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COGENERATION WITH INTERNAL COMBUSTION ENGINE AND ABSORPTION REFRIGERATION SYSTEM (ARS) OPERATING WITH NATURAL GAS: TECHNICAL, ECONOMICAL AND ENVIRONMENTAL ISSUES

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Abstract. *This study evaluates the feasibility of a cogeneration system composed of Internal Combustion Engine, Absorption Chiller and Heat Exchangers, to meet the thermal and electric demands of a Brazilian hypothetical hotel. The modeling is performed based on the hotel requirements of 310 TR (cold water) and 800 kW of electricity. The frigorific power and the hot water are produced using the residual heat from exhaust gases and the condenser of the absorption refrigeration system. The analysis includes technical, economical and ecological aspects, and for this are calculated the thermal efficiency, the payback period, the costs of production, the pollutant indicator and the ecological efficiency. The study shows that the implementation of this type of system is advantageous for tertiary sector, indicating a low payback period, less than 3 years for all economic parameters considered. In addition, the energy efficiency of the internal combustion engine is 35%, and the global efficiency of the cogeneration system is 74%, which proves that the use of the residual heat to produce hot and cold water promotes a financial economy.*

Keywords: *Cogeneration, Hot and Cold Water, Ecological Efficiency, Economical Analysis, Electricity*

1. INTRODUCTION

Cogeneration is an energy conservation method that can be defined as the simultaneous production of power (electrical or mechanical) and useful heat from a single fuel source (Silveira et al., 2002). This is not a new concept, industrial plants led to the concept of cogeneration back in the 1880s when steam was the primary source of energy in industry, and electricity was just surfacing as a product for both power and lighting (Orland JA, 1996 apud Onovwiona, et al., 2006). In the case of the electricity generation from internal combustion engines, the waste heat contained in the exhaust gases, and in the engine cooling water jackets, may be used to produce thermal energy for other processes.

This technology is also known as Combined Heat and Power (CHP) or Combined Colling Heating and Power (CCHP), when the useful heat is used to produce hot and cold water, associated to an Absortion Refrigeration System (ARS) (Wang, et al. 2014 apud Wang, et al., 2015). These systems are considered worldwide as an energy-saving and environmental-friendly energy system for buildings. (Dong, L. et al. 2009 apud Wang, J-J. et al., 2015)

Therefore, cogeneration plants allow the best use of the energy generated in the engines for, in addition to electricity, produce hot water for the different requirements of the building, and cold water for the cooling system. In the tertiary sector, such as hospitals and hotels, these plants have been widely used and studied because of the possibility of savings generated in the use of the fuel and the use of electricity network, which is no longer necessary to drive electric refrigerators, usually used.

In this article, the technical, economical and ecological aspects of the cogeneration use in a hotel are analyzed. The physical information of an enterprise located in the town of Salou, in the province of Tarragona, Spain, is used to create a model. Based on the thermal and electric power data of this hotel, will be analyzed the implementation of a hotel in the state of São Paulo using an internal combustion engine associated with an absorption chiller and heat exchangers to produce electricity, hot water and cold water.

1.1. THE ENERGY REQUIREMENTS

The hotel complex has an electrical total power installed of 1.109,4 kW, of which 331.7 kW (nominal power) are used in cooling and heating systems. This system consists in using three Compression Refrigeration Systems that produce together hot water (COP 2.54) or cold water (COP 2.48) depending on the season and the need for cooling or heating of the hotel accommodations. As the cooling system is replaced completely by the absorption refrigeration system, the electrical demand will be considered to be 800 kW.

For heating domestic hot water, the complex has 2 boilers natural gas 225 kW of individual power. In these boilers water is heated to 70 ° C and sent to 4500 liters accumulators from which the is mixed with water in environmental temperature from the network and sent to use by 58 ° C temperature, as recommended by local law.

Table. 1 shows the values of thermal demand according to the internal and external spaces, building materials and environmental conditions, taking into account winter and summer seasons.

Table 1. Thermal demands of the hotel according to Magán (2004)

	Cooling Demand (kcal/h)	Hot Water Demand (kcal/h)	TOTAL (kcal/h)
Winter	881861.90	994750.00	1876611.90
Summer	934897.12	618933.45	1553830.57

The values shown in Tab. 1 were obtained applying the calculations for thermal load. They are higher than the heating and cooling compression system capacity presented by Magán (2004), 724919.89 kcal/h and 707795.79 kcal/h respectively. This fact is justified because the thermal demand values are the maximum possible according to the characteristics of the accommodation and the location weather conditions.

The weather conditions for the analyzed region allow discard the use of heating systems in winter. For this reason, this paper considers only the conditions calculated by Magán (2004) for the summer.

2. TECHNICAL ANALYSIS

The system consists of a ICE (Internal Combustion Engine) associated with an ARS (Absorption Refrigeration System) and HE (Heat Exchangers) used for producing hot water through heat recovery from the cooling system of the absorption refrigeration system. Thus, the hot water generated for use in the hotel follows a single path out of the network at 25 ° C heating by heat exchange with the cooling water of the ARS at the appropriate temperature.

Figure 1 illustrates the cogeneration plant described, named for the characteristic of producing heat and electricity by the burning of a single fuel. In this case, the useful heat is reused in two ways, the first being the production of hot water for sanitary purposes and leisure areas of the hotel complex, and second, to produce cold water through the Absorption Refrigeration System.

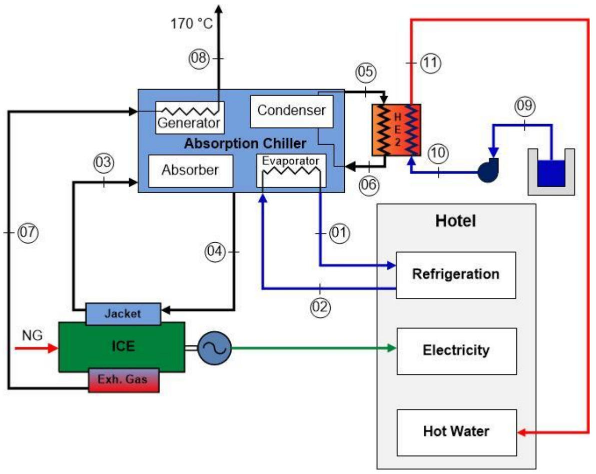


Figure 1. Cogeneration Plant Diagram

At first an absorption chiller was chosen based on the cold requirement of the hotel air conditioning system. The manufacturer data for the absorption chiller selected are presented in Table 2.

Table 2. Thermax EJ 30A TCU. (Thermax Catalog)

Cooling Capacity	1182 kW
Chilled Water Flow Rate	56.3 kg/s
Chilled Water Inlet Temperature	12.0 ºC
Chilled Water Outlet Temperature	7.0 ºC
Cooling Water Flow Rate	93.3 kg/s
Cooling Water Inlet Temperature	29.4 ºC
Cooling Water Outlet Temperature	35.4 ºC
Exhaust Gas Inlet Temperature Range	275 - 600 ºC
Exhaust Gas Outlet Temperature Range	170 - 200 ºC
Exhaust Gas Maximum Heat Input	510 kW
Hot Water Inlet Temperature Range	80 - 120 ºC
Hot Water Outlet Temperature Range	70 - 110 ºC
Hot Water Maximum Heat Input	647 kW

Looking at data reported in Tab. 2, it can be noted that the manufacturer does not provides the efficiency for this equipment. The performance of cooling equipment is usually rated in terms of COP, defined as the cooling output, or refrigeration effect, divided by the energy input. This parameter shows the efficiency of the chiller by the ratio of the capacity of the production of cold water with the energy required for this aim, and can be calculated using the data from the absorption chiller catalog. The selected absorption chiller has two heat inputs, exhaust gas from the internal combustion engine and cooler water from the engine jackets. The COP for this refrigeration machine is obtained by Eq. (1) using the maximum heat input of each source and the nominal cooling capacity.

$$COP = \frac{Q_{REFR}}{Q_{EXH\_MAX} + Q_{JACK\_MAX}} \tag{1}$$

In which:

Q_{REFR} = Cooling capacity

Q_{EXH_MAX} = Exhaust gas maximum heat input

Q_{JACK_MAX} = Hot water maximum heat input

Subsequently, it selected an Internal Combustion Engine capable of supplying the energy required to drive the absorption chiller, this because the heat wasted by the exhaust gases and engine jacket water will be used to supply the energy requirement of the absorption refrigeration system. Table 3 presents the catalog data for the selected engine.

Table 3. Guascor SFGM 560 internal combustion engine genset manufacturer data.

Engine Power	1100 kW
Speed	1800 rpm
Exhaust Gas Temperature	532 ºC
Exhaust Gas Mass Flow	1.444 kg/s
Combustion Air Mass Flow	1.388 kg/s
Electrical Power	1065 kW
Hot Water Heat	590 kW
Hot Water Flow Rate	20.8 kg/s
Hot Water Outlet Temperature	90 ºC

Natural gas comes from Campos Bay and its composition is presented in Table 4. This gas has a Lower Heating Value of the 47966 kJ/kg (Tuna, 1999).

Table 4. Campos Bay natural gas composition.

Components	% mol
CH_4	89.350
C_2H_6	8.030
C_3H_8	0.780
C_4H_{10}	0.040
C_4H_{10}	0.030
C_5H_{12}	0.010
CO_2	0.480
N_2	1.280

Fuel consumption is calculated by the difference between the exhaust gas mass flow and the combustion air mass flow. At full power the fuel consumption is 0.056 kg/s.

The Eq. (2) is used to determine the heat recovered from the internal combustion engine (ICE) exhaust gas.

$$Q_{EXH} = \dot{m}_{EXH} \cdot cp_{EXH} \cdot \Delta T \tag{2}$$

In which:

$\dot{m}_{EXH}$ = Exhaust gas mass flow

cp_{EXH} = Specific heat capacity of exhaust gas

ΔT = Difference of exhaust gas temperature between the ICE and absorption chiller.

The exhaust gas specific heat is calculated using the equation proposed by (Tuna, 1999), Eq. (3).

$$cp_{EXH} = 0.991615 + \frac{6.99703 \cdot T}{10^5} + \frac{2.71298 \cdot T^2}{10^7} - \frac{1.22442 \cdot T^3}{10^{10}} \tag{3}$$

According to (Reis, 2006), it can be assumed a value of 0.7 for the water/water heat transfers efficiency. Eq. (4) is used to calculate the heat recovered from the condenser to produce hot water.

$$\eta_{HT1} = \frac{Q_{HW}}{Q_{HT1}} \tag{4}$$

The global efficiency of the plant can be obtained considering the heat and power consumption by the system and the energy that enters in the ICE.

3. ECONOMICAL ANALYSIS

For economical analysis of the proposal cogeneration plant it is necessary to find in the literature reliable ways of determining the production costs of the inputs involved in the plant (cold water, hot water and electricity). These inputs are always analyzed separately in order to add fuel costs, investment in equipment, operation and maintenance.

Table 5 presents the data assumed to the economic calculations.

Table 5 Economic Parameters

H [h/year]	7300	Period of utilization of the plant
c_{fuel}[US$/m^3]	0.6067	Cost of the gas natural fuel (Brazilian Energy Balance, 2014)
c_{ep}[US$/kWh]	0.070	Electricity purchase price
c_{sur}[US$/kWh]	0.035	Surplus electricity sale price
c_{chw}[US$/kWh]	0.0188	Hot water production price by the boilers (conventional system)

c_{ccw}[US$/kWh]	0.032	Cold water production price by the compression system (conventional system)

Investment costs at the plant involving Internal Combustion Engine costs, Absorption Refrigeration System and Heat Exchangers. These are described by the Eq. (5), (6) and (7) (Brizi et al, 2014; Silveira et al, 2012).

$$I_{ICE} = 1200 \text{ [US\$/kW]} \tag{5}$$

$$I_{HE} = 60 \text{ [US\$/kW]} \tag{6}$$

$$I_{ARS} = 200 \times 1.2 \text{ [US\$/kWe]} \tag{7}$$

Maintenance costs of each equipment supplied is also taken into account, as they influence the final cost of production as well as the calculation of the payback period. The Eq. (8), (9) and (10) take into account the maintenance costs of the equipments of the cogeneration plant.

$$Cm_{ICE} = 0{,}0130 \text{ [US\$/kWh]} \tag{8}$$

$$Cm_{HE} = 0{,}05 \cdot \frac{I_{HE} \cdot f}{H \cdot E_{HW}} \text{ [US\$/kWh]} \tag{9}$$

$$Cm_{ARS} = 0{,}1 \cdot \frac{I_{ARS} \cdot f}{H \cdot E_{abs}} \text{ [US\$/kWh]} \tag{10}$$

In which:

E_{abs} = Absortion refrigeration system produced energy [kW]

E_{HW} = Hot water energy [kW]

The energy losses throughout the cogeneration plant can be determined taking into account the difference between total supplied energy and the useful energy harnessed (energies required for refrigeration system, electricity and hot water). Eq. (11) shows this calculation.

$$Losses = E_{fuel} + E_{abs} - E_p - E_{HW} \text{ [kW]} \tag{11}$$

In which:

E_{fuel} = Fuel energy [kW]

Production costs involve the production costs of the cogeneration plant inputs, which are the electricity, hot water and cold water, as shown in Eq. (12), (13) and (14).

$$c_{el} = \frac{(I_{ICE}) \cdot f}{H \cdot E_P} + c_{fuel} \cdot \frac{(E_{fuel} + E_{abs} - E_{HW} - {}^{losses}\!/_{2})}{E_P} + Cm_{ICE}$$

(12)

$$c_{hw} = \frac{(I_{ARS}) \cdot f}{H \cdot E_{abs}} + c_{fuel} \cdot \frac{(E_{abs} - {}^{losses}\!/_{2})}{E_{abs}} + Cm_{ARS} \tag{13}$$

$$c_{cw} = \frac{(I_{he}) \cdot f}{H \cdot E_{HW}} + c_{fuel} + Cm_{ARS} \tag{14}$$

In which:

E_P = Electricity energy [kW]

To make it possible to determine the financial benefits from the cogeneration plant deployment in the hotel complex, and the payback period of investments, the equations (15), (16), (17), (18), (19) and (20) are necessary in the calculations. The determination of these values is extremely important to analyze the financial feasibility of the cogeneration system deployment.

Annuity factor:

$$f = \frac{q^k (q-1)}{q^k - 1} \tag{15}$$

In which:

$$q = 1 + \frac{i}{100} \tag{16}$$

k = Payback period (years)

The profit due to electricity production is shown in Eq. (17).

$$Pd_{el} = E_r \cdot H \cdot (c_{ep} - c_{el}) + (E_P - E_r) \cdot H \cdot (c_{sur} - c_{el}) \tag{17}$$

The profit due to hot water production is shown in Eq. (18).

$$Pd_{hw} = E_{he} \cdot H \cdot (c_{chw} - c_{hw}) \tag{18}$$

The profit due to cold water production is shown in Eq. (19).

$$Pd_{cw} = E_{abs} \cdot H \cdot (c_{ccw} - c_{cw}) \tag{19}$$

The annual receipt expected for the cogeneration plant is shown in Eq. (20)

$$R = Pd_{el} + Pd_{hw} + Pd_{cw} \tag{20}$$

4. ECOLOGICAL ANALYSIS

For ecological analysis it is important to calculate the ecological efficiency of the cogeneration plant, which takes into account the thermal efficiency and emissions of greenhouse gases to the atmosphere and to the environment. This efficiency is calculated by the equation proposed by (Villela, 2007).

The ecological efficiency is defined as a number that evaluates the environmental impact of greenhouse gases emissions of a thermoelectric power plant, by comparing integrated pollutant emissions hypothetically equivalent CO_2 emissions with existing standards of air quality, based on CO_2 pollution effects. The Eq. (21) is used to determine the carbon equivalent from the plant in kg / kgf (carbon kilograms per fuel kilograms).

$$[CO_2]_e = CO_2 + 80 \cdot (SO_2) + 50 \cdot (NO_x) + 67 \cdot (PM) \tag{21}$$

In which PM means Particulate Matter.

The best fuel is one that will present less carbon dioxide equivalent value. And to quantify the environmental impact of this value is calculated the "pollution indicator", initially proposed by (Cardu and Baica, 1999), shown in Eq. (22).

$$\Pi_g = \frac{[CO_2]_e}{LHV} \tag{22}$$

After previous presentations, it is possible to calculate the ecological efficiency, which aims to evaluate the effect of polluting thermoelectric plants, shown in equation (23).

$$\varepsilon = \left[\frac{0{,}204 \cdot \eta_{pl}}{\eta_{pl} + \Pi_g} \cdot \ln(135 - \Pi_g) \right]^{0{,}5} \quad (23)$$

Calculations of CO2 and NOx emissions are presented as described in equations (24), (25) and (26).

$$M_{CO_2} = \frac{\left(w_1 \cdot 44 \cdot 1\right) CO_2}{M} \quad (24)$$

$$M_{NO_X} = \frac{\left[\left(2270 \cdot 22{,}4 \cdot 10^{-3}\right) / 10^6\right] NO_X}{M \cdot 10^{-3}} \quad (25)$$

$$M_{PM} = \frac{\left[\left(240 \cdot 22{,}4 \cdot 10^{-3}\right) / 10^6\right] PM}{M \cdot 10^{-3}} \quad (26)$$

In which:
M = Molecular weight of the Natural Gas = 17.710 kg/mol.
w_1= Produced amount of carbon dioxide = 1.087 kg CO2/kgNG

For the ecological analysis, the calculated parameters were the indicator of pollution and ecological efficiency. The ecological efficiency may vary between the values 0 and 1, in which 1 represents a plant with zero pollution, and 0 represents a very polluting plant.

5. RESULTS

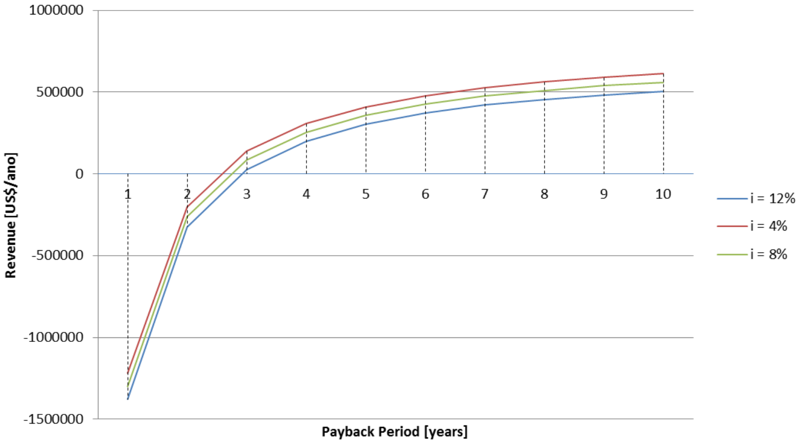
Through the observation of the data from the catalogs of equipment the proposed cogeneration plant could be analyzed point by point, according to the thermodynamic conditions of the water present in each of these points. Table 5 shows the calculated values of enthalpy and pressure at each location according to their temperature and mass flow.

Table 5. Thermodynamic properties of water at the points.

Point	T [°C]	P [MPa]	ṁ [kg/s]	h [kJ/kg]
01	7.0	0.784	56.3	30.16
02	12.0	0.784	56.3	51.15
03	90.0	0.101	22.2	376.90
04	82.0	0.101	22.2	348.00
05	35.4	0.784	93.3	149.00
06	29.4	0.784	93.3	124.00
07	532.0		1.4	
08	170.0		1.4	
09	25.0	0.101	76.9	104.93
10	25.0	0.101	76.9	104.93
11	70.0	0.101	1.2	293.08

Figure 2 presents the curve of the payback period due to the expected revenue depending on the interest rate applied.

Figure 2. Payback period in function of revenue.



The ecological efficiency calculated for the system was 96.7%, which means a plant with high ecological efficiency, ie, low pollution. Comparing to the values found by Coronado (2009), who evaluated the ecological efficiency of internal combustion engines burning different fuels, such as natural gas, diesel and gasoline, obtaining values of 91.95%, 77.34% and 82.52%, respectively.

6. CONCLUSIONS

This study designed a cogeneration system based on the electricity and thermal demands of a hotel from Spain to be adapted to a Brazilian situation. To recover waste heat from the exhaust gases of the Internal Combustion Engine was associated to an Absorption Cogeneration System to produce cold water and heat exchangers to produce hot water. The fuel considered was natural gas because of its LHV (Low Heating Value) and the proximity to the pipelines mesh existing in the country.

Through the results obtained by the analysis of the proposed cogeneration plant, it is possible to highlight ecological efficiency of 96.7% and 85.5% of thermal efficiency. The payback period up to 3 years, depending on the interest rate used to return investment in the plant, showed that the return on investment will be considered satisfactory.

These results lead to the conclusion that the implementation of a cogeneration system, even when it comes to tertiary sector, is very advantageous. The cycle efficiency raised from 35.7% (for producing electricity) to 85.5% when the waste heat from the exhaust gases and engine cooling water are used to the association with the Absorption Refrigeration System and the Heat Exchangers.

This study can be seen as an incentive and motivation for continuing studies about the use of the cogeneration systems for the tertiary sector, and develop deeper cycles for applications in actual locations. The cogeneration is an important tool to bring satisfactory results regarding the rational use of energy.

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