EXERGO-ECONOMIC APPROACH TO OPTIMIZE AN AIR TREATMENT UNIT FOR CLIMATE CONTROL OF A COVERED SWIMMING POOL

F. BOZZINI [1], P. G. ANOAICA [2]

[1] UNIVERSITATEA „POLITEHNICA“ – Bucureşti, Romania
[2] UNIVERSITATEA DE MEDICINA SI FARMACIE – Craiova, Romania
* E-mail: faustobozzini@virgilio.it

Abstract. This paper presents the optimization analysis applied to a real case study of the air treatment unit for winter climatization of a covered swimming pool. The optimization is based on exergo- economic approach. This approach had allowed to calculate the exergetic efficiency and exergetic costs before and after optimization of the air treatment unit. The air treatment unit is equipped by a vapor compression heat pump, that is constituted by evaporator heated with exhaust air and condenser cooled with fresh air. This type of heat pump operates at a temperature equal or greater to reference temperature of the dead state (T_a = 268 K). In this case the exergetic flux calculated of the evaporator isn't outlet, but inlet in the evaporator itself. The optimization consists by introducing in the heat pump cycle, an additional evaporator for heating swimming pool water by increasing the COP of the heat pump itself. The results obtained with exergo-economic analysis are as follows: the exergetic cost per unit of exergy is reduced by 12.5% introducing a sub-cooler. The value of the exergo-economic factor of the heat pump is calculated pre and post optimization cases, growing from 13.2 to 18.2% about 37%. It was obtained improvement of exergy efficiency by 7.6% of the heat pump with a relative increase of its capital cost and the relative difference is reduced by 4%. In conclusion the results obtained have led to an increase of exergetic efficiency and a consequent reduction of the cost per unit exergy of the air treatment unit.
Keywords: climatization, air, optimization, exergy, exergo-economic.

1. INTRODUCTION

The air treatment unit studied was installed in a covered swimming pool with hall's dimensions of 50×33 m, and a water basin with an area of 450 m^2. The treatment unit has an air flow rate of 4.3 kg/s to compensate the air fresh, the dehumidification, the heat losses of the hall swimming pool and of the water basin. The air treatment unit is shown in Figure 1.

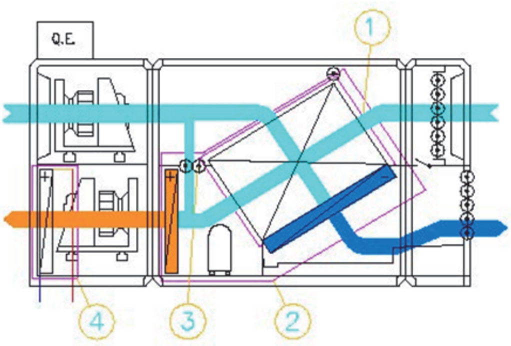


Fig. 1. Air treatment unit (UTA) for swimming pool.

This unit is composed of the following components:

1) polypropilen plate heat exchanger recovery;
2) heat pump air-air;
3) mixing section;
4) post-heating section.

The supply and exhaust air fans of the treatment unit, are plug-fan type with variable speed according to the air density and total heat load required. The electric heat pump is inside the UTA. Its compressor is located between the battery post-heating and heat recovery, while the evaporator and condenser are installed respectively at the outlet of the heat exchanger recovery and at the inlet of the supply fan. Typically, a water heat exchanger is installed after the fan to integrate the heat pump during the periods when it can't satisfy the heating requirements. This battery is fed by hot water through a condensing boiler with natural gas.

2. EXERGETIC ANALYSIS: REAL CASE STUDIED

The air treatment unit optimized is presented in figure 2. This figure shows the unit with another heat exchanger that works as sub-cooling on the incorporated heat pump cycle [1, 2]. The heat exchanger is cooled with pool water when indoor heat exceeds the comfort limit.

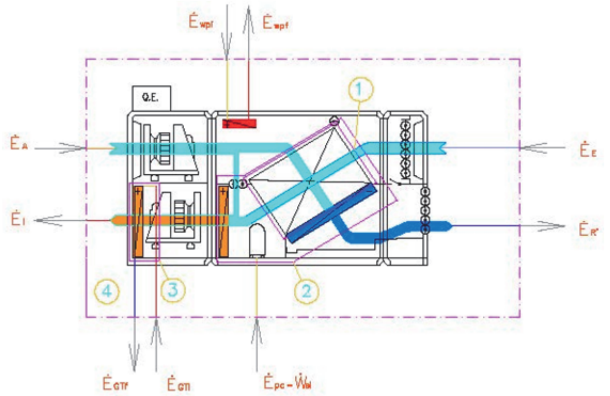


Fig. 2. Air treatment unit optimized.

The analysis of the unit consists in several steps:

a) exergetic analysis of Mollier cycle;
b) calculation of UTA's exergetic flows;
c) exergo-economic analysis of UTA.

The step a) establishes that the pool hall has the following microclimatic conditions: T_A = 303 K (30 °C), ϕ_A = 55%, while the outdoor air conditions are; T_E = 268 K (–5 °C), ϕ_A = 80% [3].

In order to avoid the rapid evaporation of the pool water, the water temperature must be at least two degrees more of the pool hall itself [4]. Based on the technical data of the UTA, it was obtained on the Mollier diagram the thermodynamic process indoor air (Fig. 3).

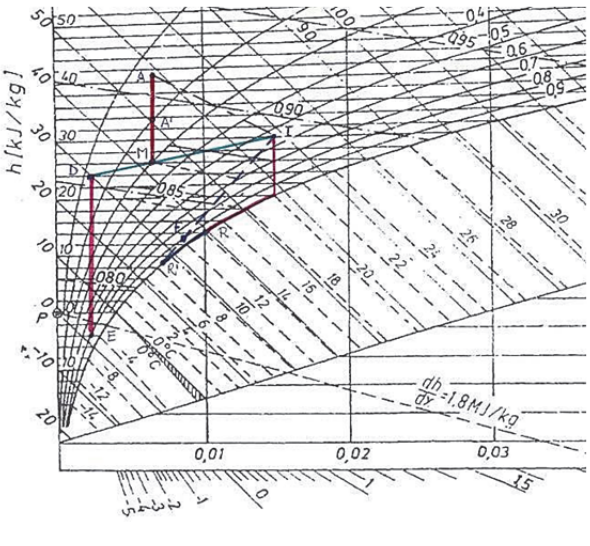


Fig. 3. Indoor air's thermodynamic process of the hall.

There were calculated the specific exergies per flow air rate of each point on the diagram of the thermodynamic process obtained and the exergetic efficiencies of each UTA's component obtained by calculating the ratio between product and fuel rates of each component[5][6].

In the following graphs (Figures 4, 5, 6), there are shown the trends of the exergetic efficiency of the UTA before and after optimization according to the main climatic parameters, (flow rate, temperature and relative humidity outdoor).

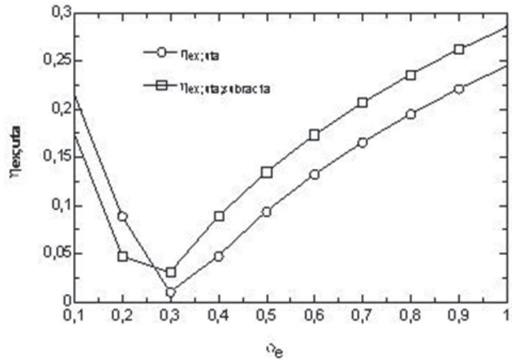


Fig. 4. Comparison of UTA's exergetic efficiencies between case without and with sub-cooler as a function of outdoor air's relative humidity.

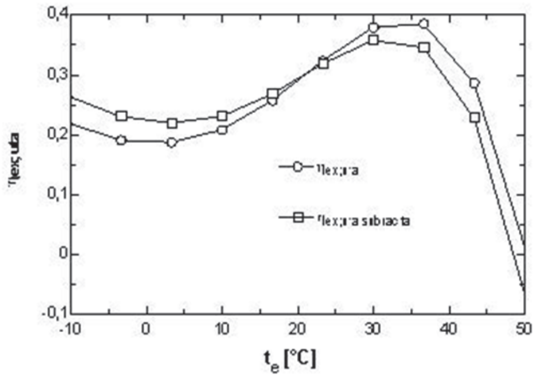


Fig. 5. Comparison of UTA's exergetic efficiencies between case without and with sub-cooler as a function of outdoor air's temperature.

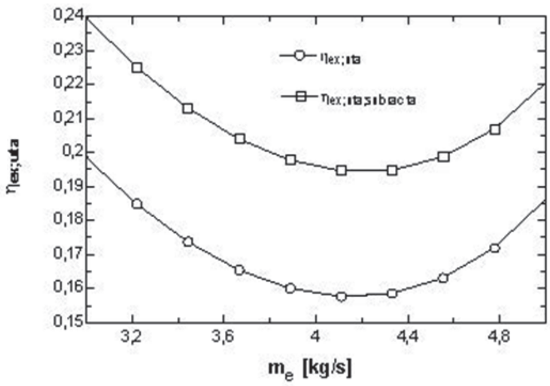


Fig. 6. Comparison of UTA's exergetic efficiencies between case without and with sub-cooler as a function of outdoor air's flow rate.

The step b) establishes the exergetic powers of each point of the Mollier thermodynamic process, are obtained by multiplying the air flow rate by the specific exergy of each point (Table 1). There are further represented, the exergetic specific costs to each point of the thermodynamic indoor air process.

Table 1

Exergetic powers of treatment unit working point

State	Flux	Massic volumic rate *m* [kg/s]	Temperature *T* [K]	Pressure *p* [bar]	Specific exergy *e* [kJ/kg]	Exergy *E* [kW]	Rate of cost C_i [€/h]	Exergetic specific cost c_i [€/kWh]
E	air fresh	3.2	268.15	1.013				
A	air exh	4.3	303.15	1.013	4.19	18.02	2.34	0.130
A'	air exh	1.1	303.15	1.013	4.19	4.61	0.60	0.130
A''	air exh	4.2	303.15	1.013	4.19	17.60	2.29	0.130
D	air fresh	3.2	294.75	1.013	1.24	3.97	1.23	0.310
R	air exp	3.2	288.15	1.013	**1.78**	5.70	0.74	0.130
R'	air cool	3.2	283.15	1.013	**1.21**	3.87	0.50	0.130
M	air mix	4.3	296.34	1.013	**1.53**	6.58	2.89	0.440
I'	air inlet	4.3	304.76	1.013	**2.44**	10.49	4.62	0.440
I	air inlet	4.3	314.15	1.013	3.77	16.21	7.13	0.440
Bpi	water	1.37			28.46	38.99	3.39	0.087
Bpu	water	1.37			22.25	30.48	2.65	0.087
HP	thermic					45	14.85	0.330

These specific costs are a function of the total cost (Z_{tot}), which is expressed by the sum of the maintenance and transportation ($Z_{\text{O\&M}}$) and investments costs (Z_{CI}), that must be levelized [7].

$$Z_{\text{tot}} = Z_{\text{O\&M}} + Z_{\text{CI}} \qquad (1)$$

In the recent years, the discount rate and escalation rate have taken the following values: $i_{\text{eff}} = 0.5\%$, $r_n = 1.2\%$, and the UTA life span N assumes $N = 10$ years. With these data we compare the two investment costs; $I' =$ € 68,000, and $I'' =$ € 70,000 that is respectively UTA without and with sub-cooler. We obtained the following values levelized in both cases respectively: $I_L' =$ € 72,618, $Z_L'{}_{\text{O\&M}} =$ € 2,264 (pre-optimization) and $I_L'' =$ €75,000, $Z_L''{}_{\text{O\&M}} =$ € 3,225 (post- optimization). These levelized values are obtained from the following equation:

$$Z_L = CRF \cdot \sum_{k=1}^{N} P_k \qquad (2)$$

where: Z_L – levelized value of the cost; N – life span of the UTA; P_0 – estimated cost of the payment at the beginning of the first year; i_{eff} – discount rate interest; CRF – capital recovery factor, CRF = $i_{eff}(1 + i_{\text{eff}})^N/(1 + i_{\text{eff}})^{N-1}$; P_k – the present value of a future amount, $P_k = C_k / (1 + i_{eff})^k$; C_k – payment in year k, $C_k = P_0(1 + r_n)^k$; k – number of year or time period ($k = 1 \div 10$).

The exergetic specific costs are obtained by solving a system of equations applied to each individual component of the UTA. Initially, the system has 4 equations and 8 unknowns as follows:

$$c_D \dot{E}_D + c_R \dot{E}_R = c_A \dot{E}_A + c_E \dot{E}_E + \dot{Z}_{rec}$$

$$c_R \dot{E}_R + c_I \dot{E}_I = \\ = c_M \dot{E}_M + c_R \dot{E}_R + c_{el} \dot{W}_{el} + \dot{Z}_{pdc} \qquad (3)$$

$$c_M \dot{E}_M = c_A \dot{E}_A + c_D \dot{E}_D + \dot{Z}_{mix}$$

$$c_I \dot{E}_I + c_{hu} \dot{E}_{hu} = c_r \dot{E}_r + c_{hi} \dot{E}_{hi} + \dot{Z}_{bpi}$$

Hence it is necessary to look for 4 complementary relations that solve the system[8]. The relations are the following

$$c_D = c_E;\ \ c_A = c_{A'} = c_{A''} = c_R = c_{R'} = \\ = C_M = C_I = c_{I'};\ \ c_{el} = c_{R'} + c_I;\ \ c_{hi} = c_{hu}$$

Introducing these relations, the system is reduced to 2 equations with 2 unknowns and takes the following form:

$$c_A(\dot{E}_R - \dot{E}_{A''}) + c_D(\dot{E}_D - \dot{E}_E) = \dot{Z}_{rec} \qquad (4)$$

$$c_A(\dot{E}_{R'} + \dot{E}_{I'} - \dot{E}_M - \dot{E}_R) + c_D(\dot{E}_{I'} - \dot{E}_M) = \\ = c_{el} \dot{W}_{el} + \dot{Z}_{pdc}$$

Calculated the unknown c_A and c_D, we can identify to all the other unknowns including the UTA final specific exergetic cost c_I, in [€·kWh^{-1}]:

3. EXERGO-ECONOMIC ANALYSIS

The step c) establishes that in order to obtain the thermo-economic optimization of the air treatment unit, it is necessary to determine the minimum of the function cost thus called the ***objective function***. On this purpose, the objective function must be expressed in relation with the overall system exergy [7, 9]:

$$I = B\left(\frac{\varepsilon}{1-\varepsilon}\right)^n \cdot \left(\dot{E}_p\right)^m \qquad (5)$$

where: I – total capital investment; ε – exergetic efficiency of each unit components (UTA, condensing boiler, etc.); $\dot{E}_p$ – exergetic flow considered constant output by a component of the treatment unit; B, m, n – constants derived from the costs of the parts of the air treatment unit given by producer.

In this way the capital cost of the unit is related to the thermodynamic quality (exergetic) and size of each component. The total fixed cost of overall system is expressed by the relation:

$$Z = (CRF + \sigma)\cdot I + \omega \cdot \tau \cdot \dot{E}_p + R \qquad (6)$$

dividing the entire equation for τ obtain:

$$\dot{Z} = \frac{CRF + \sigma}{\tau} \cdot I + \omega \cdot \dot{E}_p + \frac{R}{\tau} \qquad (7)$$

where: σ – the fixed rate coefficient of the cost related to maintenance; ω – constant that expresses the variable part of the cost referred to maintenance and operation of the UTA; τ total annual number of hours of the UTA's operation; R – remaining operating and maintenance costs that are independent of the total investment and the exergy of the product.

The objective function to be minimized expresses the cost per exergy unit of product for the kth component. Replacing the (7) and (5) expressions we can write:

$$\text{Minimize } c_p = \frac{c_F \dot{E}_F + \dot{Z}}{\dot{E}_p} = = \frac{c_F}{\varepsilon} + \frac{(CRF + \sigma)}{\tau \cdot \dot{E}_p^{1-m}} \cdot \left(\frac{\varepsilon}{1-\varepsilon}\right)^n + \omega + \frac{R}{\tau \cdot \dot{E}_p} \qquad (8)$$

The minimum cost per exergy unit of product is obtained by differentiating (8) equation and setting the derivative to zero:

$$\frac{dc_p}{d\varepsilon} = 0 \Rightarrow \mathbf{e}^{OPT} = \frac{1}{1+F}$$

where: $$F = \sqrt[n+1]{\frac{(CRF + \sigma)\cdot B \cdot n}{\tau \cdot c_F \cdot \dot{E}_P^{1-m}}} \qquad (9)$$

The function F expresses the exergo-economic similitude made by Szargut [10]. This function can be transformed as follows:

$$f(\omega) = A \cdot \left(\frac{\varepsilon}{1-\varepsilon}\right)^n + \frac{c_f}{\varepsilon} + \omega + \frac{R}{\tau \cdot E_p} \qquad (10)$$

where: $A = \dfrac{(CRF + \sigma)\cdot B}{\tau \cdot E_p^{1-m}}$

Exchanging the variables:

$$e/(1 - e) = x \Rightarrow e = x - x \cdot e \Rightarrow$$

$$e\,(1 + x) = x \Rightarrow 1/e = 1/x + 1 \qquad (11)$$

the function becomes:

$$f(\omega) = A \cdot \left(\frac{\varepsilon}{1-\varepsilon}\right)^n + \frac{c_f}{\varepsilon} + \omega + \frac{R}{\tau \cdot E_p} \qquad (12)$$

The pre and post optimization exergo-economic results, are summarized in the tables 2 and 3 for each UTA component.

The parameters mentioned are respectively the purchased-equipment cost known of each component (PEC), the exergetic cost of fuel cf = = 0,287 €/kWh, while the following parameters, are obtained from the expressions:

$$e_j = E_{P,j}/E_{f,j} = 1 - (E_{D,}i + E_{Pi,j})/E_{f,j} \qquad (13)$$

$$E_{D,j} = E_{F,j} - E_{P,j} \qquad (14)$$

$$y_{D,j} = E_{D,j}/E_{f,tot} \qquad (15)$$

$$C_{D,j} = c_{f,j} \cdot E_{D,j} \qquad (16)$$

$$Z_j = Z_{jCI} + Z_{j\ O\&M} \qquad (17)$$

$$r_j = (1 - e)/e + Z_j/c_{f,j}E_{p,j} \qquad (18)$$

$$f_j = Z_j/(Z_j + C_{D,j}) \qquad (19)$$

Now, we can make the diagrams showed in figure 7a and 7b, which will allow us to extract the economic parameters A, B, n, m more appropriate values. The first two diagrams in the figure 7a and b have a series of several curves with economic parameter A in function of B and m in the both UTA cases with and without subcooling.

Table 2

Exergo-economic parameters pre-optimization

Sub sistem	PEC [10^6€]	e	$\dot{E}_D$ [kW]	y_D [%]	c_f [€/kWh]	c_p [€/kWh]	$\dot{C}_D$ [€/h]	Z [€/h]	$\dot{C}_D \cdot \dot{Z}$ [€/h]	r [%]	f [%]
HRC	0,022	0,32	8,4	18,56	0,130	0,440	1,09	0,28	1,36	2,64	20,40
MIX	0,010	0,46	1,2	2,58	0,440	0,440	0,51	0,13	0,64	1,44	19,82
HP	0,032	0,39	6,1	13,46	0,440	0,440	2,66	0,40	3,07	1,78	13,19
Bpi	0,004	0,67	2,8	6,20	0,440	0,527	1,23	0,05	1,28	0,51	3,96

Table 3

Exergo-economic parameters post-optimization

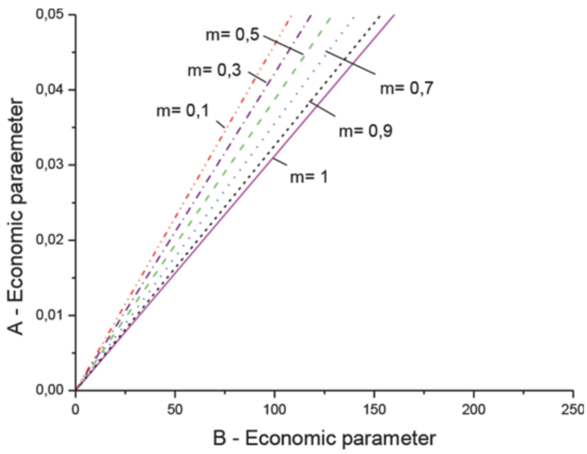
Sub sistem	PEC	e	$\dot{E}_D$	y_D	c_f	c_p	$\dot{C}_D$	Z	$\dot{C}_D \cdot \dot{Z}$	r	f
	[106€]		[kW]	[%]	[€/kWh]	[€/kWh]	[€/h]	[€/h]	[€/h]	[%]	[%]
HRC	0,022	0,32	8,4	18,56	0,130	0,440	1,09	0,35	1,43	2,78	24,20
MIX	0,010	0,46	1,2	2,58	0,440	0,440	0,51	0,16	0,67	1,51	23,54
HP	0,034	0,42	5,5	12,13	0,440	0,440	2,40	0,54	2,94	1,71	18,24
Bpi	0,004	0,67	2,8	6,20	0,440	0,527	1,23	0,06	1,29	0,51	4,89

Tables 4

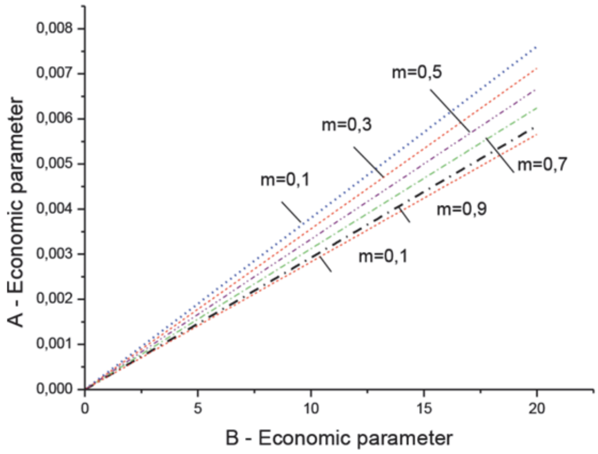
Exergetic flows of individual components of the UTA in the both cases pre and post optimization

UTA without sub-cooler				
Sub sistem	Product		Fuel	
		kW		kW
HRC	$\dot{E}_D$	3,97	$\dot{E}_A-\dot{E}_R$	12,32
MIX	$\beta(\dot{E}_M-\dot{E}_D)$	1,01	$(1-\beta)(\dot{E}_A-\dot{E}_M)$	2,17
HP	$\dot{E}_{I'}-\dot{E}_M$	3,91	$Q_{pc}/COP+\beta(\dot{E}_R-\dot{E}_{R'})$	9,97
Bpi	$\dot{E}_I-\dot{E}_{I'}$	5,72	$\alpha(\dot{E}_{hai}-\dot{E}_{hau})$	8,51

UTA with sub-cooler				
Sub sistem	Product		Fuel	
		kW		kW
HRC	$\dot{E}_D$	3,97	$\dot{E}_A-\dot{E}_R$	12,32
MIX	$\beta(\dot{E}_M-\dot{E}_D)$	1,01	$(1-\beta)(\dot{E}_A-\dot{E}_M)$	2,17
HP	$\dot{E}_{I'}-\dot{E}_M$	3,91	$Q_{pc}/COP+\beta(\dot{E}_R-\dot{E}_{R'})$	9,37
Bpi	$\dot{E}_I-\dot{E}_{I'}$	5,72	$\alpha(\dot{E}_{hai}-\dot{E}_{hau})$	8,51



a) UTA without sub-cooler



b) UTA with sub-cooler

Fig. 7. Curves of economic parameters A, B, m;
a) UTA without sub-cooler; b) UTA with sub-cooler.

This procedure can be applied to find the minimum economic parameters for each component of the UTA. But we highlight that it is unnecessary to analyze each component because the output exergy flow of the UTA without sub-cooler is equal to that of UTA with sub-cooler.

The only thing that allows the increase of final exergy is the COP growth of the heat pump due to sub- cooling of the water pool.

The output and input exergy flows for each component are shown in Tables 4.

Knowing the parameter A we draw the further diagram in function of n represented in figure 8.

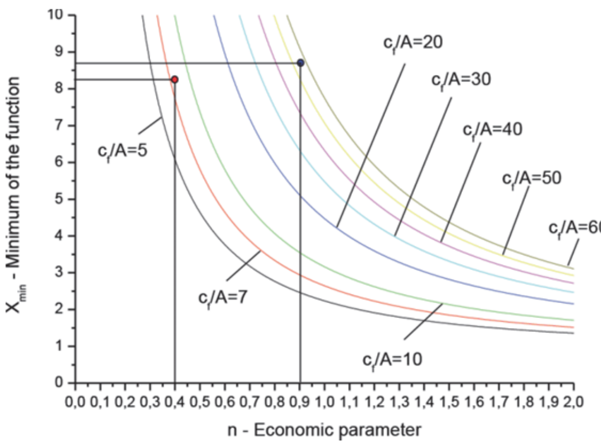


Fig. 8. Curves of the exergetic products as a function of economic parameters n and $c_f/_A$ ratio.

The curves obtained using the parameters A and n represent the curves of the first derivate of the function 7.

In this way, we can be chosen the value $x_{\min}$ of the function with optimals economic parameters between the two cases.

The values of the minimum exergetic cost of the products per kWh, can be expressed as a function of the value x_{min} obtained by the diagram in figure 8, which is a function of exergetic efficiency values ε.

This diagram is valid in general for the overall system or for each component.

In UTA without sub-cooler we get x_{min} = 8.37, while in the case of UTA with sub-cooler x_{min} = 8.67. Based on these two values, we can plot the graphs of the minimum exergy cost function of according to the expression 11 in the two cases studied.

The minimum exergetic cost of the products per kWh obtained in both cases, is represented by the diagrams presented in the Figures 9 and 10.

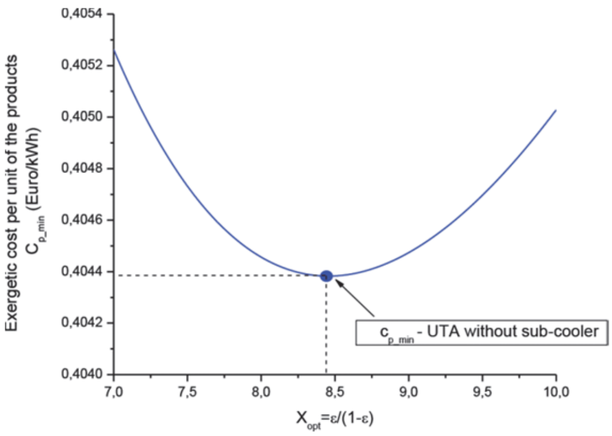


Fig. 9. Function of the minimum exergetic cost of the product per kWh for UTA without sub-cooler, depending on the parameter *x* which is a function of the optimal exergetic efficiency component (heat pump).

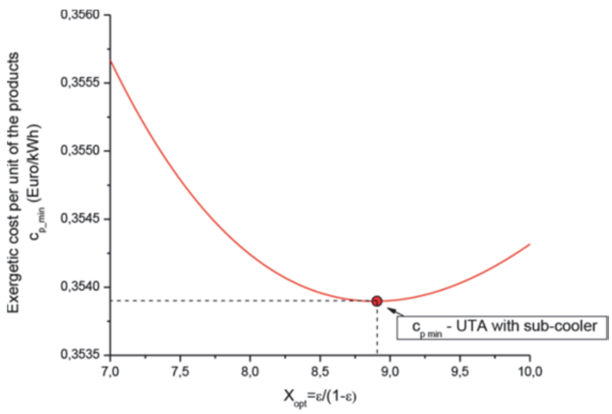


Fig. 10. Function of the minimum exergetic cost of the product per kWh for UTA with sub-cooler, depending on the parameter *x* which is a function of the optimal exergetic efficiency component (heat pump).

4. CONCLUSIONS

In the air conditioning field the exergetic and especially exergo-economic analysis for complex installations, aren't well documented. The few known examples do not always correspond from the practical point of view or are not comparable because they are made only on standard cases. The purpose of the analysis carried out on a UTA actually installed in a sport center, is to understand better the orders of sizes of the exergetic and exergo-economic parameters that we can achieve and to be useful from the practical point of view.

The exergetic analysis applied to our real case study of the air treatment unit for winter climatization of an covered swimming pool, before and after introducing an additional evaporator in the heat pump cycle, has led to the improvement of the exergetic efficiency showed as following specified:

The diagrams showed in Figure 4, 5, 6, represent the variation of exergetic efficiency according to the main climatic parameters (flow rate, temperature and relative humidity of the outdoor air). In the diagram of Figure 4 is presented the variation of exergetic efficiency as a function of outdoor air's relative humidity before and after UTA's optimization. The exergetic efficiency has a minimum value in both cases at ϕ_e = 30%. Generally the UTA works to maintain the air's relative humidity in the hall at ϕ_e = 50% then the difference of efficiency in correspondence of this value, is about 30% higher in the case of UTA optimized with sub-cooler.

In the diagram of Figure 5 is presented the variation of exergetic efficiency in function of temperature before and after UTA's optimization. The exergetic efficiency in correspondence of operation temperature T = 303 K is slightly reduced, but to a negligible percentage around 3%.

In the diagram of Figure 6 the exergetic efficiency as a function of air flow rate is a minimum in both cases with a percentage improvement which is maintained around 20% for each air flow rate.

The exergo-economic analysis applied in both cases (before and after optimization) has lead to the follows considerations:

The obtained results demonstrated that the exergetic cost of the products per kWh is reduced from 0,4 €·kWh-1 to 0,35 €·kWh-1 throughout sub-cooler optimization with a consequent reduction of exergetic cost of the overall UTA system of about 12.5%

In the case of UTA without sub-cooler we obtained a low value of exergo-economic factor for the overall UTA system. This fact suggests that the saving in the overall system could be achieved improving the component's efficiency even if the total capital investment for this component rises.

The exergo-economic factor percentage of the heat pump is increased, from 13.2 to 18.2%, that represents an improvement of 37%.

In the case of the heat pump we obtained an improvement of its exergy efficiency of 7.6% with a relative increase of its capital cost and a reduction of the relative difference of 4%.

We can conclude that the obtained results allowed us to demonstrate the exergetic efficiency improvement, with a consequent reduction of the cost per unit exergy, of our optimized air treatment unit.

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NOMENCLATURE

ε_j	exergy efficiency of the component	[%]
$E_{D,j}$	exergy distruction of the component	[kW]
$y_{D,j}$	exergy distruction percent of the component	[%]
$C_{D,j}$	the associated cost to exergy distruction of the component	[€·h^{-1}]
Z_j	levelized cost of the component	[€·h^{-1}]
r_j	relative difference	[%]
f_j	exergo-economic factor specific cost of	[%]
c_{el}	electricity	[€·kWh^{-1}]
c_h	specific cost of heat water	[€·kWh^{-1}]
c_f	specific cost of fuel	[€·kWh^{-1}]
c_p	specific cost of product	[€·kWh^{-1}]
I	investment cost	[€]
PEC	purchased-equipment cost	[€]