attempt to virtualize the Chato's Equation (Dobson and Chato, 1998), concluded that the heat transfer coefficient presents an accentuated decrease from a pressure equal to 20 kPa, also finding that the coefficient of heat transfer by condensation in the range of pressures $5 \leq P_{Back} < 36 kPa$ it manifests a clear tendency governed by a functional continuous type potential. A similar criterion was raised by the authors and (Lee *et al.*, 2005)

In the analysis carried out, it was found that this complex combination directly intervenes the quality, flow and pressure of the exhausted steam incorporated in the ACC, as well as the equivalent interior diameter of the condensation ducts in the ACC cells. The pressure range studied was fragmented in 5 regions, in which the heat transfer coefficient shows a clear decreasing asymptotic tendency, governed by a straight line with a certain negative slope with respect to the horizontal one (see figure 1). The five regions are located in the following intervals:

Asymptote 1	$5 \le P_{Back} < 9kPa \rightarrow \theta_1 = 49.5^0$
Asymptote 2	$9 \le P_{Back} < 15kPa \rightarrow \theta_1 = 25.1^0$
Asymptote 3	$15 \le P_{Back} < 21kPa \rightarrow \theta_1 = 15.9^0$
Asymptote 4	$21 \le P_{Back} < 30kPa \rightarrow \theta_1 = 11.5^0$
Asymptote 5	$30 \le P_{Back} < 36kPa \rightarrow \theta_1 = 6.3^0$

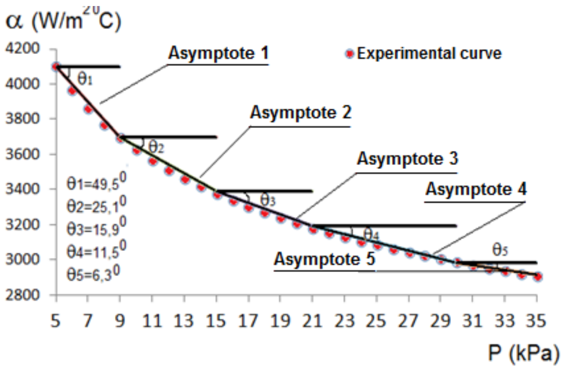

Figure 1. Asymptotic trend and inclination angle of the coefficient of heat transfer by condensation as a function of pressure

In all cases the asymptotes are linear and inclined with negative slope. The experimental curve shown in Figure 1 is the one obtained as the best fit to the experimental data that gave rise to it, these being summarized in Table 1. As shown in Figure 1, the heat transfer coefficient decreases with the increase in pressure, however the value of the numerical reduction of its value is unknown. In ACC systems the turbine output pressure is dependent on the dry bulb temperature and the wind speed incident on the installation. This problem was dealt with previously by the main author in, being generated a group of expressions that allow obtaining its numerical value, which are given by the following relations (in kPa):

$$0 \le V < 6.4\, km/h \qquad P_{Back} = 17.464\, Ln(T_{TBS}) - 45.3 \tag{1}$$

$$6.4 \le V < 12.8\, km/h \qquad P_{Back} = 22.045 Ln(T_{TBS}) - 58.2 \tag{2}$$

$$12.8 \le V < 19.2\, km/h \qquad P_{Back} = 22.928\, Ln(T_{TBS}) - 60.4 \tag{3}$$

$19.2 \leq V < 25.6\ km/h$ $$P_{Back} = 22.146\,Ln(T_{TBS}) - 56.85 \quad (4)$$

$25.6 \leq V < 32.0\ km/h$ $$P_{Back} = 21.794\,Ln(T_{TBS}) - 55.15 \quad (5)$$

$V \geq 32.0\ km/h$ $$P_{Back} = 22.708\,Ln(T_{TBS}) - 57.05 \quad (6)$$

2.2. Application of the Breshnetzov method

Once the exhausted steam pressure is known, it is also required to have the flow rate, the steam quality at the entrance of the ACC and the equivalent internal diameter of the tubes of the cells. As the fundamental problem to be studied consists of four independent variables, its correlation in a single expression that is sufficiently precise becomes a complex task, which is why we resort to the method of cross-overlapping variables or the Breshnetzov method (Yan and Lin, 1999; Rifert and Sereda, 2015).

In this method, we take at random from the group of independent variables, one of them, which is correlated with the dependent variable, being considered constant the rest of the independent variables, later cross-linking to establish the level of participation of the remaining variables independent in a fixed amount that is preset from the first generated correlation.

Here the dependent variable is the average coefficient of heat transfer, while the independent variables are:

1- Vapor pressure in the turbine exit, (kPa)

2- Vapor quality in the turbine outlet. (0-1)

3- vapor flow rate (kg/s)

4- Equivalent internal diameter of the condenser ducts. Summary of the experimental quantities used.

As established by the Breshnetzov method, the primary condition is established, here the vapor pressure is taken for this purpose (although any independent variable can be taken) and a correlative adjustment is established between the dependent variable and the first independent variable considered, while the rest of the variables are arbitrarily set their values (here they are taken as pre-established d=0.025m, m_{vapor}=1kg/s and x=0.9).

The correlation established between the pressure and the average coefficient of heat transfer is given in Figure 2. Therefore, it is possible to establish a potential dependence between the heat transfer coefficient and the condensation vapor pressure. The obtained relationship responds to the following expression:

$$\alpha = 4061.3 \cdot \left(1 - 0{,}003(P_{back} - 5)^{0.7}\right) \quad (7)$$

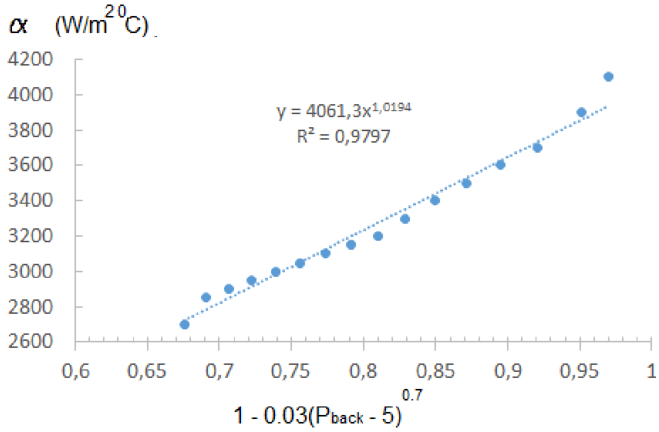

Figure 2. Correlation between the average coefficient of heat transfer and the turbine output pressure

In the expression (7) there is a constant 4061.3 in the numerator, which will be coincident with an unknown relation that includes the effect of the three remaining independent variables.

In the second step, the cross-relation between the remaining variables minus one is established, and since three variables remain, then there are two variables that will be used to establish the cross-relation. The two variables taken here will be the variables flow and steam quality. The established primary function (7) for the correlation was a potential type, so the use of this type of function in the remaining analyzes is mandatory.

In the deduction of Equation (7) the pressure was varied for a predetermined value of the flow and quality of the steam. Now keeping the denominator of Equation (7) fixed, the flow and vapor quality values are changed in jumps, and as in the deduction of Equation (7), a correlation is made between the heat transfer coefficient and the values of pressure, for each new value of flow and quality of the steam, fixed in each iterative jump.

As in each case a new correlation is established, it is required that the numerator values of the new potential relationship obtained in each case be tabulated, and since two independent variables are considered, then n+1 combinations of one variable depending on the second. The steam quality at the turbine outlet for ACC systems varies between 0.88 and 0.99, therefore since it is a small range of values, this variable is selected and the three intervals examined would be 0.88, 0.95 and 0.99, while the flow is varied in a greater spectrum, that is, between 1 to 90 kg/s. For this process, the professional manager Microsoft Excel 2010 is assisted. The results obtained are given in table 2.

Table 1. Summary data for application of the Breshnetzov method

Source	**Number of Data**	**Fluid**	**Diameter (mm)**	**G (kg/m²s)**	**x**
(Rosson, 1967)	31	Water	40.0	24 48	0.96 0.88
(Mollamahmutoglu, 2012)	9	Water	28.2	3	0.97 0.9
(Tang, 2016)	11	Water	47.5	10	0.94 0.9
(Borishankiy *et al.*, 1976)	34	Water	10.0 19.3	12 590	0.92
(Lee *et al.*, 2008)	15	Water	12.0	27 45	0.98 0.95
(Gooykoontz, 1967)	26	Water	7.4	131 264	0.99 0.9
(Pourmahmoud *et al.*, 2016)	19	Water	15.9	22 74	0.99 0.91
(Nasser *et* Duwairi, 1978)	21	Water	30.0	4 69	0.99 0.94
(Annaniev *et al.*, 1961)	63	Water	8.0	38 160	0.99 0.91
(Thome, 2005)	12	Water	11.6	16 140	0.97 0.95
(Ackers *et al.*, 1959)	68	Water	8.0	38 160	0.99 0.91
(Wojtan *et al.*, 2011)	20	Water	49.0	12	0.95 0.89
(Derby *et al.*, 2011)	20	Water	15.9	20 74	0.99 0.9
Total	349		7.4 49.0	3 590	0.99 0.88

Source	**Re_L**	**Re_V**	**P_R**	**Deviation [%]**
(Rosson, 1967)	3427 6854	79438 158870	0.0046	7.7 1.4
(Mollamahmutoglu, 2012)	173	8210	0.0008	12.1 9.7
(Tang, 2016)	2554	32642	0.023	16.2 -6.1
(Borishankiy *et al.*, 1976)	763 58540	8284 333120	0.036 0.308	12.7 -1.3
(Lee *et al.*, 2008)	1183 1944	27421 45071	0.0046	16.9 8.1
(Gooykoontz, 1967)	3827 6567	78853 167186	0.002 0.0062	13.8 2.5
(Pourmahmoud *et al.*, 2016)	660 2300	1320 4560	0.005 0.017	17.6 8.4
(Nasser *et* Duwairi, 1978)	408 7474	9173 252428	0.0046	22.9 -0.3

(Annaniev *et al.*, 1961)	1025 4324	21158 89085	0.031 0.004	25.3 19.4
(Thome, 2005)	692 5934	15686 .134474	0.0046	21.2 12.8
(Ackers *et al.*, 1959)	1025 4324	21158 89085	0.051 0.004	25.3 19.5
(Wojtan *et al.*, 2011)	1808	54415	0.0023	6.2 1.5
(Derby *et al.*, 2011)	660 2800	1320 4960	0.005 0.017	17.4 8.1
Total	660 58540	1320 333120	0.0008 0.031	16.6 7.5

Even with the values of crossed constants obtained from the three required intervals, the correlation generated for each cross-jump can be established in each case. The method used establishes that in cross jumps of variables if a part of the correlation expression is prefixed, in all cases the matching of the preset part is required and mandatory.

Varying the flow rate for three fixed values of steam quality (see table 1.2), establishing as mandatory the use of a potential function as an adjustment curve, (which is required as this is the first correlation function used) and prefixing an amount or fixed value as a function of the changing variable (flow) $(m_{vapor})^{0.8}$ equal to three sets of adjustments are obtained which are given in figures 1.3 to 1.5. As it can be verified, the imposed condition $(m_{vapor})^{0.8}$ is fulfilled in all three cases, finally having three new expressions, which are given by:

$$\text{to } x=0.88 \quad 1136.6(m_{vapor})^{0.8} \tag{8}$$

$$\text{to } x=0.95 \quad 1152(m_{vapor})^{0.8} \tag{9}$$

$$\text{to } x=0.99 \quad 1114.5(m_{vapor})^{0.8} \tag{10}$$

In equations (8) to (10) we now have three constants for ascending values of the independent variable used in the cross analysis, so the first quantity is taken as a unit reference, while the two remaining ones grow or decrease proportionally with respect to the unit amount, that is:

$$to \quad x=0.88 \quad \rightarrow \quad \frac{1136.6}{1136.6}=1 \tag{11}$$

$$to \quad x=0.95 \quad \rightarrow \quad \frac{1152}{1136.6}=1.0135 \tag{12}$$

$$to \quad x=0.99 \quad \rightarrow \quad \frac{1114.5}{1136.6}=0.9805 \tag{13}$$

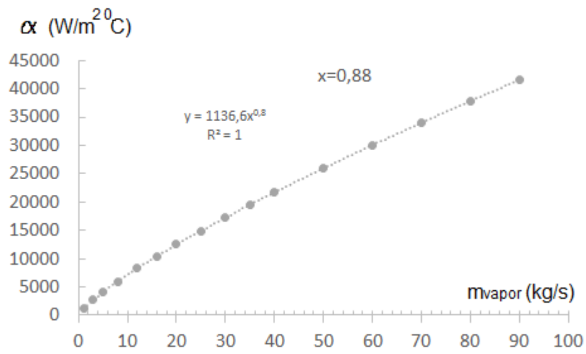

Figure 3. Correlation between the numerator of the Equation (7) and the steam flow rate, for a vapor quality x=0.9

Table 2. Fixed values in the numerator of Equation (7) in the crossed combination of two independent variables

	Steam Quality		
Flow rate (kg/s)	0.88	0.95	0.99
1	1136.8	1151.9	1114.8
3	2736.7	2774.4	2683.8
5	4119.1	4174.9	4037.4
8	5999	6080.8	5881
12	8299.4	8407.6	8135.4
16	10446	10584	10240
20	12487	12653	12241
25	14928	15127	14633
30	17272	17502	16931
35	19539	19799	19154
40	21743	22032	21313
50	25990	26338	25480
60	30074	30473	29478
70	34020	34471	33347
80	37855	38359	37108
90	41596	42150	40773

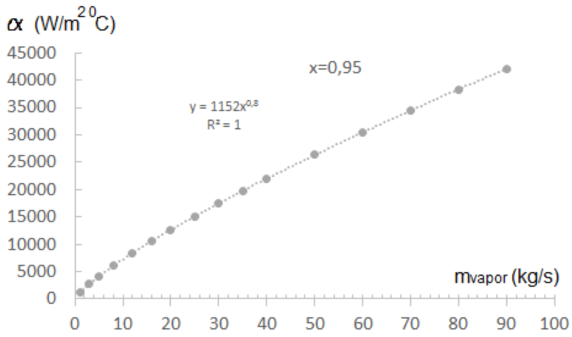

Figure 4. Correlation between the numerator of the Equation (7) and the steam flow rate, for a vapor quality x=0.95

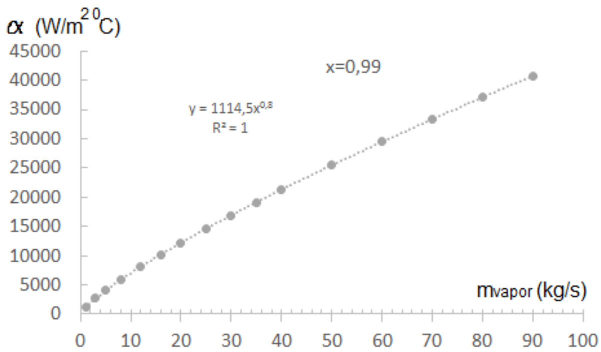

Figure 5. Correlation between the numerator of the Equation (7) and the steam flow rate, for a vapor quality x=0.99

Since two independent variables were used in the cross-analysis, two intervals are required in the forced correlation of the third variable. These intervals are:

Intervals 1. . . . . $0.88 \le x \le 0.95$

Intervals 2. . . . . $0.95 < x \le 0.99$

An important detail, the correlation of the last variable involved in the cross analysis admits any type of functional, as long as it is reducible to the first employee, that is, to a potential equation.

By conveniently combining the constants given in Equations (11) to (13) with the steam qualities that generate it, one has to:

$$\text{For} \quad 0.88 \le x \le 0.95 \quad C_1 = 0.25Ln(x) + 1.026/(W_N)^{0.04} \qquad (14)$$

$$\text{For } 0.95 < x \leq 0.9 \;\; C_1 = -0.8Ln(x) + 0.972 / (W_N)^{0.04} \quad (15)$$

Finally, only one variable remains to be considered, the equivalent diameter. For this variable, a correlation adjustment is also made under the same primary conditions that led to the obtaining of (7), but since the value of the denominator was fixed throughout the analysis, it is now required in the final superposition that the variation of the numerator is analyzed, according to the last variable, prefixing the remaining variables under the initial conditions of the problem analyzed. This is justified by taking into account that the value of the numerator is equal to an arbitrary function that involves the independent variables not considered in the initial analysis. The variation of the equivalent diameter for the fixed conditions of flow and steam quality established at the beginning generate a group of values, which are tabulated in table 3.

For the correlation between diameter and the numerator constant, a potential function is used, which with R2=1, is described by the following expression:

$$\alpha = \frac{5.2063}{d^{1.8}} \quad (16)$$

The representation of the correlation (16) is given in Figure 6. Finally, we are in a position to form the definitive expression, but since two intervals of cross-analysis were used, then the definitive expression will have two application zones and therefore it will also be constituted by two equations.

For the first application zone (0.88≤x≤0.95) it was shown that the denominator of equation (7) is equal to the product of Equations (16) and (14) with the term $(m_{vapor})^{0.8}$. For the second application area (0.95<x≤0.99), this will be equivalent to the product of Equations (16) and (15) with the term. Then, we have to:

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For (0.88≤x≤0.95)

$$\alpha = C_1 \frac{\left[1 - 0{,}03 \cdot (P_{back} - 5)^{0{,}7}\right] \cdot (m_{agua})^{0.8}}{2180{,}7 \cdot d^{1{,}8}} \quad (17)$$

For 0.95<x≤0.99

$$\alpha = C_2 \frac{\left[1-0{,}032\cdot\left(P_{back}-5\right)^{0{,}7}\right]\cdot\left(m_{agua}\right)^{0.8}}{2184{,}6\cdot d^{1{,}8}} \tag{18}$$

Equations (17) and (18) were obtained by a mathematical method of variables superposition, and are valid for: $5\leq(P_{back})\leq36kPa$; $0.015\leq d\leq0.05m$; $1\leq m_{vapor}\leq90kg/s$; $0.9\leq x\leq0.99$

Table 3. Numerator variation in Equation (7) as a function of the independent variable of superposition

Diameter (m)	Constant for Equation (7)
0.015	9989.1
0.02	5951.8
0.021	5451.3
0.025	3982.9
0.03	2868.6
0.035	2173.6
0.04	1709.2
0.045	1382.7
0.05	1143.8

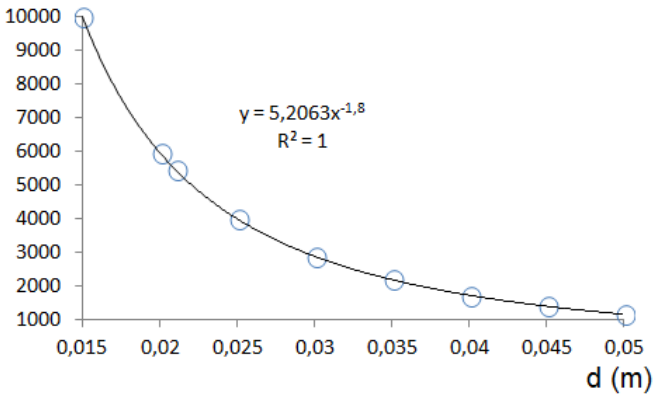

Figure 6. Correlation between the numerator of expression (7) and the equivalent diameter

In the denominator of equations (17) and (18) the complex is present, which indicates that in ACC systems the pressure is inversely proportional to the coefficient of heat transfer by condensation in a power 0,7. This cause causes them to experience a reduction of the heat transfer coefficient of approximately 0.95% for each kPa of increase in the turbine output pressure, becoming a weight element in the proportionality between the penalty of the efficiency of the ACC and the increase of turbine outlet pressure.

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3. Conclusions

By using a variable crossing method (Breshnetzov method) to perform a combinatorial analysis of the independent variables that directly influence the condensation heat transfer process in ACC systems, it is obtained that:

1- In the exhausted steam pressure ranges between 5 to 36 kPa the heat transfer coefficient experiences asymptotic decreases, taking an approximately constant behavior from 28 kPa, with an inclination angle of 6.30

2- The combination of the independent variables generates two non-homogeneous expressions of analysis, the quality of the vapor being the variable that decides the area of applicability of each one, being both described by:

To $0.88 \leq x \leq 0.95$ -- $$\alpha = C_1 \frac{\left[1 - 0{,}03 \cdot (P_{back} - 5)^{0{,}7}\right] \cdot (m_{agua})^{0.8}}{2180{,}7 \cdot d^{1{,}8}}$$

To $0.95 < x \leq 0.99$ --- $$\alpha = C_2 \frac{\left[1 - 0{,}032 \cdot (P_{back} - 5)^{0{,}7}\right] \cdot (m_{agua})^{0.8}}{2184{,}6 \cdot d^{1{,}8}}$$

3- In ACC systems, the pressure is inversely proportional to the coefficient of heat transfer by condensation in a power 0.7. This cause causes them to experience a reduction of the heat transfer coefficient of approximately 0.95% for each kPa of increase in turbine outlet pressure,

Acknowledgments

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