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Thermodynamic performance investigation of a trigeneration cycle considering the influence of operational variables

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Abstract

A rational use of fossil fuels together with a growing concerning about environmental issues have led to many researches aiming at an improvement of energy systems performance, trying to develop more economical and also more eco-friendly solutions. A cogeneration system (Combined Heat and Power - CHP) is an alternative technique that produces heat and power consuming less of primary energy sources, especially fossil fuels. Recently trigeneration systems, also named Combined Heat, Cooling and Power (CHCP), have gained great interest for industrial and commercial applications, due to a better energetic efficiency when compared with CHP systems. CHCP is an economical and available technology, demanding a single source of primary energy, with the advantages of saving energy, money, and making a clever user of fossil fuels with benefits to the environment. The main objective of this work is to evaluate the thermodynamic performance of a trigeneration system, using a process simulation software, considering the influence of some operational variables: compression ratio in the compressor, expansion ratio and efficiency of the power cycle turbine; boiler operation pressure; and operational pressure of the absorption cycle in both sides (high and low pressure). Natural gas is used as primary energy source. In the absorption refrigeration cycle the pair solvent-refrigerant used is H_2O-NH_3. For the base case studied total thermal efficiency was 78% and COP of the absorption refrigeration cycle was 0.57, while for the optimized case these values are 82% and 0.48. The most important operational variables to improve efficiency of the cycle are compressor ratio in the compressor and expansion ratio in the turbine.

Keywords: Trigeneration; simulation; performance; efficiency; optimization

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Nomenclature

COP	coefficient of performance of the absorption refrigeration cycle
h_i	specific enthalpy of stream *i* ($kJ.kg^{-1}$)
HRSG	heat recovery steam generator
LHV_j	low heat value of fuel *j* in the natural gas ($kJ.kg^{-1}$)
$\dot{m}_i$	mass flow rate of stream *i* ($kg.s^{-1}$)
$\dot{m}_{i,j}$	mass flow rate of component *j* in stream *i* ($kg.s^{-1}$)
P	absolute pressure (kPa)
$\dot{Q}_{evap}$	heat removal rate in the evaporator (kW)
$\dot{Q}_{HRSG}$	heat flow in the heat recovery steam generator (kW)
$\dot{Q}_{in}$	total input of heat flow in the trigeneration system (kW)
$\dot{Q}_{reboiler}$	heat flow in the reboiler of the distillation column (kW)
RV	reference value taken from literature
T	temperature (^oC)
TW	values obtained in this work
$\dot{W}_{turb}$	power produced by the gas turbine (kW)
$\dot{W}_{comp}$	power consumed in the compressor (kW)
$\dot{W}_{net}$	net power produced by the trigeneration system (kW)
x_j	mass fraction of component *j*

Greek letters

η	total thermal efficiency of the trigeneration system (%)
ΔP	absolute pressure drop in the valve of the absorption cycle (kPa)

Subscripts

i	index for the stream process
j	index for the fuel component

1. Introduction

Two of the main concerns related to the sustainability of energy production is the availability of energy sources and global warming, leading to intense discussions between researchers and governments, trying to develop new technologies which would be able to increase the efficiency of thermal systems. The use of fossil fuels is critical to these two issues mentioned before, because their availability is reducing year after year and their use is responsible for the increase in greenhouse gases emissions into the atmosphere.

Thermodynamic efficiency of conventional power plants are no more than 39% [1] and the use of some alternative systems like cogeneration systems (Combined Heat and Power - CHP) and trigeneration systems (Combined Heat, Cooling and Power – CHCP) helps to increase system efficiency to 80% [1]. These combined systems have the advantage to produce process utilities like power, heat and cooling (in the case of CHCP systems) from a single energy source, which is used more efficiently than if the desired products were produced separately, saving energy, money and making a clever user of energy sources, especially fossil fuels, with benefits to the environment. Lin *et al.*[2] have shown that, for a household size trigeneration based on a small-scale diesel engine generator, the total thermal efficiency of trigeneration reaches 67.3% at the engine operating with full load, while the original single generation efficiency was only 22.1% and the reductions of CO_2 emissions per kWh of trigeneration output were from 67.2% to 81.4% compared to those of single generation. According to the International Energy Agency, the expected reduction in CO_2 emissions as a result of using trigeneration and cogeneration plants will be 170 Mt/year in 2015, while in 2030 the expected reduction will be 950 Mt/year [3]. Many different applications of trigeneration systems may be found in the literature. Some examples are: hospitals [4,5]; supermarkets [6,7] and industrial processes [8,9,10] and airports [11,12].

The principle of a trigeneration plant consists in using the waste energy from a generation unit, such as a gas turbine, to drive both the heating and cooling system [1]. In general, trigeneration plants are used as decentralized plants, since it is necessary to keep the needed temperatures of the cooling and heating demands, which requires an adequate insulation for pipes and equipment, implying that trigeneration plants almost always are located close to the final user.

A trigeneration system can be described in a simple manner as follows: a fuel is burned with a certain quantity of air in a combustion chamber generating gases at high pressure and temperature; these gases produce mechanical power when they pass through a gas turbine and this mechanical power is used to rotate an electrical generator; then the waste heat of the gas stream at the exit of the gas turbine is used to produce the heating demand (generally a heat recovery steam generator – HRSG – is used) and finally, the waste heat of the gas stream living the HRSG is used to meet the cooling demand, for example, in an absorption chiller, which is a good alternative to meet the cooling demand because the power required in the generator to initiate the cycle may be of low quality. Besides this, absorption chillers consist of a cleaner technology when compared to vapor compression refrigeration cycles with less damage to the environment [13].

In designing a trigeneration plant, its optimized use must consider that the plant should be flexible enough with the heating and cooling demand variations [1]. So, considering the advantages of a trigeneration plant, the great number of different applications of this system and the need to operate it in an optimized manner, with flexible demands of heating and cooling, the objective of this work is to investigate thermodynamic performance of a trigeneration system considering the influence of operational variables over the total thermal efficiency and over the distribution of utilities produced in the system, using a process simulator. With this tool it is possible to evaluate the influence of the following variables: compression ratio in the compressor and expansion ratio in the turbine of the power cycle; boiler operation pressure; heat removal rate in the evaporator of the absorption cycle and operational pressure of the absorption cycle in both sides (high and low pressure). As primary energy source natural gas is burned in the combustion chamber of the power cycle. In the absorption refrigeration cycle the pair solvent-refrigerant used is H_2O-NH_3. After evaluating the influence of these variables, an optimization procedure with an objective function defined to maximize the total thermal efficiency of the system was performed.

2. Methodology

2.1. Trigeneration system

The trigeneration system used in this work is shown in Figure 1 and it was developed based in the works of Ameri *et al.* [14] and Colonna and Gabrielli [8]. Trying to obtain data from literature in order to develop process simulations that could be validated by comparison with these data a combination of these two works was used to compose our trigeneration system. From [13] data of the cogeneration plant (Brayton cycle and steam boiler) were taken and from Colonna and Gabrielli [8], data of the absorption refrigeration cycle. The reason to combine these two works instead of using only one work from literature was the easy access to process data, allowing a good evaluation of the simulations, comparing the results obtained with the ones from literature.

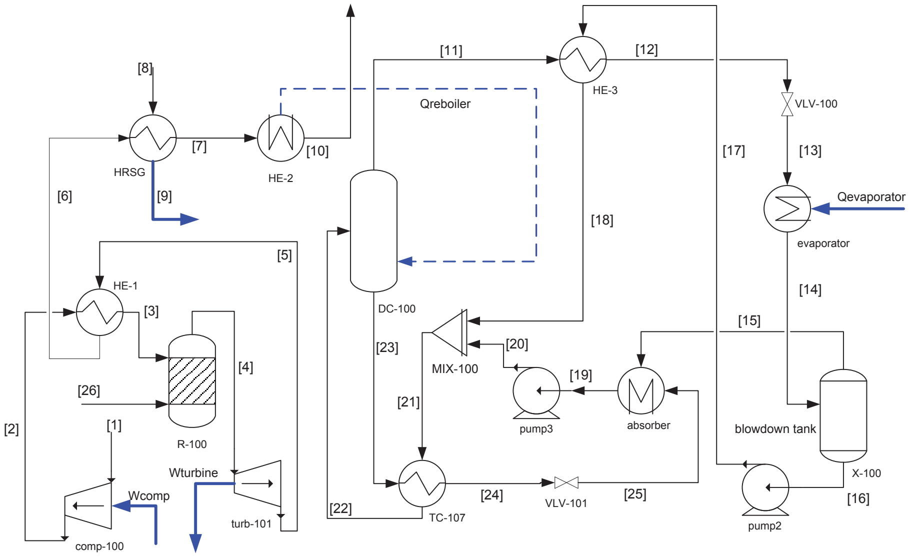

Fig. 1. Flow diagram of the trigeneration system (blue arrows indicate the main energy streams)

The description of the trigeneration system, according to Figure 1 is as follows: a stream of dry atmospheric air {1} containing oxygen in excess is fed in the compressor, where its temperature and pressure is increased generating stream {2} that enters in a heat exchanger where it is heated even more, generating stream {3} that feeds the combustion chamber together with a stream of natural gas {26}. The stream of hot gases {4} that leaves the combustion chamber passes through a gas turbine to produce power, the first product of the trigeneration system. Part of this power is used to move the compressor. The stream that leaves the gas turbine {5} passes through the heat exchanger, heating stream {2} and leaves the heat exchanger as stream {6} going to the HRSG where it heats a stream of pressurized water {8} to produce a vapor stream {9} that is the second product of the trigeneration system. Stream {6} becomes stream {7} at the exit of the HRSG which passes through the generator of the absorption refrigeration cycle (this generator is the reboiler of the distillation column of the absorption refrigeration cycle). Then stream {7} becomes stream {10} at the exit of the generator, which is the final exhaust gas stream of the process.

In the absorption refrigeration cycle the pair solvent-refrigerant used is H_2O-NH_3. Stream {22} containing a mixture of H_2O-NH_3 is fed into the distillation column to obtain a vapor phase rich in ammonia, which passes through a total condenser, to obtain a liquid phase, generating stream {11}. This stream passes through a subcooler, generating stream {12} that goes to an expansion valve generating stream {13} at low temperature and pressure, which passes through a heat exchanger (evaporator) removing heat from some fluid of interest. This heat removal (refrigeration charge) is the third and last product of the trigeneration system. The refrigerant stream at the exit of the evaporator {14} is then sent to a blowdown tank generating a vapor stream {15} and a liquid stream {16}. Stream {16} passes through a pump increasing pressure, generating stream {17} that goes to the subcooler exchanging heat with stream {11} and transforming into stream {18} at the exit of the subcooler. Stream {15} goes to the absorber where it is mixed with stream {25} which comes from the bottom stream of the distillation column {23}. Stream {19} at the exit of the absorber passes through another pump, generating stream {20} which is mixed with stream {18} generating stream {21}, that exchanges heat with stream {23}. Then stream {23} becomes {24} at the exit of the heat exchanger and expands becoming stream {25}. Stream {21} transforms into stream {22} which is fed to the distillation column, closing the cycle.

2.2. Simulation of the trigeneration system

The process simulator used in this work is *Aspen Hysys*® from Aspen Technology, version 7.2 and the fluid package chosen to obtain thermodynamic properties was the Peng-Robinson equation of state. Both, power and absorption cycles, taken from literature [8, 14] were validated separately, before being used together to model the trigeneration system. Table 1 shows a comparison between simulated temperature of this work and reported temperature for the cogeneration cycle extracted from [14], presenting the errors obtained. Table 2 shows the errors between simulated data of this work and reported data for the absorption cycle extracted from [8]. The results have shown a good agreement between simulated and reported data. Errors are calculated by Equation 1, where RV means reference value from literature and TW is the value obtained in this work.

$$\text{Error }(\%) = abs\left[\frac{(RV - TW)}{RV}\right] \times 100 \qquad (1)$$

Table 1. Comparison between literature [14] and simulated data for the cogeneration system

Stream #	Reference [14] (°C)	This work (°C)	Error (%)	Variation (ΔT)
2	351.0	338.8	3.48	12.2
4	1194.0	1167.0	2.26	27.0
5	692.0	685.8	0.90	6.2
6	489.0	465.1	4.89	23.9
9	448.0	450.1	0.47	2.1

Table 2. Comparison between literature [8] and simulated data for the absorption refrigeration cycle

Stream #	Molar flow (kgmol/s)			NH_3 concentration (mol %)			Temperature (ºC)		
	Reference [8]	This work	Erro (%)	Reference [8]	This work	Error (%)	Reference [14]	This work	Variation (ΔT)
11	0.750	0.724	3.47	-	-	-	-	-	-
12	0.750	0.724	3.47	-	-	-	-	-	-
13	0.750	0.724	3.47	-	-	-	-	-	-
14	0.750	0.724	3.47	-	-	-	-	-	-
15	0.711	0.686	3.52	-	-	-	-	-	-
16	0.039	0.038	2.56	93.95	94.14	0.20	-	-	-
17	0.039	0.038	2.56	93.95	94.14	0.20	-	-	-
18	0.039	0.038	2.56	93.95	94.14	0.20	40.00	40.84	2.10
19	3.331	3.332	0.03	35.50	35.48	0.06	43.88	40.55	7.59
20	3.331	3.332	0.03	35.50	35.48	0.06	-	-	-
21	-	-	-	36.15	36.77	1.71	-	-	-
22	-	-	-	36.15	36.77	1.71	-	-	-
23	2.620	2.646	0.99	-	-	-	152.60	154.08	0.98
24	2.620	2.646	0.99	-	-	-	56.60	56.75	0.27
25	2.620	2.646	0.99	-	-	-	-	-	-

In Table 2 blank cells means that the variables inserted in the simulation are the same of the reference used. Considering the errors observed in Tables 1 and 2, the results obtained with the simulator and the chosen fluid package were considered to be in good agreement with literature data. Then, both systems (cogeneration and absorption chiller) were coupled to compose our trigeneration system and the molar flow of fuel and air streams of the cogeneration system were adjusted to give the necessary heat flow for the reboiler of the distillation column at the absorption chiller, for a specific heat removal rate in the evaporator. This adjustment generated what we call the base case for the thermodynamic analysis that will be performed to evaluate the influence of operational variables. The molar composition of natural gas at stream {26} used in this work was based in [14] and is: 88.82% CH_4, 8.41% C_2H_6, 0.55% C_3H_8, 1.62% N_2 and 0.60% CO_2. Table 3 shows process data for this base case.

Table 3. Properties of the streams of the trigeneration system

Stream	Temperature (°C)	Pressure (kPa)	Mass flow (kg/s)	NH_3 (mass %)	Stream	Temperature (°C)	Pressure (kPa)	Mass flow (kg/s)	NH_3 (mass %)
1	25.00	100.0	454.7	-	14	21.94	247.8	12.8	99.67
2	338.80	1000.0	454.7	-	15	21.94	247.8	12.1	100.00
3	577.00	970.0	454.7	-	16	-9.48	247.8	0.7	93.83
4	1224.00	902.5	462.5	-	17	-9.14	1728.0	0.7	93.83
5	724.80	110.0	462.5	-	18	41.4	1728.0	0.7	93.83
6	505.00	106.0	462.5	-	19	38.24	1728.0	58.8	34.80
7	168.00	102.0	462.5	-	20	38.45	1728.0	58.8	34.80
8	80.00	1200.0	57.0	-	21	39.06	1728.0	0.7	35.47
9	450.10	1200.0	57.0	-	22	114.34	1728.0	59.5	35.47
10	116.00	102.0	462.5	-	23	157.08	1728.0	46.7	17.92
11	44.00	1728.0	12.8	99.67	24	56.60	1728.0	46.7	17.92
12	41.60	1728.0	12.8	99.67	25	56.90	1728.0	46.7	17.92
13	-10.96	247.8	12.8	99.67	26	25.00	970.0	8.0	-

After validating the simulations by comparison with data taken from literature and combining the cogeneration plant with the absorption refrigeration cycle to generate a base case of a trigeneration system, a thermodynamic analysis of this system, considering the influence of operational variables was performed.

2.3. Thermodynamic analysis

Thermodynamic analysis of the trigeneration system is based in a First Law approach, considering the energy balance in some control volumes of the system. This analysis consists of measuring the total thermal efficiency of the trigeneration system. In the literature it is possible to find many different definitions for this efficiency [1, 8, 14-17]. In this work, total thermal efficiency of the trigeneration system is defined accordingly to the most frequently definition found in the literature, which is:

$$\eta = \frac{\dot{W}_{net} + \dot{Q}_{evap} + \dot{Q}_{HRSG}}{\dot{Q}_{in}} \quad (2)$$

where

$$\dot{W}_{net} = \dot{W}_{turb} - \dot{W}_{comp} \tag{3}$$

$$\dot{W}_{comp} = \dot{m}_1 \left(h_2 - h_1 \right) \tag{4}$$

$$\dot{W}_{turb} = \dot{m}_4 \left(h_4 - h_5 \right) \tag{5}$$

$$\dot{Q}_{evap} = \dot{m}_{13} \left(h_{14} - h_{13} \right) \tag{6}$$

$$\dot{Q}_{HRSG} = \dot{m}_8 \left(h_9 - h_8 \right) \tag{7}$$

$$\dot{Q}_{in} = \sum_{j=1}^{3} \dot{m}_{26,j} LHV_j \tag{8}$$

$$\dot{m}_{26,j} = x_j \dot{m}_{26} \tag{9}$$

All necessary thermodynamic data for using Equations 2 to 9 were taken from the process simulator (including the *LHV* of the three fuels: CH_4, C_2H_6 and C_3H_8 present in the natural gas stream). Equations 4 to 7 are written to obtain positive values, independently to the direction of energy flow.

The coefficient of performance (COP) is a frequently thermodynamic parameter used to characterize the performance of a refrigeration cycle [18], which can be calculated by Equation 10. Some authors consider compression work of the pumps used in the absorption refrigeration cycle to calculate COP values, but as mentioned before, they were neglected in this work.

$$COP = \frac{\dot{Q}_{evap}}{\dot{Q}_{reboiler}} \tag{10}$$

These two indexes, total thermal efficiency and coefficient of performance, were used in the thermodynamic analysis of the trigeneration system to evaluate the influence of operational variables.

3. Results and discussion

Using Aspen Hysys® and the validated simulation for the trigeneration system, five different process variables were chosen to evaluate their influence over total thermal efficiency of the system (calculated by Eq. 2) the COP of the absorption refrigeration cycle (Eq. 10). The variables chosen are: compression ratio in the compressor (given by P_2/P_1); expansion ratio in the turbine (given by P_5/P_4); pressure variation of the absorption refrigeration cycle ($\Delta P = P_{12} - P_{13}$); boiler operation pressure (P_9) and heat removal rate in the evaporator of the absorption cycle ($\dot{Q}_{evap}$); because these variables influences directly in the temperatures of the streams and so, in the efficiency of the system.

To perform a sensitivity analysis of these variables, different values for each one, based in the values taken from the literature [8, 14], were chosen and are shown in Table 4. The combination of all these values generated a set of 108 different scenarios used in the simulated process to obtain total thermal efficiency and COP for each scenario. The original values of the other variables that were used as inputs in the base case were kept .

Figure 2 shows the results for total thermal efficiency and COP for each one of the 108 scenarios. It is possible to identify 9 different sets of efficiency with small variations and that COP presents only three different values, distributed in the 108 scenarios. Analyzing individual results, it was possible to observe that the compression ratio in the compressor and the expansion ratio in the turbine are the most sensitive variables considering the set of variables chosen, that influences total thermal efficiency. COP values depend mostly of the pressure variation of the absorption cycle and does not vary too much when the heat removal rate in the evaporator is increased in 50%.

Table 4 – Values of operational variables used in the simulations.

Variables	Values used
Compression ratio in the compressor (kPa)	9; 11; and 13
Expansion ratio in the turbine (kPa)	0.30; 0.20 and 0.10
ΔP in the absorption cycle (kPa)	1120; 1320 and 1520
Boiler operation pressure (kPa)	1000; 3000
Heat removal rate in the evaporator (kW)	10000; 15000

This is because as $\dot{Q}_{evap}$ increases, $\dot{Q}_{reboiler}$ also increases and so, COP remains more or less constant. But when the degree of expansion increases, COP is highly affected. The greatest total thermal efficiency is achieved when the highest expansion rate in the turbine is combined with the lowest compression rate in the compressor and the also with the lowest operation pressure. This means that the greatest the turbine power, more efficient will be the system. This is also important because work is a more valuable form of energy than heat.

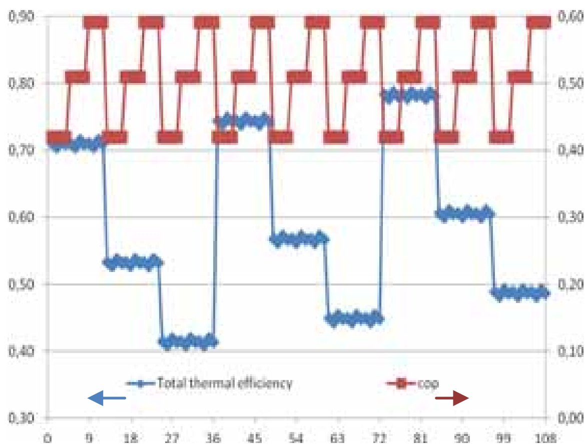

Fig. 2. Total thermal efficiency and COP considering the influence of operational variables.

After testing the sensitiviy of operational variables, an optimization procedure was performed using the *Optimizer* tool of the simulator software, an the defined objective function was to maximize the value of the total thermal eficciency, given by Equation 2, with the following constraints: $P_{12} > P_{13}$, $P_{25} > P_{26}$ and $\eta \leq 1$. The software also defines low and high bounds for all inputs. After this optimization procedure, it was possible to define a set of optimized input pressures, that maximize total thermal efficiency, but this does not correspond to a maximum for the COP. This is an important conclusion because it shows that the most important aspect of a trigeneration system is the definition of the distribution of the utilities produced as pointed out by [1], afirming that in designing a trigeneration plant, its optimized use must consider that the plant should be flexible enough with the heating and cooling demand variations. Table 5 shows the values of optimized pressures taken as manipulated variables in the optimization procedure. For the optimized case, total thermal efficiency is 82%, COP is 0.48 and mass flow rate of stream {1} is 442.5 kg/s, while for the base case they were 78%, 0.57 and 454.7 kg/s, respectively. It is important to mention that the base case used had already a good total efficiency, but this increase of 4% in the efficiency may be significant, especially when considering industrial trigeneration systems operating continuously.

Table 5. Comparison with base case and optimized case.

Stream	Base Case (kPa)	Optimized Case (kPa)
1	100.0	119.8
2	1000.0	939.4
5	110.0	135.0
8	1200.0	1159.9
11	1728.0	1769.8
15	247.8	253.1
16	247.8	265.6
17	1728.0	1757.3
21	1728.0	1736.7
22	1728.0	1736.7
23	1728.0	1787.7
25	247.8	278.0

4. Conclusions

In this work a trigeneration system based on literature data was simulated and validated in order to investigate the influence of some operational variables over the total thermal efficiency of the system and the COP of the refrigeration cycle. It was confirmed that using a trigeneration system it is possible to obtain a higher global efficiency when comparing with the ones achieved by traditional thermal systems and also with cogeneration systems. The worst scenario investigated has show a greater efficiency (more than 40%) while with traditional thermal systems it is not possible to reach this range.

Besides this higher efficiency, there are many other advantages of trigeneration systems, like: losses and waste reduction, reduction in the operating cost, reduced greenhouse gas emissions, better use of resources, short transmission lines, fewer units, multiple generation options, increased reliability and less grid failure [1].

In this work, an optimized procedure has allowed an increase of 4% in total thermal efficiency, using a departure base case with an efficiency of 78%. The study has also showed that it is important to verify the distribution of energy in the utilities produced by the trigeneration plant, especially because work is a higher quality form of energy. In this case, a thermodynamic analysis also based in a Second Law approach, exergy analysis, coupled with an economic analysis is essential to evaluate the feasibility of the application of this trigeneration system.

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