THERMO-ECONOMIC ANALYSIS AND OPTIMIZATION OF THE STEAM ABSORPTION CHILLER NETWORK PLANT

by

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Original scientific paper
https://doi.org/10.2298/TSCI200619058P

Absorption chillers are one of the most used equipment in industrial, commercial, and domestic applications. For the places where high cooling is required, they are utilized in a network to perform the cooling demand. The main objective of the current study was to find the optimum operating conditions of a network of steam absorption chillers according to energy and economic viewpoints. Firstly, energy and economic analysis and modelling of the absorption chiller network were carried out to have a deep understanding of the network and investigate the effects of operating conditions. Finally, the particle swarm optimization search algorithm was employed to find an optimum levelized total costs of the plant. The absorption chiller network plant of the Marun Petrochemical Complex in Iran was selected as a case study. To verify the simulation results, the outputs of energy modelling were compared with the measured values. The comparison with experimental results indicated that the developed model could predict the working condition of the absorption chiller network with high accuracy. The economic analysis results revealed that the levelized total costs of the plant is 1730 $/kW and the pay-back period is three years. The optimization findings indicated that working at optimal conditions reduces the levelized total costs of the plant by 8.5%, compared to the design condition.

Key words: *absorption chiller network, energy and economic analysis, levelized total costs, particle swarm optimization*

Introduction

Absorption chillers represent an exciting alternative to the conventional vapor-compression chillers because they can supply cooling without high electrical consumption [1-3]. The mechanical compressor of a compression chiller is indeed substituted by a thermal compressor, where the refrigerant vapor at the outlet of the evaporator is first absorbed in an absorbent solution, pumped to the higher-pressure level, and then desorbed again in the generator [4, 5]. To drive this process, a low temperature heat source is necessary at the generator [6-9]. The absorption refrigeration cycle is gaining considerable attention because it can make fair use of low grade waste heat for cooling demand and employ eco-friendly refrigerant [10, 11]. It is evident

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the uses of the thermo-economic analysis to verify the viability of the cogeneration systems have been used and applied along with different thermal plants [12, 13], aiming the best proposal to generate steam, electricity, and chilled water for the ice factory industry [14], to generate enough energy for achieving the demand of the swimming pool indoor buildings [15] or even to generate air cooling and electricity for buildings in the university [16, 17]. Since the thermo-economic analysis aims to investigate the energetic technical parameters and also the financial indices to estimate if any thermal plant would be feasibly or not [18], the needs to search for the ideal input configuration in terms of the energetic and economic domain have been mentioned in many studies on polygeneration systems, as it could be seen in [19, 20]. In this context, using different technical methods to optimize the thermal systems have been applied to find the best configuration for energetic and economic efficiency using the Four E technique [21], artificial neural network [22], using the TRNSYS function the optimization of the economic index [23], MOPSO algorithm [24] or even combining different techniques of optimization such as pessimistic and optimistic criteria [25]. Previously, Panahizadeh *et al.* [26] presented an analogous study using the exergetic parameters as the basis of the optimization method trying to minimize the exergy destruction by applying the particle swarm optimization (PSO) algorithm. However, in the present study, we aimed to use the financial parameters such as levelized total costs, net present value (NPV), internal rate of return, and pay-back period (PP) as the basis of the objective function the optimization method. Hence, the main goal of this study was to implement an optimization analysis with an energetic-economic view to find the best configuration for the network of the absorption chiller to operate efficiently. Although extensive research has been done on thermo-economic analysis of absorption chillers, insufficient research has been carried out on the absorption chiller network (ACN) plant. Also, the limited thermodynamic analysis of the ACN plant has been carried out. However, to the best of the author's knowledge, no comprehensive analyses have been done in identifying the optimum operation conditions of the ACN plant. To bridge this gap, the main contributions of this state-of-the-artwork can be drawn as follows, proposing a novel computer algorithm for simultaneous thermo-economic analysis of the ACN plant, performing accurate and detailed energy and economic simulation of the mentioned plant, evaluating the influence of changing operating conditions like cooling tower water temperature and steam temperature on the levelized total costs of the ACN plant, applying the two most important economic methods of PP and NPV for evaluating the mentioned plant, presenting a comprehensive sensitivity analysis for investigating the effects of design parameters on assessment criteria of the plant aforementioned, and performing a PSO search algorithm for finding the optimal levelized total costs of the stated plant.

Description of the absorption chiller network plant

An ACN includes more than one chiller that work together in a series or parallel arrangement to produce the desired cooling capacity. Apart from absorption chillers, the absorption chiller network plant (ACNP) should have also additional equipment including the main boiler, chilled water storage tank, cooling tower, cooling tower water pump, chilled water pump and air handling or heat exchangers to generate required cooling demand. In this research, the ACNP used for the cooling process in the mono-ethylene glycol (MEG) factory of Marun Petrochemical Complex (M.P.C.) in Iran is selected as a case study as shown in fig. 1. The plant consists of four single effect steam absorption chillers with a cooling capacity of 4775 kW, two forced draft fan cooling towers, a storage tank, cooling tower pumps, and chilled water pump. Also, in this study, it was assumed the steam boiler produced required steam of four chillers with a capacity of 44 tons of steam per hour with 1.5 bar pressure and consumed natural gas.

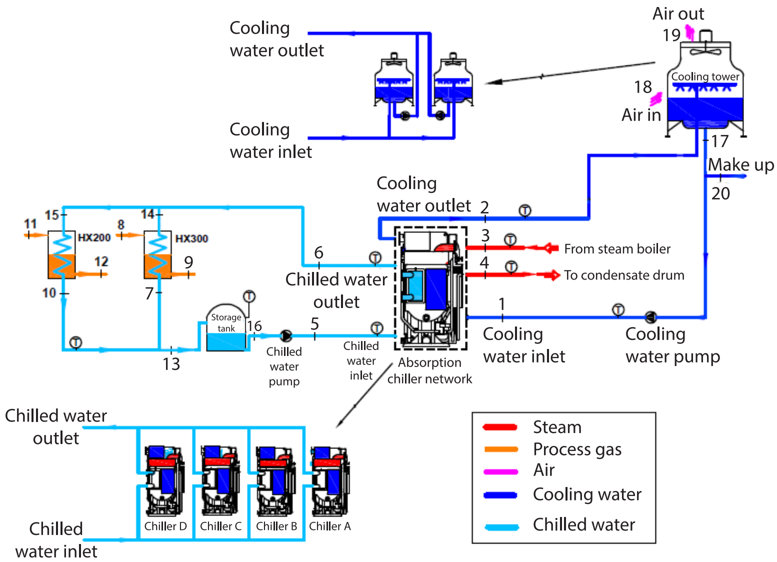

Figure 1. Schematic of the ACNP: Case study

Thermo-economic and optimization modelling of the absortion chiller network plant

This section shows the energy analysis, economic and optimization modelling of the ACN plant.

The energy analysis of the absorption chiller network plant

For evaluating the performance of a system from different viewpoints, it is necessary to perform the energy analysis of the whole system. The general forms of the mass and energy balance equations for a control volume at steady-state flow are expressed [27]:

$$\sum_i \dot{m} - \sum_o \dot{m} = 0 \tag{1}$$

$$\sum_i \dot{m}h - \sum_o \dot{m}h + \dot{Q} - \dot{W} = 0 \tag{2}$$

where $\dot{m}$, h, $\dot{Q}$, and $\dot{W}$ represents the mass-flow rate, specific enthalpy, heat power, and mechanical power, respectively. Also, the subscripts i and o are related to the inlet and outlet streams of the control volume. For concerned ACNP the final form of the energy balance equations for each component is described in tab. 1. In the following equations, indexes 1-20 are stream numbers as shown in fig. 1.

The variables $\dot{Q}_B$, $\dot{m}_f$, LHV$_f$, and η_c are boiler heat input in [kW], fuel mass-flow rate in [kgs^{-1}], fuel lower heat value in [kJkg^{-1}], and combustion efficiency, respectively. The variables $\dot{m}$, h, $C_{P\mathrm{a}}$, T, h_g, P_g, P_atm, and ω are mass-flow rate in [kgs^{-1}], specific enthalpy in [kJkg^{-1}], specific heat at a constant pressure of air in [kJkg^{-1}°C^{-1}], temperature in [°C], water vapor enthalpy in [kJkg^{-1}], absolute humidity in kg$_{\mathrm{H2O}}$/kg$_{\mathrm{dryair}}$, water saturation pressure in [kPa], atmospheric pressure in [kPa], and the relative humidity of the air, respectively. The variables $\dot{m}_\mathrm{chw}$, $C_{P\mathrm{w}}$, T_chwni, and T_chwno are chilled water flow rate in [kgs^{-1}], the specific heat at constant

Table 1. Energy balances of the ACNP

Equipment				
Boiler		$\dot{Q}_B = \eta_c \times \dot{m}_f \times \text{LHV}_f$		(3)
Cooling tower		$\dot{m}_{18}h_{18} + \dot{m}_2 h_2 = \dot{m}_{19}h_{19} + \dot{m}_{17}h_{17}$		(4)
		$h_{19} = (C_{Pa}T_{19} + \omega_{19}h_{g19})$		(5)
		$\dot{Q}_{\text{cooling},t} = \dot{m}_{\text{chw}} \times C_{P\text{w}} \times \left(T_{\text{chwni}} - T_{\text{chwno}}\right)$		(6)
		$\omega = 0.622 \dfrac{\varphi \times P_{\text{g}}}{P_{\text{atm}} - \varphi \times P_{\text{g}}}$		(7)
		$h_{18} = \left(C_{Pa}T_{18} + \omega_{18}h_{\text{g}18}\right)$		(8)
ACN		$\dot{m}_1 h_1 + \dot{m}_3 h_3 + \dot{m}_5 h_5 = \dot{m}_6 h_6 + \dot{m}_4 h_4 + \dot{m}_2 h_2 + \dot{W}_{\text{ACN}}$		(9)
HX200	HX300	$\dot{m}_{15}h_{15} + \dot{m}_{11}h_{11} = \dot{m}_{12}h_{12} + \dot{m}_{10}h_{10}$	$\dot{m}_{14}h_{14} + \dot{m}_8 h_8 = \dot{m}_7 h_7 + \dot{m}_9 h_9$	(10) (11)
Cooling tower pump	Chilled water pump	$\dot{W}_{\text{cwp}} = \dfrac{\dot{m}_{\text{cwni}} \times \text{g} \times h_{\text{cwp}}}{\eta_{\text{cwp}}}$	$\dot{W}_{\text{chwp}} = \dfrac{\dot{m}_{\text{chwni}} \times \text{g} \times h_{\text{chwp}}}{\eta_{\text{chwp}}}$	(12) (13)
Cooling tower fan		$\dot{W}_{\text{cwf}} = \dfrac{\dot{m}_{\text{a,i}} \times P_{\text{cwf}}}{\rho_{\text{a,i}} \times \eta_{\text{cwf}}}$		(14)

pressure of water in [kJkg^{-1}°C^{-1}], chilled water inlet and outlet temperatures in [°C], respectively. The variables $\dot{W}_{\text{ACN}}$, $\dot{W}_{\text{cwp}}$, $\dot{m}_{\text{cwni}}$, g, h_{cwp}, and η_{cwp} are the input work of the ACN in [kW], the input work of cooling water pump in [kW], cooling water network inlet flow rate in [kgs^{-1}], gravity acceleration in [ms^{-2}], cooling water pump head in [km] and cooling water pump efficiency, respectively. Also, the variables $\dot{m}_{\text{a,i}}$, ΔP_{cwf}, $\rho_{\text{a,i}}$, and η_{cwf} are inlet air-flow rate in [kgs^{-1}], cooling tower fan pressure difference in [kPa], inlet air density in [kgm^{-3}], and cooling tower fan efficiency, respectively.

The COP_{ACN} with *M* chillers and the COP_{ACNP} are defined [26]:

$$COP_{\text{ACN}} = \frac{\dot{Q}_{\text{cooling},t}}{\sum_{j=1}^{M}\left(\dot{Q}_{\text{GEN},j} + \dot{W}_{P,j}\right)} \tag{15}$$

$$COP_{\text{ACNP}} = \frac{\dot{Q}_{\text{cooling},t}}{\dot{Q}_B + \dot{W}_{\text{ACNP}}} \tag{16}$$

where $\dot{Q}_{\text{cooling},t}$, $\dot{Q}_{\text{GEN}}$, $\dot{W}_P$, and $\dot{W}_{\text{ACNP}}$ are a total cooling load of the network in [kW], ACN's generators heat input in [kW], ACN's pumps power input in [kW], and ACNP's pumps power input in [kW], respectively.

Economic analysis

Economic analysis includes the estimation of different fixed and operating costs. Here, a comprehensive economic analysis is done, which involves all of the important financial variables. The fixed costs, FC, of the project include the investment costs of the system, C_{invs}, as shown in tab. 2, and the costs of installing the system components and their related piping, C_{inst}. Usually, C_{inst} in the investigations is considered between 5-15% of C_{invs}. In this study, it was assumed 10% of C_{invs} [23].

Table 2. Cost functions of various components of the ACNP

System equipment	Cost function	Ref.
Absorption chiller	Z_{AC} = 122.2 [\$/kW]	[28]
Storage tank	Z_{ST} = 290 [\$/m^3]	[29]
Cooling tower	$Z_{CT} = 746.749 \times \dot{m}_{CT}^{0.71} \times \Delta T_{CT}^{0.57} (T_{i,CT} - T_{o,CT})^{-0.9924} \times$ $\times (0.022 T_{wb,o} + 0.39)^{2.447}$ [\$]	[30]
Pump	$Z_P = 705.48 \times \dot{W}_P^{0.71} \left(1 + \dfrac{0.2}{1-\eta_P}\right)$ [\$]	[30]
Boiler	Z_B = ton of steam × 6500 [\$]	[31]

The operating cost, OC, of the system consist of the operating and maintenance cost, $C_{O\&M}$, fuel and electricity cost, $C_{f\&e}$, and the environmental cost due to the penalty of the pollutant emissions, C_{env}. The $\dot{W}_{Net}$ and N are the plant's desired net produced power in [kW] and plant's expected lifetime in the year, respectively. Levelized total costs of the plant during the considered lifetime, defined in \$/kW [20]:

$$LTC = \frac{\text{Total costs during system lifetime}}{\text{Net produced power}} = \frac{FC + (OC \times N)}{\dot{W}_{Net}} \tag{17}$$

$$C_{invs} = \sum_{j=1}^{m} Z_j \tag{18}$$

$$C_{f\&e} = (z_f \times \dot{m}_f \times LHV_f) \times 3600 \times t_{year} + (z_e \times \dot{W}_{elc}) \times t_{year} \tag{19}$$

$$FC = C_{invs} + C_{inst} \tag{20}$$

$$OC = C_{O\&M} + C_{f\&e} + C_{env} \tag{21}$$

In the previous equations z_f, z_e, $\dot{W}_{elc}$, and t_{year} are fuel price in [$10^{-6} \times$ \$/GJ], electricity price in [\$/kWh], electricity consumption in [kW] and total working hours of the system each year, respectively. The CO_2 emission penalty cost of the ACNP related to electric and fuel consumption and calculated [32]:

$$C_{env} = Z_{env} \times (\dot{m}_{CO_2,f} \times 3600 + \mu_{CO_2,e} \times \dot{W}_{elc}) \times t_{year} \tag{22}$$

In the previous equation Z_{env} and $\mu_{CO2,e}$ are environmental tax factor and emission conversion factor for electricity consumption from grid which are 0.024 \$/kg$_{CO2}$ [21] and 0.571 kg$_{CO_2}$/kWh [33]. Also, the variable $\dot{m}_{CO2,f}$ is a CO_2 flow rate and calculated by using natural gas combustion relation in kg$_{CO2}$/s. After completion of the plant's economic assessment, the economic reliability of the plant is evaluated through two important standard methods of PP, and NPV. Based on the definition, the PP is expressed as the length of time which takes to return all of the investment costs [2].The amount of NPV at the end of the system's lifetime is calculated [11]:

$$PP = \frac{FC}{AS} \tag{23}$$

$$NPV = -\left(FC \times IF_0 \times RDF_0\right) + \sum_{i=1}^{N}\left(AS \times IF_i \times \mathrm{RDF}_i\right) \tag{24}$$

where the annual net saving money, AS, the inflation factor, IF_i, and the real discount factor, RDF, are defined [20]:

$$AS = AI - OC \tag{25}$$

$$IF_i = \left(1 + \frac{R}{100}\right)^{-\mathrm{i}} \tag{26}$$

$$RDF_i = \left(1 + \frac{RIR}{100}\right)^{-i} \tag{27}$$

where AI is the total annual income of the plant, R – the rate of inflation, DR – discount rate, and $RIR = DR - R$ – the real interest rate. Also, i stands for the i^{th} year during the plant's lifetime and IRR is an internal rate of return [20]:

$$NPV = 0 = \sum_{i=1}^{N} \frac{\text{Net cash flow}}{\left(1 + IRR\right)^{i}} - FC \tag{28}$$

In the economic analysis of the plant if:

$$NPV > 0 \tag{29}$$

$$IRR > DR \tag{30}$$

where the plant investment is feasible.

Single objective optimization

The PSO algorithm has been used to search for optimal values of decision variables of the concerned study. According to the set of benchmark test problems, it has been shown that the PSO searching algorithm adopts in terms of both speed and memory requirements has superior computational efficiency rather than a genetic algorithm (GA) in finding the global optimal solution. The PSO algorithm does not need evolution operators such as crossover and mutation which are necessary for the GA algorithm. The parameters used for optimization in MATLAB by the PSO algorithm in this study are shown in tab. 3. The maximum number of iterations, the function tolerance, and the maximum number of stall iterations were used as a stopping criterion of MATLAB code. Inertia weight was used to define the percent of exploration (the ability to generate new solutions) and exploitation (the ability to utilize current solutions) in the searching algorithm. Self and social coefficients show the personal and global learning factors related to the self-cognitive experience of particle and particle ability to learn from global. A swarm size is the number of particles in the studied swarm.

Table 3. Parameters used for optimization in MATLAB for PSO algorithm

Parameter	Value	Parameter	Value
Function tolerance	10^{-4}	Maximum number of stall iterations	250
Inertia weight	0.6	Self and social learning coefficients	1.1
Swarm size	100	Maximum number of iterations	1800

Results and discussions

This section first deals with the comparison between the experimental and numerical results to show the accuracy of the modelling developed. Then, presents the economic analysis results and the optimization values find for the ACNP.

Verification of the modelling results

The operating data of the concerned ACNP on June 10th, 2017, were measured with an infrared thermometer (uncertainty ±0.1 °C), ultrasonic mass-flow meter (uncertainty ±22 kg/s), and a digital multimeter (uncertainty ±1 kW) are listed in tab. 4. For numerical results validation, the outlet chilled water temperature of the case study ACN was recorded in tab. 5 at different temperatures of the inlet cooling tower water. These values compared with the values calculated by numerical code while the steam temperature and the inlet chilled water temperature of the ACN were the same.

Table 4. Data measured on the site

Parameter	Value	Unit	Parameter	Value	Unit
The chilled water inlet temperature	16.8	[°C]	Steam outlet temperature (generator)	95	[°C]
The chilled water outlet temperature	10.2	[°C]	Steam flow rate	12	[kgs^{-1}]
Chilled water flow rate	672	[kgs^{-1}]	Steam inlet temperature (generator)	145	[°C]
Cooling water inlet temperature (absorber)	35	[°C]	Cooling tower air-flow rate	520	[Nm^{3}s^{-1}]
Cooling water outlet temperature (condenser)	43	[°C]	Each cooling tower fan power consumption	90	[kW]
Cooling water flow rate	1398	[kg/s]	Each cooling tower pump power consumption	485	[kW]
Each absorption chiller pumps power consumption	8.9	[kW]	Chilled water pump power consumption	216	[kW]

The comparison was made considering the experiment values as can be seen in tab. 5, the highest relative error between the numerical and experimental results was around 5% and the lowest one was less than 2%, which proves that the developed model was accurate. The relative errors can be attributed to the following facts as simplified assumptions underlying the thermodynamic model, chiller's solution heat exchanger efficiency was considered 58% in the numerical code, which may not be in the experimental case of this value, non-consideration of the fouling factor of heat exchangers of chillers in the numerical study, used constant UA product along with the operating conditions in the simulation and the thermodynamic analysis was considered as global, that it does not take into account all the phenomena in the process.

Table 5. Comparison of numerical and experimental values of the ACNP

T_{cwni} [°C]	Numerical [°C]	Experimental [°C]	Relative error [%]
35	10.06	10.2	1.37
36	10.12	10.6	4.53
37	10.24	10.8	5.19

Energy analysis results

Table 6 presented all the important thermodynamic properties of streams in the cycle, by using the computer code written in the engineering equations solver (EES) for a typical working day of concerned ACNP. This energy balance helps to have comprehensive analysis and investigate the effects of key criteria for the ACNP.

Table 6. Thermodynamics properties at each point for the ACNP

Point, i	T_i [°C]	P_i [kPa]	m_i [kgs^{-1}]	h_i [kJkg^{-1}]	Point, i	T_i [°C]	P_i [kPa]	m_i [kgs^{-1}]	h_i [kJkg^{-1}]
1	35	608	1384	147.1	11	37	1447.9	400.1	152.5
2	41.1	506.6	1384	172.6	12	32	1346.6	400.1	131.7
3	145	148.9	8.96	2762.4	13	15.5	506.6	672	63.4
4	95	101.3	8.96	398	14	10	506.6	336	42.5
5	15	608	672	63.5	15	10	506.6	336	42.5
6	10	506.6	672	42.5	16	15	506.6	672	63.4
7	15	506.6	336	63.4	17	35	506.6	1364	147
8	25	49.6	179	105	18	43.5	101	520	71
9	15.7	44.7	179	65.7	19	40	101.3	520	144.7
10	15.9	506.6	336	67.2	20	25	506.6	20	105

By using the values of tab. 6 and eq. (16), the coefficient of performance of the ACNP was equal to 61.2%.

Economic analysis results

In this section as shown in tab. 7, the investment or capital cost of the ACNP was calculated by using the equations in tab. 2 and eq. (18). In this study, the operating and maintenance cost, $C_{\text{O\&M}}$, is assumed to be 6% of the plant's investment cost [18]. The N is considered to be 20 years for the ACNP. The price of natural gas and interest rate is supposed to be 0.222 ($/GJ) [34, 32] and 14%, respectively, [35]. The inflation rate, real interest rate, price of buying electricity, and t_{year} are considered 5%, 18%, 0.018 ($/kWh) [32], and 7000 (hour per year), respectively.

Table 7. The investment cost for each equipment of the ACNP

Component	Cost [$]	Component	Cost [$]
Absorption chillers	2334020	Storage tank	130500
Cooling towers	205586	Cooling tower pumps	62156
Boiler	286000	Chilled water pump	28734
		Total	3046996

Table 8. Main modelling outputs for the ACNP

Parameter	Value	Unit
OC_{ACNP}	1484000	[$year^{-1}]
LTC_{ACNP}	1730	[$ kW^{-1}]

Since ACNP produces cooling, $\dot{W}_{\text{Net}}$ is plant cooling capacity and calculated by using eq. (8). For the annual income, AI, calculation of the ACNP, the case study plant has been considered. If the chilled water temperature increases 1 °C, the EO production of the MEG factory according to afield data in the Marun petrochemical company reduces 112 kg per hour and the MEG production reduces 145.6 kg per hour, as well. Therefore, by considering 560 $/(ton of MEG) [36], 7000 hour per year working time for the plant and 5 °C chilled water temperature decrement, the annual income will be $AI = (145.6 \times 7000 \times 5 \times 560)/1000 = 2853760$ $ per year. The operation cost and LTC of the ACNP according to used data from tab. 6 are reported in tab. 8.

$C_{\text{invs}} = 3046996$ $, $C_{\text{inst}} = 0.1 \times 3046996 = 304700$ $, and $FC_{\text{ACNP}} = C_{\text{invs}} + C_{\text{inst}} = 3351696$ $

The cash flow (cost over the useful life of the plant) of the ACNP which compromised the NPV and internal rate of return (IRR) economic indices is shown in tab. 9. The row related to the cumulative cash flow in this table shows that for the first two years of working plant the income does not meet the investment cost. From the third year the cash flow becomes positive, so, ACNP's PP is three years. Also, the results of the NPV and IRR economic indices verify that the plant investment is feasible. The sensitivity analysis of economic indices concerning cost and income are shown in figs. 2 and 3. As can be seen in these figures the IRR economic index is more sensitive to change in the income and cost of the ACNP. In the most pessimistic scenario, where the revenue is 20% lower than the estimated value and the costs 20% higher than the initial calculation of the ACNP, NPV, and IRR are not economically justified because the NPV is negative, but in other cases it is feasible. During the ACN operation, changing the thermodynamic conditions of the inlet variables such as the cooling tower water temperature, steam temperature, and chilled water temperature affect the chillers operating parameters and LTC_{ACNP}.

Table 9. The cash flow of the ACNP

Year	0	1	2	3	5	10	20
Investment cost	3351696						
Operation cost		1484000	1484000	1484000	1484000	1484000	1484000
Cash out	3351696	1484000	1484000	1484000	1484000	1484000	1484000
Annual income	0	2853760	2853760	2853760	2853760	2853760	2853760
Salvage							486882
Cash in	0	2853760	2853760	2853760	2853760	2853760	2853760
Net cash flow	–3351696	1369760	1369760	1369760	1369760	1369760	1369760
Cumulative cash flow	–3351696	–1981936	–612176	757584	3497104	10345904	24530386
DR	18%						
NPV	3998056 $						
IRR	40.8%						

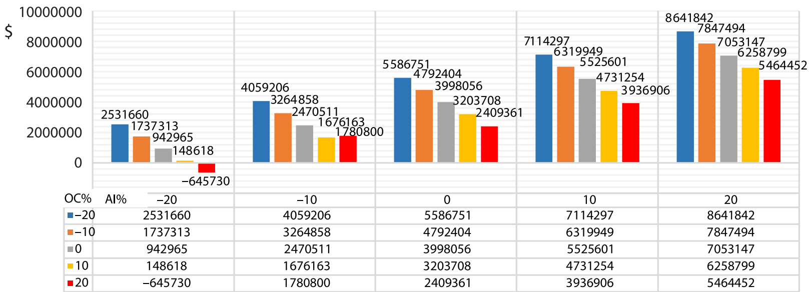

Figure 2. The NPV economic index sensibility analysis for the ACNP [$]

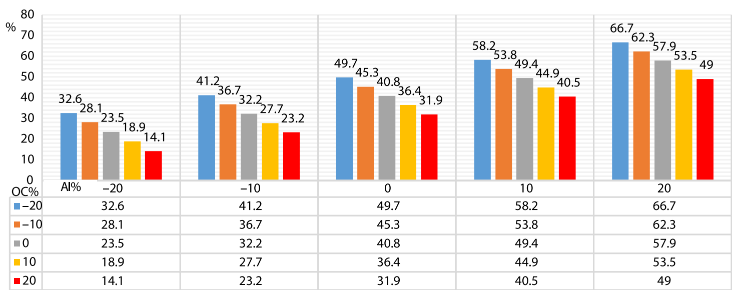

Figure 3. The IRR economic index sensibility analysis for the ACNP [%]

Figure 4(a) demonstrates the variation of the outlet chilled water temperature and LTC_{ACNP} with network inlet steam temperature. As observed, an increase in the network inlet steam temperature increases the heat transfer rate in the chiller's generator and leads to the higher separation of the refrigerant from LiBr/H_2O solution and higher generator pressure. These two factors cause more refrigerant to be condensed in the condenser and sent to the chiller evaporator for spraying, which reduces the outlet chilled water temperature of the network to setpoint temperature (10 °C). Also increasing the steam temperature due to the increased cooling capacity, reduces the LTC of the plant. Figure 4(b) provides the variation of the LTC of the plant and outlet chilled water temperature to the inlet cooling water temperature of the network. As shown, decreasing the cooling water temperature decreases the network outlet chilled water temperature and LTC of the plant due to increasing the cooling capacity of it.

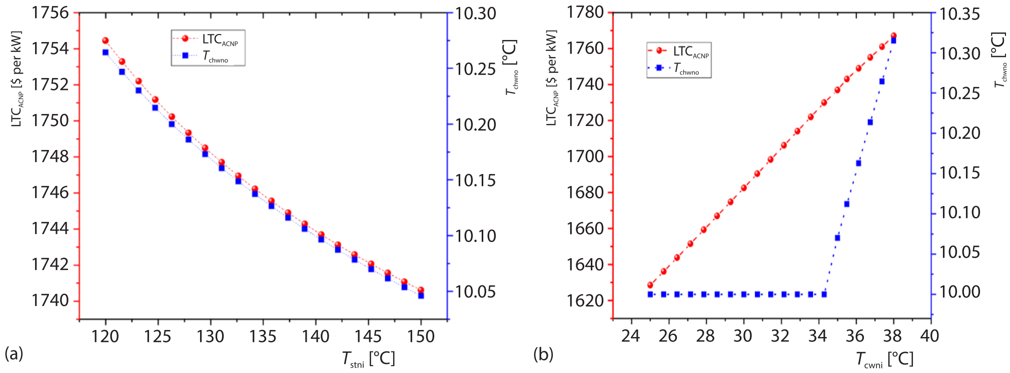

Figure 4. (a) The behavior of LTC_{ACNP} and T_{chwno} by changing the inlet network steam temperature (T_{chwni} = 16.8 °C, T_{cwni} = 35 °C, η_{SHX} = 0.58) and (b) the behavior of LTC_{ACNP} and T_{chwno} by changing inlet network cooling temperature (T_{chwni} = 16.8 °C, T_{stni} = 145 °C, η_{SHX} = 0.58)

Optimization of the ACNP

In the present study to optimize the ACNP by PSO algorithm needs to be linked EES with MATLAB™ and used the parameters of the PSO algorithm are shown in tab. 3. This optimization is done to minimize the LTC of the plant. The range of allowable values for decision variables and the optimum value of those which are obtained by using the PSO algorithm are listed in tab. 10.

Table 10. Range of decision variables and their optimal values in the ACNP

Decision variable	Range of variation	Optimal value
Steam inlet temperature [°C]	120-150	149.5
Cooling water inlet temperature [°C]	25-38	25
Chilled water outlet temperature [°C]	10-11	10
Solution heat exchanger efficiency [–]	0.5-0.7	0.7
Steam control valve opening [%]	50-100%	84
LTC_{ACNP} [$\$kW^{-1}$]	1500-1800	1583

Conclusions

This study was carried out to find the optimal operating conditions of an ACNP based on energy and economic analysis. A high accuracy computer code was developed to predict the performance of the ACNP and investigate the effects of various parameters. To verify the developed code, the ACNP of the M.P.C. was selected as a case study. The comparison between the modelling results and experimental values showed good accuracy of the developed model. Based on the present investigation, some conclusions can be drawn as follows.

- An increase in the ACN inlet steam temperature decreases the ACN outlet chilled water temperature and the LTC of the plant. Reduction in the ACN inlet cooling water temperature decreases the LTC of the plant too.
- The optimization of the ACNP by using the PSO optimization algorithm shows that the cooling water inlet temperature has a more significant effect on the LTC of the plant rather than the steam inlet temperature. The PSO optimization algorithm results demonstrate that working at optimal condition reduces the LTC of the plant 8.5%, rather than design condition.

Acknowledgment

The authors express their thanks to the department of research and innovation of the M. P. C. for the technical support in this research. The fourth author thanks the CNPq for the scholarship of productivity No. 309154/2019-7 and the IFPE for its financial support throughout the Call 10/2019/Propesq.

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Paper submitted: June 19, 2020
Paper revised: December 5, 2020
Paper accepted: December 10, 2020