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AN EXERGY ANALYSIS OF COMBINED COOLING AND POWER SYSTEMS USING ABSORPTION CHILLERS: A COMPARATIVE APPROACH

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Abstract. Combined cooling and power has been appointed as a good alternative to supply energetic demands in several commercial sectors. In addition, natural gas has become a feasible source to power these systems. In this study, four cogeneration scenarios are evaluated considering power and cold generation in an effort to point out the most technically workable one. First and second laws of thermodynamics are applied. The scenarios consider internal combustion engine and microturbine as prime movers with a nominal power of 1200 kW_e. For the refrigeration system, steam and hot water fired chillers are studied. In general, the results indicate the scenario composed by engine and hot water absorption chiller as the best alternative. This configuration has presented 88,2% and 49,9% of thermal and exergetic efficiencies, respectively.

Keywords: Natural gas cogeneration, gas engine, gas turbine, absorption chiller

1. INTRODUCTION

In Brazil, there is a large potential to install small plants in special on tertiary sector. According to reports of Procel (2008), 40.3% of the demand commercial of electricity was destined to air conditioning. In more specific sectors, such as shopping centers and supermarkets, the electrical demand for air cooling and refrigeration are 54% and 70%, respectively (Fig. 1). Due the large demand for cooling in this sector, CCP systems can be a good alternative to provide thermal and electrical energy, decreasing the costs related to grid usage.

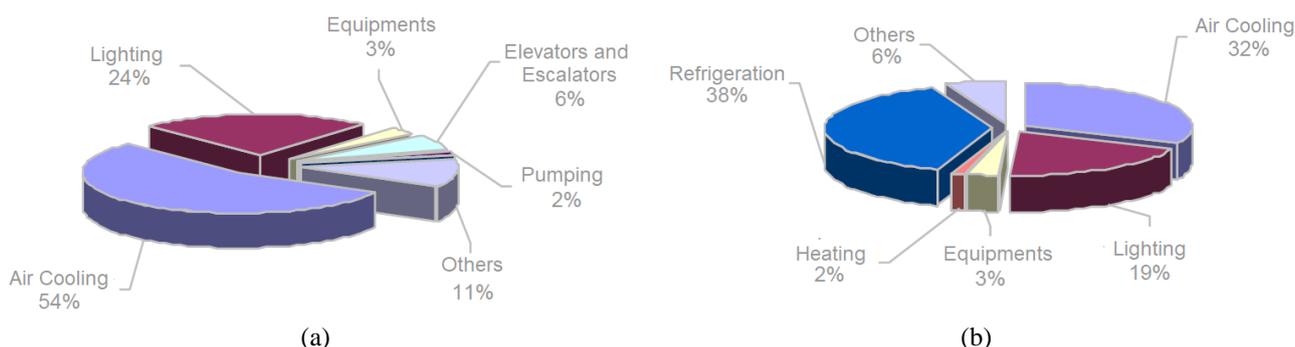


Figure 1. Electrical demand in commercial sectors: (a) Shopping Centers; (b) Supermarkets. (Procel, 2008)

Since 1997, with the objective of increasing the range of gas natural use, ANP (national agency of petroleum, natural gas and biofuels) has started a incentive policy to expand the R&D resources in this area, through partnerships with universities and research centers (AZEVEDO, 2016). In this respect, LabCET/UFSC has developed several works in cogeneration systems in order to improve the energy utilization of natural gas.

First results were reported by Rucker (2005) regarding an exergoeconomic analysis of a small cogeneration plant powered by a 28 kW microturbine, a 30 kW LiBr/H₂O absorption chiller and a heat exchanger transferring the energy from exhaust gases to water. Rossa and Bazzo (2009) carried out a thermodynamic modeling of the power plant powered by a 28 kW microturbine studied using a NH₃/H₂O hot water chiller connected by a thermosiphon heat exchanger. The proposed configuration changes the heat source of the absorption chiller, replacing the original natural

gas burning system. The reported results showed an increase about 67% in the plant global efficiency when compared to the single microturbine. In the same way, Bazzo *et al.* (2013) reported experimental results considering a HRSG (heat recovery steam generator) where saturated steam is generated using the exhaust gases. Tests with the microturbine at full load produced 9,2 kW of refrigeration that is a COP in order of 0,44.

Several works have addressed CCP systems worldwide. Demirkaya *et al.* (2013) presented an extensive review exploring distinct configurations for cooling and power generation. This paper considers absorption/adsorption, ejector and vapor compression cycles as the refrigeration system of the cogeneration plants. For the prime movers, this work shows classical cycles, such as Rankine, Otto and Brayton, as well as innovative solutions, such as the Kalina cycle and fuel cells.

In general, the proposed systems use fossil fuels, such as the oil products and biomass, which are already found as mature technologies. In this context, natural gas appears as a promising alternative. According to Kalogirou (2016), the natural gas has an availability estimate of around 54 years and, although a non-renewable energy, it has an important role for supporting the transition from fossil fuels to renewable sources, with low associated cost and easy integration.

Although the availability of natural gas is of the same order as oil with adequate investments in pipelines and infrastructure components, gas can be the main source of energy for many years. In Brazil, the law project 6407/13, which deals with an update in the gas market, is under discussion. If approved, the gas production chain concerning the exploration, production, transportation, distribution, and commercialization will be updated and, consequently, the product price would have an expect reduction of about 27% (CNI, 2020).

This work aims to evaluate four selected scenarios of cogeneration powered by a nominal 1200 kWe prime mover (internal combustion engine and microturbine) using gas natural as fuel, combined with absorption chillers.

2. PROPOSED SCENARIOS

The four proposed scenarios are in the following: (i) Scenario A - internal combustion engine and steam fired absorption chiller; (ii) Scenario B - internal combustion engine and hot water fired absorption chiller; (iii) Scenario C - microturbine and steam fired absorption chiller and (iv) Scenario D - microturbine and hot water fired absorption chiller.

The scenarios A and B are shown in Fig. 2. The prime mover consists in an ICE Caterpillar® model CG170-12. The points 1 and 2 represent the natural gas and air intakes, respectively. According to catalog data, point 3 corresponds the cooling water outlet in 93 °C and point 4 the feedback in 80 °C. The point 5 represents the exhaust gases. In scenario A, a Heat Recovery Steam Generator (HRSG) produces saturated steam required by chiller (point 10). In scenario B, hot water is produced by a heat exchanger.

The scenarios C and D are shown in Fig. 3. The prime mover consists in a microturbine Saturn 20 Caterpillar® model T 1601. The point 1 represents the air intake. The fuel is injected directly in the combustion chamber. Finally, exhaust gases are rejected in point 4. The heat recovery in scenarios C and D are similar to scenarios A and B, respectively.

3. METHODOLOGY

The first and second laws of thermodynamic were taken into account at every scenario subjected to the following assumptions:

1. Steady state condition;
2. Kinetic and potential energies are neglected;
3. Adiabatic heat exchangers;
4. Pressure drop in pipes are neglected;
5. Electrical consumption for thermal fluids pumping is neglected.

The dead state of 25°C and 101,325 kPa is considered. All the exergetic losses related to wall heat losses in the prime movers were here considered as exergy destruction. Thermodynamic calculations were performed using the Engineering Equations Solver – EES software (KLEIN, 2015). The mass flow rates and thermodynamic properties are shown in appendix.

The exergetic analysis was focused on the prime movers and the heat exchangers in order to evaluate the cooling and power generation in every scenario as proposed. In other words, the main goal is this work is to know the effective energy availability for cold production. The exergy analysis of the chiller does not own the scope of this paper. The Lower Heating Value, LHV, of natural gas was calculated according to the NBR 15213 Standard (ABNT, 2008).

The natural gas mass flow rate is obtained by

$$\dot{m}_{NG} = \frac{\dot{Q}_{comb}}{LHV} \quad (1)$$

where Q_{comb} represents the invested heat, in this case, the nominal energy consumption, as indicated in the catalogs (ENERIA, 2013 and TURBOMACH).

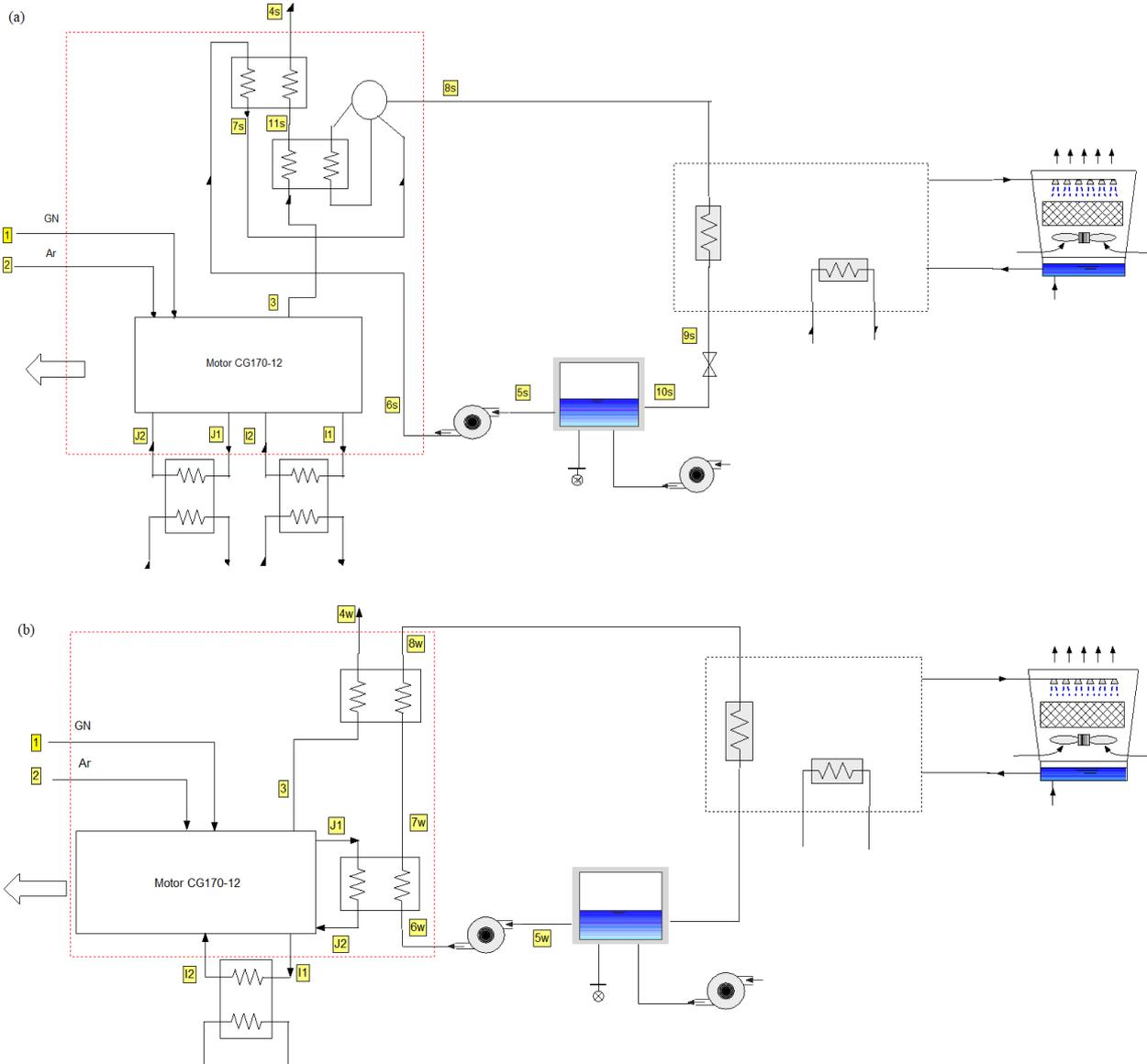


Figure 2. Cogeneration plants powered by ICE: (a) Scenario A – steam fired chiller ; (b) Scenario B – hot water fired chiller.

The system cooling capacity, Q_{cool} , is calculated by

$$\dot{Q}_{cool} = COP \cdot \dot{m}_{fluid} \cdot (h_{in} - h_{out}) \quad (2)$$

where COP is the coefficient of performance of the chiller, m_{fluid} is the feeding fluid mass flow rate (steam or hot water), and h_{in} and h_{out} are the fluid temperatures at inlet and outlet, respectively.

To evaluate the thermal efficient usage of the CCP cycle, two parameters are considered: thermal efficiency and utilization factor. The thermal efficiency evaluates the amount of energy recovered from the heat invested by the fuel, so that

$$\eta_{th} = \frac{\dot{W}_{mec} + \dot{m}_{fluid} (h_{in} - h_{out})}{\dot{Q}_{comb}} \quad (3)$$

where W_{mec} is the mechanical power. The utilization factor, as proposed by Çengel and Boles (2015) takes into account the desired energy flows (power and cooling) related to the invested heat, as

$$\epsilon_u = \frac{\dot{W}_{ele} + \dot{Q}_{cool}}{\dot{Q}_{comb}} \quad (4)$$

where W_{ele} is the electrical power delivered by the prime mover.

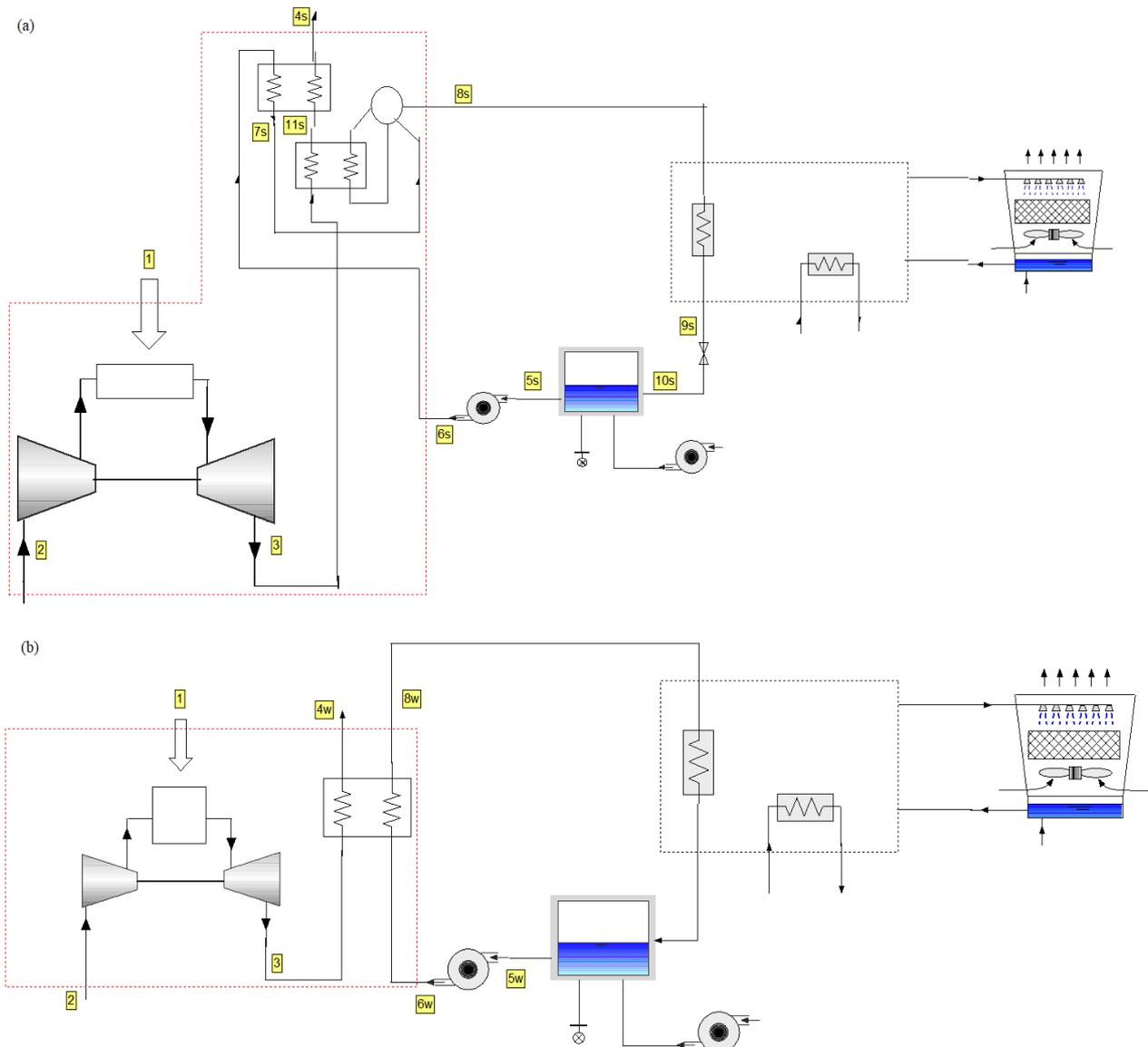


Figure 3. Cogeneration plants powered by microturbine: (a) Scenario C – steam fired chiller ; (b) Scenario D – hot water fired chiller.

To identify opportunities for improving the systems efficiency, exergetic analysis is also carried out with a focus on the exergy destruction in the prime movers, heat exchangers, and HRSG.

The chemical exergy associated to the natural gas, Ex_{ch} , is calculated by

$$\dot{Ex}_{ch} = \beta \cdot LHV \quad (5)$$

The ratio β is here estimated considering natural gas as a mixture of gaseous hydrocarbons, so that

$$\beta = 1,0334 + 0,0183 \frac{H}{C} - 0,0694 \frac{1}{C} \quad (6)$$

where H and C are the numbers of hydrogen and carbon atoms in the corresponding molecule, as proposed by Szargut *et al.* (1988). The chemical exergy is calculated by multiplying the molar fractions and chemical exergies of each fuel component.

The physical exergy, Ex_{ph} , of the other points of interest is calculated using

$$\dot{Ex}_{ph,i} = \dot{m}_{fluid} \cdot [h_i - h_{ref.} - T_{ref.} (s_i - s_{ref.})] \quad (7)$$

where the indexes i and $ref.$ represent the point of interest and the reference state, respectively, h and s represent enthalpy and entropy and T is the temperature in kelvin.

The exergy destruction is accounted for using

$$\dot{Ex}_{fuel} = \dot{Ex}_{destruction} + \dot{Ex}_{products} + \dot{Ex}_{losses} \quad (8)$$

Finally, exergetic efficiency is calculated by

$$\eta_{ex} = \frac{\dot{Ex}_{products}}{\dot{Ex}_{fuel}} \quad (9)$$

$$\eta_{ex} = 1 - \frac{\dot{Ex}_{destruction} + \dot{Ex}_{losses}}{\dot{Ex}_{fuel}} \quad (10)$$

4. RESULTS AND DISCUSSIONS

The calculation was performed considering the prime mover features showed in the table 1, using elementary analysis of the natural gas giving in table 2, respectively.

Table 1. Input data for cogeneration plants simulation

Parameters [Unit]	ICE	Turbine
Energetic consumption [kW]	2748	4750
Air-Fuel ratio (mass basis) [-]	29,32	62,51
Mechanical Power [kW]	1232	1175
Jacket water heat [kW]	608	-
Intercooler heat [kW]	106	-
Irradiation heat [kW]	41	-
Steam fired chiller and HRSG	-	
Absolute pressure [kPa]	800	
Pitch Point [°C]	15	
Approach Point [°C]	15	
COP [-]	1,51	
Hot water fired chiller	-	
Chiller water inlet temperature [°C]	95	
Chiller water outlet temperature [°C]	72	
COP [-]	0,8	

Table 2. Natural gas composition (SCGÁS, 2016)

Component	Methane (CH ₄)	Ethane (C ₂ H ₆)	Propane (C ₃ H ₈)	Butane (C ₄ H ₁₀)	Nitrogen (N ₂)	Oxygen (O ₂)
Fraction	0,89	0,06	0,02	0,01	0,005	0,015

The corresponding results including the natural gas parameters and the prime movers simulations are described in Tab. 3.

In this work, it was considered the elementary analysis of the natural gas available in Santa Catarina. So, as can be seen in Tab. 3, the lower heating value calculation of the fuel used in the analysis presented a higher value than that suggested by the catalog, resulting in a decrease in fuel consumption and an increase in the exhaust gases temperature.

Table 3. Natural gas parameters calculation and prime movers simulation

Parameters [Unit]	Calculated	Catalog
Fuel chemical exergy [kJ/kg]	49832	-
Beta – β [-]	1,041	-
ICE		
Lower Heating Value [kJ/kg]	47887	44503
Natural gas mass flow rate [kg/s]	0,05738	0,06179
Air intake mass flow rate [kg/s]	1,683	1,741
Exhaust gases outlet temperature [°C]	419,7	414
Turbine		
Lower Heating Value [kJ/kg]	47887	-
Natural gas mass flow rate [kg/s]	0,0992	-
Air intake mass flow rate [kg/s]	6,2	-
Exhaust gases outlet temperature [°C]	546,7	506

According to the results showed in Tab. 4, different decisions can be taken in respect to the best alternative, scenario B, if considered the thermal efficiency and scenario C, if considered the utilization factor.

Table 4. Gas natural parameters calculation and prime movers simulation

Parameters [Unit]	Scenario A	Scenario B	Scenario C	Scenario D
Cogeneration thermal efficiency (1 st Law) [%]	59,64	88,20	73,93	86,68
Cooling capacity [kW]	614,3	953,4	3529	2362
Utilization factor [%]	66,02	78,36	98,29	73,55
Exergy destruction and losses [kW]	1508	1435	2935	3285
Exergetic efficiency [%]	47,25	49,93	40,62	35,58

From the point of view of thermal efficiency, higher values were found in the scenarios B and D related to use of hot water chillers, as a consequence of the constructive characteristics of heat exchange systems.

The use of hot water heat exchanger allows to remove heat from the exhaust gases up to 120 °C, while HRSGs has restrictions related to the pitch and approach points, as a consequence of the saturated steam temperature. So, in scenarios B and D, the outlet temperature of the exhaust gases was 155.4 °C. Finally, among the four systems, scenario B showed the highest thermal efficiency of cogeneration.

In respect of the utilization factor, the difference observed in cogeneration efficiency is mitigated due to the high COP of steam chillers. Among the internal combustion engine scenarios, the hot water chiller system (scenario B) showed the greater cooling capacity and, consequently, the greater utilization factor, due to the high flow of hot water that outweigh the lower COP. In systems that use microturbine, the configuration with a steam chiller showed the highest cold production. In this scenario, the superior COP allowed the difference in thermal efficiency to be overcome. In general, scenario C presented the highest utilization factor among all configurations.

When considering the exergetic parameters together with the utilization factor, scenario C seems to be a good alternative. However, from the point of view of exergetic efficiency, scenario B is also a good alternative. And, finally, taking into account all the results found, scenario B appears as the most technically feasible proposal to meet the demands for cold energy and power for the case under analysis.

5. CONCLUSIONS

In this work, thermodynamics simulations were performed in combined cooling and power systems, in order to indicate the most suitable configuration for a cogeneration plant powered by natural gas. Four scenarios were analyzed associating a prime mover (internal combustion engine or microturbine) and an absorption chiller (hot water and steam). The analysis of first law demonstrated that the scenario B (engine and hot water chiller) has reached the greatest performance, because this configuration has presented the best usage of the fuel energy. The utilization factor pointed out the scenario C (microturbine and steam chiller) as the most feasible for this criterion. This is attributed to the high Coefficient of Performance of the steam chillers and the lowest efficiency of microturbine. Finally, the exergetic parameters showed the Scenario B as the most suitable.

This paper carried out an introductory analysis of CCP systems that can be employed in establishments of the tertiary sector. For further works, the authors recommend the simulations of other technologies and scenarios to expand the range of possibilities, as for example hybrid systems using natural gas and a renewable source (solar, biomass), in order to demonstrate the feasibility of other proposals. In this case, it is indicated scenarios with the same fuel consumption. It is also recommended a more specific exergetic analysis contemplating investigations in each specific component associated with exergoeconomic studies aiming the most techno and economically suitable scenario.

6. ACKNOWLEDGMENTS

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7. REFERENCES

- ABNT, 2008, “NBR 15213 – Cálculo de propriedades físico-químicas a partir da composição do gás natural”.
- Azevedo, P., 2016. *A interação UFSC e PETROBRAS para o desenvolvimento inovativo sob a óptica institucionalista-evolucionária*. Ph.D. thesis, Federal University of Santa Catarina, Florianópolis, Brazil.
- Bazzo, E., Carvalho, A.N. and Matelli J.A., 2013. “Experimental results and thermodynamic analysis of a natural gas small scale cogeneration plant for power and refrigeration purposes”. *Applied Thermal Engineering*, Vol. 58, p. 264-272.
- Çengel, Y. A. and Boles, M. A., 2015, “Thermodynamics: An engineering approach”, McGraw Hill Education, New York, United States of America.
- CNI, 2020. “Uma Análise da Nova Lei do Gás à Luz do Interesse Público”. Brasília, Brazil.
- Demirkaya, G., Padilla, R.V. and Goswami, D.Y., 2013. “A review of combined power and cooling cycles”. *Wiley Interdisciplinary Reviews: Energy and Environment*. Vol. 00, p. 1-14.
- ENERIA, 2013, “CATERPILLAR Gas genset, natural gas – CG170-12/1200 kWe”, Overijse, Belgium.
- Kalogirou, S. A. 2016, “Engenharia de energia solar: Processos e Sistemas”, Elsevier, Burlington, United States of America.
- Klein, S. A., 2015, EES-Engineering Equation Solver. Version 7.413-3D, F-Chart Software, Madison, WI.
- LG, 2015, “LG HVAC Solution – Absorption Chiller”, Seoul, South Korea.
- Procel, 2008. “Pesquisa de posse de equipamentos e hábitos de uso – Ano base 2005”. Rio de Janeiro, Brazil.
- Rossa, J.A. and Bazzo, E., 2009. “Thermodynamic Modeling of an Ammonia-Water Absorption System Associated with a Microturbine”. *International Journal of Thermodynamics*. Vol. 12, p. 38-43.
- Rucker, C. P. R., 2005. Análise exergoeconômica de uma planta de cogeração baseada em microturbina a gás natural e refrigeração por absorção pela teoria do custo exergetico. Master's thesis, Federal University of Santa Catarina, Florianópolis, Brazil.
- Szargut, J., Morris, D.R. and Steward, F.R., 1988, “Exergy analysis of thermal, chemical, and metallurgical processes”, Springer Verlag, Berlin, Germany.
- Turbomach, 2012, “Gas turbine generator package – SATURN 20”

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.

APPENDIX

Table A1. Mass flow rates and thermodynamic properties of Scenarios A and B.

Points	m [kg/s]	P [kPa]	T [°C]	h[kJ/kg]	s[kJ/kg K]
1	0,05738	101,3	25	-	-
2	1,683	101,3	25	298,6	5,696
3	1,74038	-	419,6	705,8	6,561
4s	1,74038	101,3	153,8	428,6	6,058
4w	1,74038	101,3	120	394,3	5,974
5s	0,1987	101,3	89,99	377	1,193
5w	-	-	-	-	-
6s	0,1987	800	90,17	377,8	1,195
6w	12,34	101,3	72	301,5	0,9794
7s	0,1987	800	155,4	655,7	1,896
7w	12,34	101,3	83,75	350,8	1,12
8s	0,1987	800	170,4	2768	6,662
8w	12,34	101,3	95	398,1	1,25
9s	0,1987	800	170,4	720,9	2,046
10s	0,1987	101,3	99,47	720,9	2,116
11s	1,74038	101,3	185,4	460,9	6,131
J1	11,56	101,3	93	389,7	1,227
J2	11,56	101,3	80	335,1	1,076
I1	9,641	101,3	43	180,2	0,6122
I2	9,641	101,3	40	167,6	0,5724

Table A2. Thermodynamic properties of Scenarios C and D.

Points	m [kg/s]	P [kPa]	T [°C]	h[kJ/kg]	s[kJ/kg K]
1	0,0992	101,3	25	-	-
2	6,201	101,3	25	298,6	5,696
3	6,3002	-	551,5	849,4	6,751
4s	6,3002	101,3	135,2	409,8	6,013
4w	6,3002	101,3	120	394,3	5,974
5s	1,141	101,3	89,99	377	1,193
5w	-	-	-	-	-
6s	1,141	800	90,17	377,8	1,195
6w	30	101,3	72	301,5	0,9794
7s	1,141	800	155,4	655,7	1,896
7w	-	-	-	-	-
8s	1,141	800	170,4	2768	6,662
8w	30	101,3	95	398,1	1,25
9s	1,141	800	170,4	720,9	2,046
10s	1,141	101,3	99,47	720,9	2,116
11s	1,74038	101,3	185,4	460,9	6,131