

ENERGY SAVINGS POTENTIAL USING BOILER´S EXHAUST GASES IN AN EVAPORATIVE DESICCANT AIR CONDITIONING SYSTEM

José Rui Camargo, rui@unitau.br
Marco Antonio Medeiros Santos, marcoams@uol.com.br
Ederaldo Godoy Junior, godoyjr@unitau.br
University of Taubaté - Professional Master Program in Mechanical Engineering - Energy and Industrial Environment Management, Rua Daniel Danelli, s/n – 123060-440 – Taubaté - SP

Abstract. *This paper presents a technical and economical analysis about the use of process residual heat, applied as heat source for the reactivation of the adsorbent material in an evaporative-desiccant cooling system for industrial use. This system has great usual potential in low or high relative humidity air conditions places and good performance in closed environment cooling, however it can be penalized by the high cost of the energy for the heat source, however it can become more advantageous using boiler's exhaust gases. The advantage of using boiler's exhaust is that this utility is a residual heat of industrial process; therefore there is an energetic optimization of the system, becoming its use cheaper. Thus, in this paper the feasibility of the use of boiler's exhaust gases is demonstrated and compared with electric power as a heat source. It can be seen that the pay-back is about 44 months when using boiler's exhaust gases comparing with electric power. When it is considered only the relative investments to the utilities used for the heat source the stated period for the investment return will be about 3 months. These results can help to take decision of using the utilities. It concludes that it is better to use boiler's exhaust gases to heat the reactivation air because it is a resource available for high temperatures, able to supply the energetic power need.*

Keywords*: evaporative cooling, desiccant dehumidification, thermal comfort*

NOMENCLATURE

A_{GC}	area of the boiler's exhaust gases duct (m²)
C_{EE}	cost of electric energy (US$/kWh)
CI_{EE}	cost of electric energy to the pumps, fans and equipments (US$/TRh)
CI_{FC}	cost of utility to the heat source (US$/TRh)
CS	thermal power of the system (TR)
CUI	cost of the utilities use (US$/TRh)
CO	operational cost of the systems (US$/TRh)
CP_{AR}	specific heat of the dry air at constant pressure (kJ/kg K)
CP_{GC}	specific heat of the boiler's exhaust gases (kJ/kg K)
CTI	total investment cost (US$/TRh)
D	diameter of the duct for the boiler's exhaust gases (m)
F	annuity factor (1/year)
H	equivalent period of use of the system (h/year)
I_{BB}	investment in pumps (US$)
I_{DT}	investment in ducts, grates and diffusers (US$)
I_{MD}	investment in the desiccant wheel (US$)
I_{RE}	investment in evaporative coolers (US$)
I_{VE}	investment in fans (US$)
II_{FC}	investment in the installations of utility for heat source (US$)
II_{EE}	investment in the electric installation (US$)
II_{RE}	investment in the water installations for evaporative coolers (US$)
ITE	total equipment investment (US$)
ITI	total utilities installation investment (US$)
IPL	total implantation investment (US$)
k	time (years)
$\dot{m}_{GC}$	mass flow of the condensate steam (kg/s)
P_{ARR}	cost of cooling air (US$/TRh)
P_{INST}	installed power for the reactivation air (kJ/s)
P_{REQ}	required power for the reactivation air (kJ/s)
R	revenue (US$/year)
r	interest rate (%)
T	temperature (ºC)

$\dot{V}_{AR}$	volumetric air flow (m³/s)
$\dot{V}_{ARR}$	average volumetric cooling air flow (m³ARR/h)
$\dot{V}_{GC}$	volumetric boiler's exhaust gases flow (m³/s)
V_{GC}	speed of boiler's exhaust gases (m/s)
v_{GC}	specific volume of boiler's exhaust gases (m³/kg)

Greek symbols

η	efficiency [1]
ρ_{AR}	specific mass (kg/m³)
ΔT	temperature difference (ºC)

1. INTRODUCTION

The present world-wide appeal for the ecological awareness, places the studies of engineering directed toward a concern with the echo-efficiency, assuming important positions before using technologies to take into account the central factor that is the man, his comfort and his relation with the environment. It is evident that the maximum conservation of energy, mainly in industries, it is not benefits just the economic and financial interest, but also, environmental interest having like main focus the "permanent" sustainable development of the man in the universe.

2. OBJETIVE

This paper presents a technical and economical analysis about the use boiler's exhaust gases compared with electric power as a heat source for the reactivation of the adsorbent material in an evaporative-desiccant cooling system for industrial use, ecologically correct, proposed by Camargo (2003). This system has great usual potential in low or high relative air humidity conditions places and a good performance in the cooling of environment. Thus, in this paper the feasibility of the use of residual heat of process is demonstrated as an energetic optimization of the system, becoming its use cheaper.

3. LITERATURE REVIEW

Watt (1963) carried out the first rigorous analysis of the direct and indirect evaporative systems, enumerating its advantages and disadvantages, indicating its applications and establishing considerations about project. From his works the evaporative refrigeration start to be investigated scientifically.

Schibuola (1997) comments that, in the applications, which the cooling coil dehumidifies the air, is possible to increase the reuse of the return air to recoup energy. The system presented by him, uses the evaporative cooling to pre-cool the return air and heat exchangers to cool caught external air.

Foster (1998) present performance data of the saving energy, benefits and evaporative systems manufacture for several cities in U.S.A. and Mexico.

Cardoso (1999) developed a work that presents a system with pre-dehumidification by adsorption and commentaries are made about water vaporization submitted in pressures below atmospheric pressure and the use of an air/steam/fuel system for automotive application.

Camargo *et al.* (2000) present the basic principles of functioning and technical considerations for the use of the evaporative cooling in air conditioning for human thermal comfort, discoursing about direct and indirect evaporative cooling systems, multi-stages and hybrid systems. They present, still, some environmental and economical benefits resultants from the efficient use of these systems.

Yanjun *et al.* (2000) analyze composed hybrid systems of a section of dehumidification from adsorption, evaporative cooling and steam compression system. They demonstrated that the production of cold in these system increases from 20% to 30% and the performance coefficient increases from 20% to 40% when compared with the vapor compression system.

Zhang and Niu (2003), consider a new system with desiccant cooling: an environmental control with Munters pre-cooling (PMEC) that combines it with panels of ceiling cooler. The result indicates that the ceiling cooler combined with acclimatization for desiccant could conserve until 40% of the consumption of preliminary energy, in comparison with a conventional system of constant volume.

Niu *et al.* (2002), considered a system of HVAC combined with a ceiling conditioner with acclimatization from desiccant for hot and humid climates, where the air dehumidification is required and where the internal humidity will have to be kept in a comfort zone. The results indicate that ceiling conditioner with acclimatization from desiccant can save until 44% of consumption of preliminary energy, in comparison to the conventional system.

Halliday *et al.* (2002), analyze the feasibility of using solar energy to power the desiccant cooling cycle and also presents a study, in which a solar desiccant cooling model is used to evaluate installations placed in the southeast and midlands of England, and in central Scotland. The project demonstrates that solar powered desiccant cooling is a feasible solution for cooling and heating buildings in United Kingdom.

Mavroudaki *et al.* (2002), present the results of a study, in which a solar desiccant cooling was used to evaluate the potential for using solar power to drive a single-stage desiccant cooling system in several places in southern Europe. The study demonstrates that solar desiccant cooling is feasible in the parts of southern Europe, provided that the latent heat gains are not excessive. However, if the relative humidity experience is too high then desiccant cooling become impracticable simply because the regeneration temperatures required are excessive.

Daou *et al.* (2006), made a technical revision about conditional air systems that use desiccant, standing out its applicability in several climates and also showing its proven advantages it can offer in terms energy and cost savings are underscored. Some commented examples are presented to illustrate how the desiccant cooling can be a perfective supplement to other cooling systems such as traditional vapor compression air conditioning system, the evaporative cooling, and the chilled-ceiling radiant cooling. It is notably shown that the desiccant material, when associated with evaporative cooling or chilled-ceiling radiant cooling, can render them applicable under a diversity of climatic conditions.

Kanoğlu *et al.* (2004), developed for the energy and exergy analyses of open-cycle desiccant systems and it is applied to an experimental unit operating in ventilation mode with natural zeolite as the desiccant, allowing us to the identify and quantify the sites with losses of exergy, and therefore showing the direction for minimization of exergy losses to approach the reversible COP.

Camargo (2003) presented a study of the potentials and limitations of an evaporative system and desiccant cooling system applied to air conditioning when used with objective to propitiate human thermal comfort and to reduce the energy consumption. He considered a new system, in which it could be used in regions of humid climate as an alternative to the conventional systems of air conditioning, saving energy and protecting the environment.

Jeong and Mumma (2004), had searched and developed practical enthalpy wheel effectiveness correlations useful for enthalpy wheel integrated systems design and analysis. In this research, enthalpy wheel performance data generated using established fundamental enthalpy wheel models were statistically analyzed. Predicted effectiveness values corresponded well with published manufacturer's data and existing fundamental enthalpy wheel models.

Cui *et al.* (2005), analyzed the new desiccants properties, getting satisfactory results in relation to those of commonly desiccant used (i.e., silica-gel, and 13x molecular sieve). In their studies, was concluded that these new desiccants are suitable for the desiccant cooling cycle, which is operated by low-temperature or low-grade waste heat.

Santos (2005) develop the study of the use of alternative utilities in an echo-efficient air conditioning system, composed by an evaporative-desiccant system associated to a system that uses pluvial water and residual heat of process. Is compares several energy sources of heat for desiccant reactivation as: electric energy (electrical resistances), natural gas, steam, steam condensate of process and boiler's exhaust gases. An analyzis for pluvial water use for the evaporative coolers is made too. His studies arrive at a conclusion that the cost of use these utilities is higher at the moment for the implantation of the project, however it is energetically cheaper and it becomes more attractive in the environment and social point view.

4. CONFIGURATION OF EVAPORATIVE-DESICCANT COOLING SYSTEM (SISREAD)

Figure 1 shows the configuration of the system, composed by a rotary desiccant dehumidifier coupled to two direct evaporative coolers and to an indirect evaporative cooler. In this configuration the outside process air is first mixed with return air and goes through the dehumidifier loosing latent heat and receiving sensitive heat. After that, the air is first cooled in an indirect evaporative cooler (IEC) unit and than in a direct evaporative cooler (DEC) unit, entering in the room to be conditioned with satisfactory human thermal comfort temperature and moisture conditions (path 1-2-3-4 in Fig. 1). The reactivation air is also composed by a mixer of outside and return air, that is initially cooled in a DEC and after in an IEC (path 5-6-7-8-9 in Fig. 1). To analyze the influence of the heat sources it uses manufacturer's data of commercially available equipment and real data of an industrial plant placed in Paraiba's Valley, São Paulo State, Brazil. Two cases are studied and compared, named CASE 1 (electric power) and CASE 2 (boiler's exhaust gases).

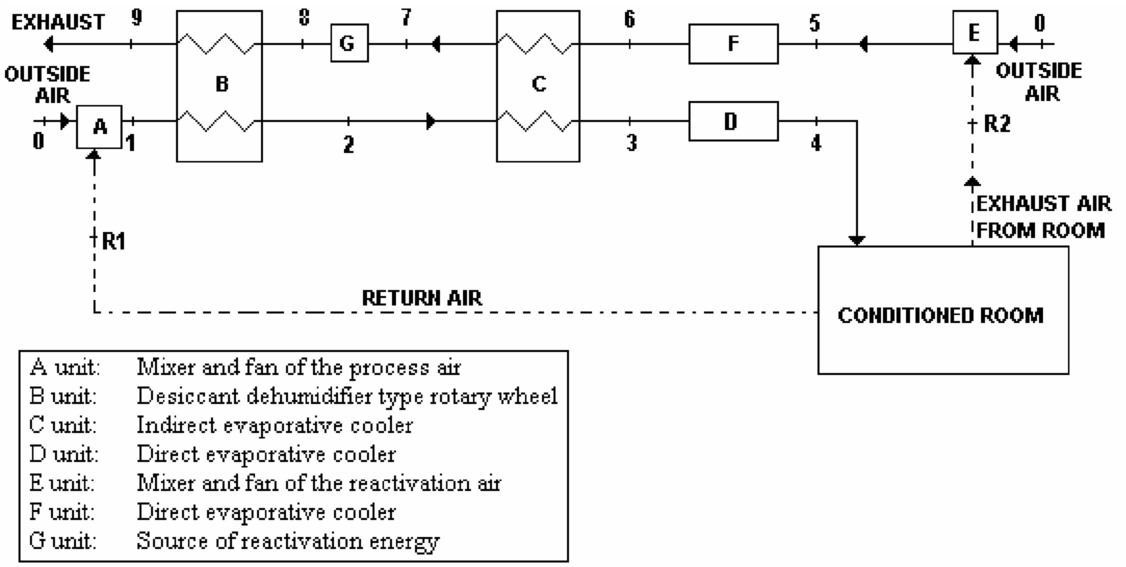

Figure 1. Diagram of the system proposed by Camargo (2003)

5. ANALIZIS OF UTILITIES CONSUMPTION IN THE REACTIVATION PROCESS

Munters offers equipments using three different kinds of utilities to heat the reactivation air for the same model in commercial catalogue M162011 Rev. 2 MUNTERS Technical Catalog. HCD-4500 EA uses electric energy (electrical resistances), HCD-4500 GA uses the natural gas and HC-4500 SA using steam, being the two last utilities used by heat exchanger or radiators. In this article the use of combustion gases of boiler is analyzed for the regeneration of desiccant and must be considered an adaptation in the heat exchanger of the equipment HC-4500 SA from the "Munters", for this utility. Figure 2 shows a scheme of the minimum heating that the reactivation air will have to suffer, or either, of 40,5 ºC (T7) for 71,1 ºC (T8). The power that will have to be employed for this heating will be calculated by equation 1, as it follows:

$$P_{REQ} = \dot{V}_{AR} \times \rho_{AR} \times CP_{AR} \times \Delta T = 58\,kW \qquad (1)$$

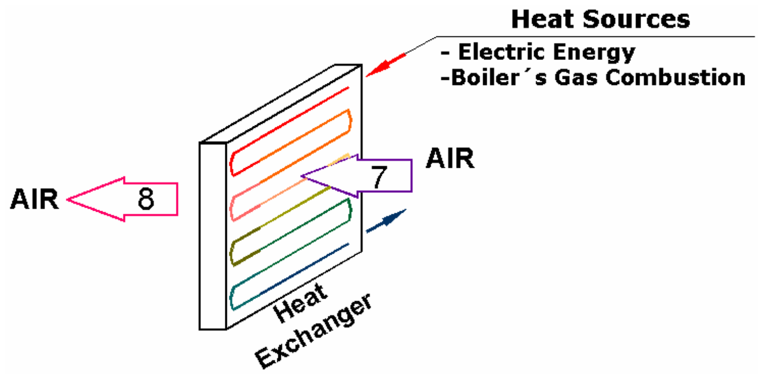

Figure 2 - Scheme of heating of the reactivation air

5.1. Electric Power

Camargo (2003), considered in his study the desiccant model HC-4500 EA, which uses the electric energy through electrical resistances to the heating of the reactivation air that needs 58 kW, having as efficiency of exchange 95%.

The power installed necessary for the exchange will be:

$$P_{INST} = \frac{P_{REQ}}{\eta} = \frac{58,00}{0,95} = 61,05\,kW$$

The cost of the electric energy bought from concessionaire is USS0,075/kWh (Bandeirante Energy S. A.).

Cost of the utility consumed in the heat source: CI_{FC}

$$CI_{FC} = P_{INST} \times H \times C_{EE} = 61{,}05 \times 240 \times 0{,}075 = \frac{US\$1.098{,}90}{month}$$

5.2 Boiler's Exhaust Gases

To use boiler's exhaust gases for reactivation, the available desiccant wheel models must have the heat exchanger adapted by manufacturer. The exchange efficiency adopted is 80%. The power installed necessary for the exchange will be:

$$P_{INST} = \frac{P_{REQ}}{\eta} = \frac{58}{0{,}80} = 72{,}50\ kW$$

The advantage of using exhaust gases from the burning of combustible oil is that this utility is a process residual heat, therefore has an energetic reuse of the system, becoming its employ cheaply. These gases are emitted in the atmosphere with a temperature of 300 ºC, having a mixture of gases CO_2, N_2, O_2, SO_2 and others. A system of steam's generation was studied in this case, through a boiler, ATA MP810, with capacity of 6,000 T/h. The gases are expelled through a fan with capacity of 110 m³/min with static pressure of 652 mmca and 2290 rpm (manufacturer data). It fits here to study the possibility to make use of gases without the necessity of installation another exclusive fan for the SISREAD. It is important to observe that the final temperature of gases after the heat exchanger could not be below 200 ºC due to SO_2 presence, that a small percentage (about 0,29%) can originate sulphureous and sulphuric anhydrides. These, in turn, in contact with the proper present steam water in the smoke, are transformed into H_2SO_3 (sulphurous acid) or H_2SO_4 (sulphuric acid) which can cause corrosion throughout the duct (Duarte, 2005).

Cost of the combustion gases:

Data: CP_{GC} = 0,86295 kJ/kg K; T_e = 300 ºC; T_s = 200 ºC (minimum); v_{GC} = 0,85 m³/kg

Necessary fluid outflow:

$$P_{INST} = \dot{m}_{GC} \times CP_{GC} \times \Delta T \qquad (2)$$

$$\dot{m}_{GC} = 0{,}84 \frac{kg}{s}$$

$$\dot{V}_{GC} = \dot{m}_{GC} \times v_{GC} = 0{,}84 \times 0{,}85 = 0{,}714 \frac{m^3}{s}$$

The diameter of the duct is:

$$A_{GC} = \frac{\dot{V}_{GC}}{V_{GC}} = 0{,}1428 m^2 \text{ and } D = 0{,}426\, m$$

With a equivalent length duct to 30 m, diameter of 430 mm, and considering special parts, the chimney and the heat exchanger, the pressure drop is about 155 Pa (Macintyre, 1990). It concludes that the existing fan could be used for the shunting line of a part of the combustion gases of the chimney, so it is well bellow its capacity. So that it will not have additional costs with electric energy, operational or maintenance costs. In this case the costs with duct computes only heat exchanger, chimney and thermal isolation that, for research of commercial market of equipment and services arrived USS3,500.00 (II_{GC}).

6. IMPLANTATION COSTS DESIGN

The air conditioning design implantation costs to evaporative-desiccant cooling presented bellow uses electric energy (CASE 1) and boiler's exhaust gases (CASE 2) as reactivation heat source. The investments applied in each project had all been raised, in which they will be expenses in the act of the investment and was made a survey of all the monthly fixed costs, in which the energy consumption, maintenance and operation will be made in accordance with. These monthly costs, here in dollar, will have to be in function of a specific refrigeration (TRh). Table 1, shows the summary of the implantation costs of studied Cases 1 and 2.

Table 1 – Summary of the Investment Costs for Cases 1 and 2.

Description	Nom.	Un.	CASE 1	CASE 2
System Capacity	CS	TR	10	10
Annual Hours of Working	H	h/year	2880	2880
Installation Invest. of Utilities to Heat Source	II_{FC}	US$	NA	2920,00
Installation Invest. of Water to the Evaporate Cooling	II_{RE}	US$	180,00	180,00
Electric Installation Investment	II_{EE}	US$	2800,00	600,00
Total Investment of Utilities Installation	ITI	US$	2980,00	3700,00
Ducts and diffusers (air insufl. and air return)	I_{DT}	US$	4500,00	4500,00
Pumps	I_{BB}	US$	117,68	117,68
Funs	I_{VE}	US$	3556,50	3556,50
Evaporative Coolers	I_{RE}	US$	2000,00	2000,00
Desiccant Wheel	I_{MD}	US$	35946,12	37743,43
Total Investment of Equipments	ITE	US$	46120,30	47917,61
Total Investment of Project Implantation	IPL	US$	49100,30	51617,61
Cost of Utilities to Heat Source	CI_{FC}	US$/TRh	0,4579	NA
Cost of Water to the Evaporate Coolers	CI_{RE}	US$/TRh	0,0021	0,0021
Cost of electric energy for pumps, compressors, funs, etc, (not include the reactivation energy)	C	US$/TRh	0,0221	0,0221
Cost of Utilities	CUI	US$/TRh	0,482	0,024
Operational Cost Systems	CO	US$/TRh	0,005	0,005
Price of Cooling Air	P_{ARR}	US$/TRh	0,4870	0,0292

6.1 Economic analysis

A method used for economic analysis in the cogeneration area was adopted allowing inquiries yield of enterprises that are taken by base also quantitative aspects of the utilities production cost that are compared with values offered by the market for a decision, Halliday (2002). In this case, is made comparisons between electric energy and the boiler's combustion gases. The equations presented here had been adapted in accordance with the studied project.

The equations are presented bellow, Balestieri (2002):

$$R = H \times CS \times (-P_{ARR} - CTI) \tag{3}$$

$$CTI = \frac{IPL \times F}{H \times CS} + CUI + CO \tag{4}$$

$$F = \frac{q^k \times (q-1)}{q^k - 1} \tag{5}$$

$$q = 1 + \frac{r}{100} \tag{6}$$

Where, R is the revenue (US$/TRh), P_{ARR}, total price of the cooled air production (US$/TRh), CTI the total cost of the used investment for utilities (US$/TRh), K is time (years) and F the annuity factor (year^{-1}). The interest's rate of 12% per year (r = 12%) was considered.

When the equations above are used, are gotten resulted of amortization to the long of the time what it makes possible to show the results through graphs, where each curve represent a studied system. This way, in the first place, the behavior of some studied systems can be observed at the same time. In the second place, it is observed that in curve "touches" or "crosses" the axle "0", because this axle means the payback in determined time from which system starts to have specific economy. The crossing of these curves with axe "0" could be gotten when the study object will have generation of proper energy, observed commonly in cogeneration systems or solar and wind energy, among others. The "space" that lacks to arrive itself until axe "0", in the cases presented here, represents how much these systems will spend of energy, maintenance and operation in long stated period. In other words, it would be the cost that would be paid to a concessionaire for the spend energy and for the operational cost. In the cases studied here, it will always be gone to use electric energy to set in motion the condensed steam pump for return to the boiler. However, these graphs if become interesting when it is compared or when the difference of expenses between a favorable system and the other less favorable is made. In this case that it is possible to cross axe "0" indicating the time where an investment in relation will be pleased to the other investment. These situations help to take a decision when it is studied analytically several investments proposed in an industry. For convention it will be call amortization of the investments to the long of the time when it will be study separate systems and to call payback when a system with another will be comparing. Adjusting it equation 3, proposed the equation (7) to get the payback, as it follows:

$$R = H \times CS \times (P_{ARR}^{Cason} - P_{ARR} - CTI) \quad (7)$$

where, P_{ARR}^{Cason} is the price of the air cooled in determined case n, which is made with comparison.

6.2 Amortization of the investments for the SISREAD along the time

Figure 3 shows the characteristics studied evaporative-desiccant cooling in this paper. Although the cost of investment of the system that uses boiler’s exhaust gases (Case 2) is bigger than the system that uses electric energy, it can be seen that the curve of this configuration is more favorable in relation to Case 1. It is the curve that is closer to axle "0".

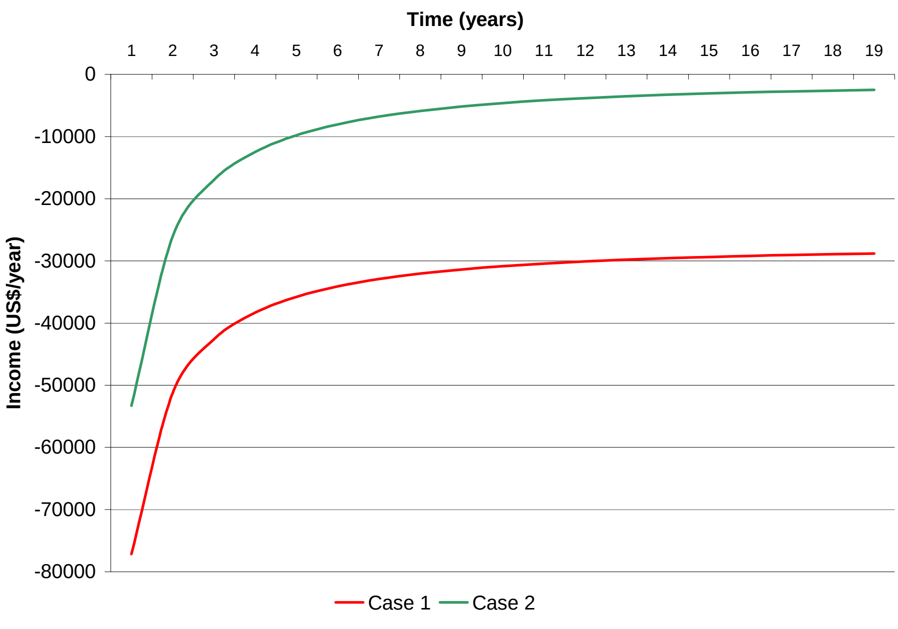

Figure 3 - Amortization of the SISREAD investments

6.3 SISREAD’s Payback

Comparing the two cases, the payback expected for the implantation of the case most favorable for the decision taking is gotten. Figure 4 shows that the payback is around 44 months using boiler’s exhaust gases related to electric energy use.

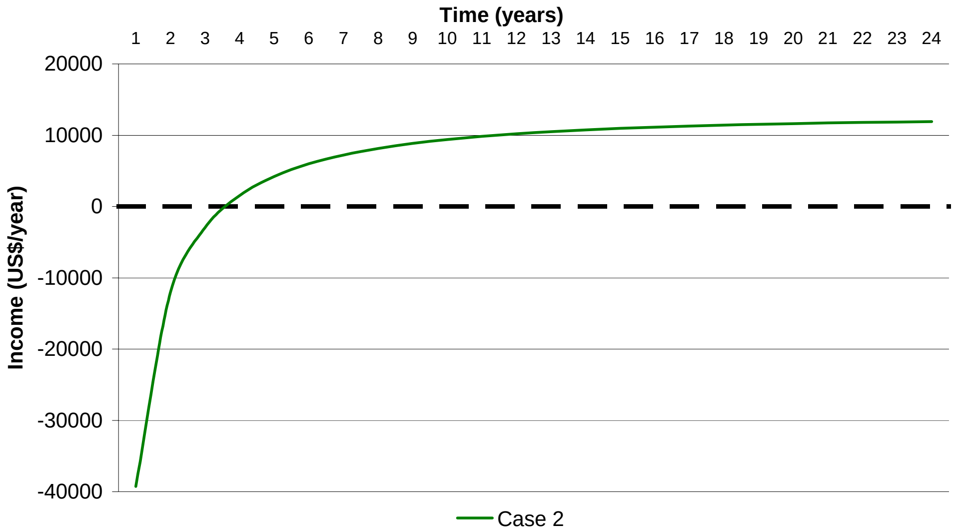

Figure 4 - Payback of the Case 2 in comparison to case 1

6.4 Economic analyzis of the energy consumption in the heat source used in the SISREAD in relation to case 1

In this topic it will be taken in consideration only the consumption utilities of the heat source for the reactivation air flow. The other utilities and investment will not be treated in this analysis; therefore the systems present equal costs for both, as water recirculation pumps in the coolers, fans, equipment, etc. Figure 5 shows the curve tendency for Case 2 in comparison to Case 1. The payback of Case 2 is given in the stated period of 3 months.

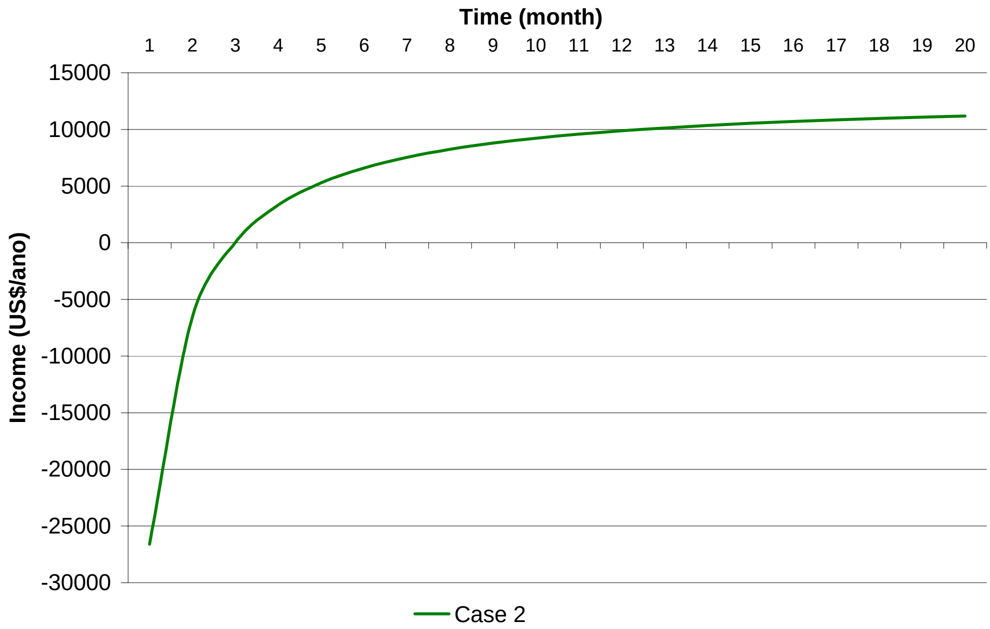

Figure 5 - Payback for the consumption energy in the heat source used in the SISREAD

7. CONCLUSIONS

This paper shows the characteristics of an evaporative-desiccant system for air conditioning proposed by Camargo (2003) and its importance in the scene of energy and environment conservation. This hybrid system, using evaporative and desiccant cooling presents promising perspectives, mainly for application in air conditioning where low cost heat sources or available residual heat exists, as in cogeneration systems. Here, electric power was become fulfilled calculations using electric energy (electrical resistances) and the combustion gases of boiler. It was concluded that the use of the combustion gases of boiler for the heating of the reactivation air is advantageous, therefore its utilities in which gotten residual heat with high temperature, able to heat the reactivation air in the necessary temperature (71,1ºC) without the use of fans or any another accessory that consummates other energies. Even though the costs of implantation of this project are higher than the electric energy, does not have monthly expenses what brings favorable resulted. It was also concluded that when studies separately the influence of the utilities and its installation and operation, for the heat source, the results are much more visible. Its happen for the fact of is not computing the costs for the both cases studies, as for example, the recirculation water pumps in the evaporators, the evaporators, the desiccant, the fans, what becomes the study most specific. It concludes that it is better to use boiler's exhaust gases to heat the reactivation air because it is a resource available for high temperatures, able to supply the energetic power needed.

8. ACKNOWLEDGEMENTS

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