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# THERMOECONOMIC OPTIMIZATION OF ABSORPTION CHILLER SUPERSTRUCTURES FOR AN INTERNAL COMBUSTION ENGINE: WASTE HEAT RECOVERY AND COLD-WATER APPLICATIONS

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***Abstract.*** *The utilization of thermal power plants using internal combustion engines has been performed a bigger role on electrical energy generation section in Brazil. UTE Viana power plant accounts on twenty internal combustion engines that release a significant amount of residual heat to the environment through jacket water and exhaust gases. Due to this reason, the application of heat recovery technologies may be fundamental to offer possible benefits. In particular, lithium bromide (LiBr) and water absorption chillers provide a cold-water system whose applications on UTE Viana might be performed through the installation of heat exchangers on radiators, HVAC system and on the intake air of the engine, thus, reducing electrical energy consumption, specific fuel consumption and increasing shaft power generation. Therefore, the goal of this work is to achieve the optimal configuration from the structural and parametric point of view on absorption chillers with cold-water system applications using superstructure optimization methodology, which allows embracing several chiller configurations. The superstructure modeling is carried out in EES for three absorption chiller designs: single effect driven by hot water or exhaust gases and Double Effect driven by exhaust gases. The results showed absorption chillers optimal configurations for UTE Viana in terms of thermoeconomic parameters.*

***Keywords:*** *Residual Heat Recovery, Internal Combustion Engine, Lithium Bromide and Water Absorption Chillers. Superstructure Modeling and Optimization.*

## 1. INTRODUCTION

Due to the energy demand and constantly pursuit on satisfying economic, social and environmental concerns, the studies relating new energies sources, as well as recovering energy residues from existent CHP systems, had been intensified, thus, aiming improvements on its efficiency and promoting a sustainable development on thermal systems design.

According to Braga *et al.* (2005), a way out to energy crisis is to reuse residues. It means to develop possible ways to use efficiently the available sources. In cases which involves Internal Combustion Engines (ICE), there are a lot of residual heat being wasted on the environment. Thus, one of the mains ways to manage the current energy crises is to reuse thermal residue, because they can increase the energy efficiency on process sites (Oluleye *et al.,* 2016). Then, the heat residue recovering technologies as organic Rankine cycle (ORC), Kalina cycle, absorption chillers and heat pumps had become significantly essentials to provide a bigger energy generation efficiency (Morawski *et al.*, 2017). In scenarios prone to high electricity cost, such as in industrial plants, it is interesting to install absorption chillers in order to reuse thermal residues (Herold *et al.*, 2016), providing a cooling system whose applications can bring economic benefits. In special, absorption chillers can provide cold-water applications on CHP systems, reducing electrical energy consumption when applied on air conditioning system, but it is also possible to use the cold-water to cool the intake air of ICE, increasing shaft power generation and decreasing specific fuel consumption (Chun, 2017). Regarding to the benefits into the engine, ISO 15550 and ISO 3046-1standards can be used to assist the calculations. Furthermore, similarity rules from Fox *et al.* (2012) can be applied on the radiator modeling to estimate the electrical energy savings.

Bear in mind that the main advantage in using absorption chillers is on the type of energy source that activates this technology, they are driven through thermal energy and do not require mechanic compression. Moreover, they do not need lubricants that degrade energy and mass transfer, allow energy consumption reduction on summer and could be driven through different types of thermal energy (Herold *et al.*, 2016). For example, exhaust gases or others fluid like hot water or vapor (ASHRAE, 2014). More (2015) presents assumptions to the thermodynamic modeling of absorption chiller, while the Single and Double Effect configurations are presented by Herold *et al.* (2016).

Some works developing applications with absorption chillers had been carried out by Misra *et al.* (2003), Castillo (2007) and Dixit *et al.* (2017). These researchers developed thermoeconomic modeling on absorption chillers through exergy analysis, optimizing systems and obtaining results in terms of cost and others thermodynamic parameters. In addition, Boehm (1987), Valero *et al.* (1994), Bejan *et al.* (1996), and d'Accadia and Rossi (1998) carried out thermoeconomic studies with CHP systems, thus, their works are consulted to assist the development of thermoeconomic modeling on absorption chillers combined with ICE.

However, in this work, the goal is to achieve the optimal configuration from the structural and parametric point of view on absorption chillers with cold-water system applications using a different approach known as superstructure optimization methodology, which allows embracing several chiller configurations. The most works in the past 30 years had been developing different superstructures modellings of CHP systems (Henao, 2012) but it was not encountered yet in the literature a specific superstructure involving only LiBr and Water absorption chillers with ICE and a cold-water system as it is proposed in this work. Thus, the superstructures modeling of this work involves synthesis and design levels in accordance with Frangopoulos (2002) and follows mainly Henao (2012) suggestions in the state of the art of superstructure definition. Also, to reach the goal of this work, it is used EES software as the main coding platform to model and optimize the superstructure, then it was used the Genetic Algorithm methodology since some studies from Dejong (1975) and Amir (2012) had been reporting advantages of using this approach to achieve the optimal results. Another work involving optimization problem used artificial variable in the thermodynamic modeling to assist the searching on optimal solution, this technique proved to be very useful when the complexity increases during the optimization problem (Donatelli, 2002).

## 2. CASE STUDY

The case study is at UTE Viana thermal power plant located in the State of Espirito Santo, Brazil, which accounts twenty internal combustion engines of Wärtsilä W20V32 model, its power capacity generation is 9000 kW and each engine is designed to produce 8730 kW of electrical power. Thus, the total power capacity of UTE Viana thermal power plant is 174.6 MW. Moreover, all engines are fueled with heavy oil OCB-1 whose Lower Heating Value (LHV) is 40785 kJ/kg. The engine residual data is presented in Tab 1.

Table 1 – Engine Residual Heat Data.

| Thermal Residue | Exhaust Gases | Hot Water |
|---|---|---|
| Temperature (ºC) | 345.0 | 78.4 |
| Flow rate (kg/s) | 16.7 | 27.0 |

The molar composition of the exhaust gases was calculated in Morawski (2016) through a complete combustion model and its values are presented in Tab 2. The onsite ambient conditions are assumed as dry temperature of 25 ºC, atmospheric pressure of 1 bar and relative humidity of 70%.

Table 2 –Molar Composition of exhaust gases.

| Substance | Molar fraction (%) |
|---|---|
| $CO_2$ | 6.360 |
| $H_2O$ | 5.580 |
| $N_2$ | 75.553 |
| $O_2$ | 11.060 |
| Ar | 0.900 |
| $SO_2$ | 0.030 |

## 3. WASTE HEAT RECOVERY ABSORPTION CHILLER SUPERSTRUCTURES

Many researchers have been contributing on superstructure modeling development in thermal systems applications. In this work, the development of thermodynamic modeling for absorption chillers is based on More (2015) assumptions, while it was used Henao (2012) assumptions to achieve the superstructure configuration. In most studies related to superstructure design, there are different types of superstructure for many applications but all of them presented high level of difficulty in the mathematical modeling due to its significant connections complexity and a numerous quantity of equipment. According to Frangopoulos (2002), the superstructure methodology means to allow the existence of all equipment and connections. Therefore, Henao (2012) suggests using only the possible connections between components inside the superstructure and the final optimal structure must be covered inside the superstructure. All these assumptions help to make simpler the path of allowing possible and existent structures inside the superstructure.

The first superstructure is carried out in a basic design, which the heat exchanger can exit or not in this configuration. Figure 1 represents the Simple Effect superstructure that could be driven by jacket water or exhaust gases from engine. This simple and easy idea of allowing the existence of heat exchanger is directly related to superstructure design.

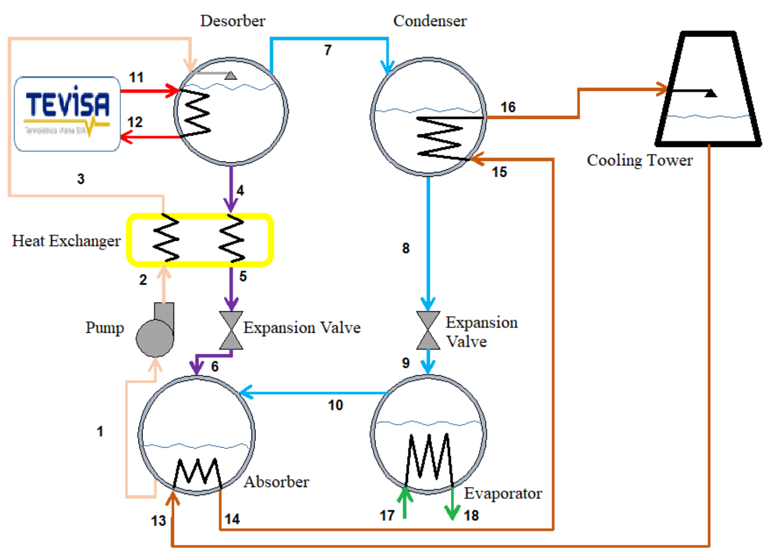


Figure 1. Flowsheet of Simple Effect superstructure

The first two Simple Effect superstructures are defined by feeding the desorber with hot water stream from jacket water and exhaust gases from engine, respectively. The development of the third superstructure is carried out by upgrading the Simple Effect to Double Effect. Herold *et al.* (2016) presents three possible flowsheets for Double Effect configuration and all of them can permit the existence of two heat exchangers inside the superstructure. In summary, Double Effect absorption chillers can be divided into two categories; parallel flow and series flow. The series flow presents two different flowsheets, one is defined according to Herold *et al.* (2016) as solution to low desorber first and the other is defined as solution to high desorber first. Figure 2 represents the flowsheet of Double Effect superstructure. The Double Effect superstructure is activated by exhaust gases from engine and do not use hot water stream. Furthermore, in this present work, the splitting B1, B2 and B3 are set as continue values, and not as binary values. Thus, the Double Effect superstructure allows not only the existence of these structures mentioned before but also permits the setting of hybrid structures that do not are represented by Herold *et al.* (2016). Figure 3 represents the possible combinations of each superstructure and the cold-water applications.

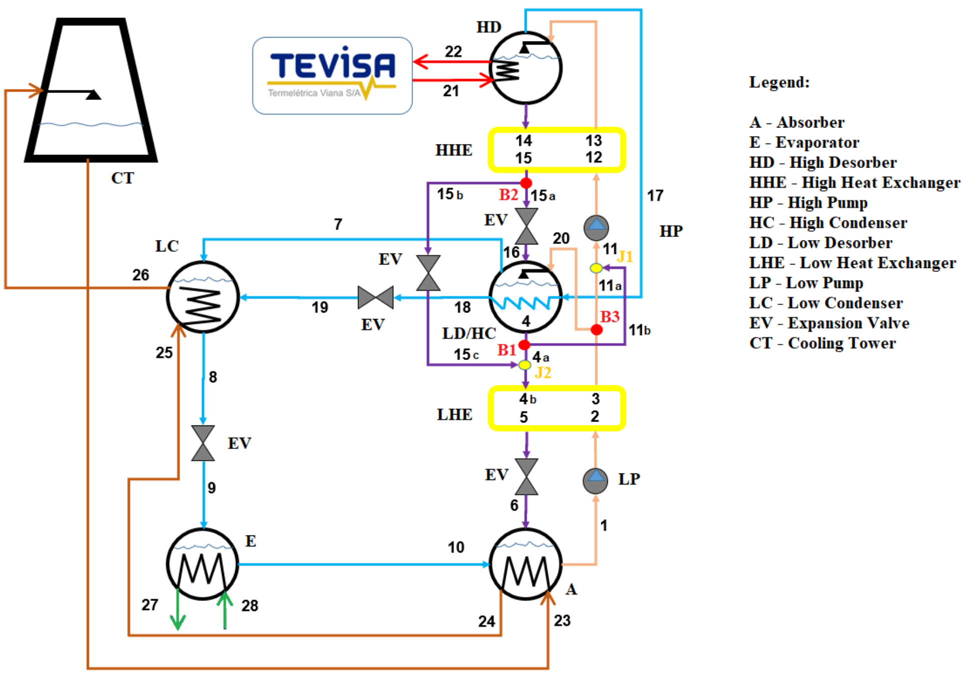


Figure 2. Flowsheet of Double Effect superstructure

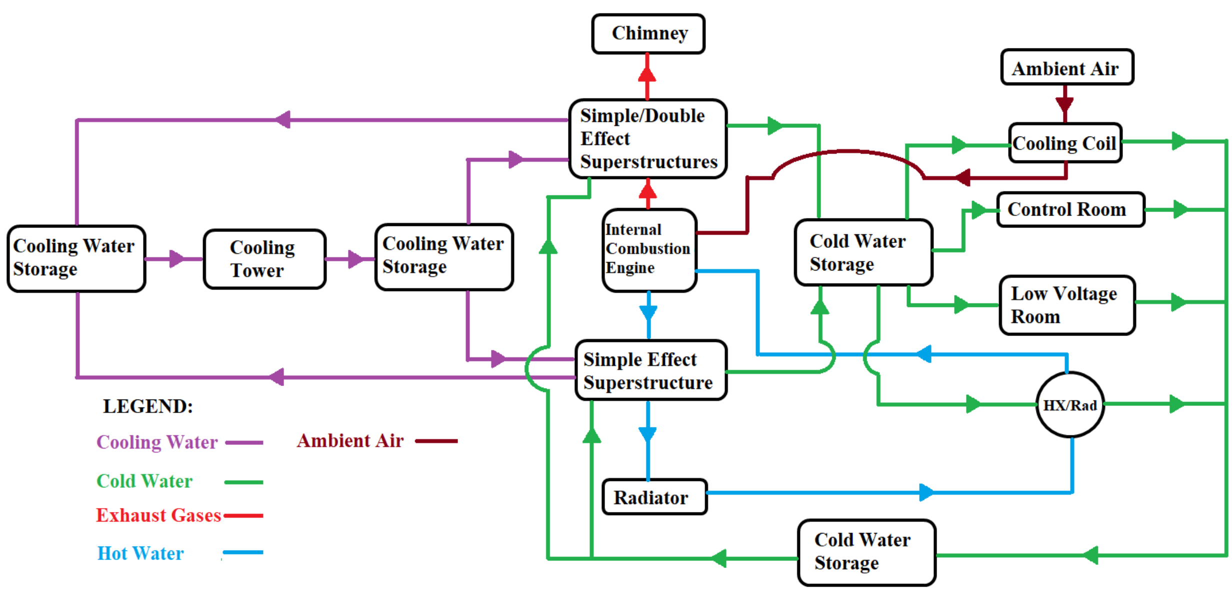


Figure 3. Flowsheet of possible combinations of each superstructure and cold-water applications

## 4. THERMOECONOMIC MODELING OF SUPERSTRUCTURES

The development of the superstructures thermodynamic modeling takes account on some general assumptions; pressure losses, heat transfer losses, and kinetic and potential energy are negligible in each equipment. For all heat exchangers devices, it is assumed a constant global heat transfer coefficient that is extracted from Dixit *et al.* (2017). The working fluid is LiBr and Water in the absorption cycle and it is assumed as incompressible flow. The inlet temperature of absorber is set to 30ºC, while the outlet temperature of condenser is defined as 35ºC. For evaporator inlet and outlet temperatures is considered 12 and 7ºC, respectively.

### 4.1 Thermodynamic Modeling

The mathematical modeling is based on Conservation of Mass and First Law of Thermodynamics in each component, as in Eq. (1) and Eq. (2), where $\dot{m}$ represents the mass flow rate, $\dot{Q}_i$ is the heat transfer rate, $\dot{W}_i$ is the work and $h$ is the enthalpy property.

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

$$0 = \dot{Q}_i - \dot{W}_i + \sum \dot{m}_{in} \cdot h_{in} - \sum \dot{m}_{out} \cdot h_{out} \tag{2}$$

For each component, the heat transfer area is determined through Energy Balance and Log Mean Temperature Difference (LMTD) definition, as is represented in Eq. (3), where $U_i$ is the global heat transfer coefficient, $A_i$ is the heat transfer area, $T_{hot}$ is the temperature from hot stream and $T_{cold}$ is the temperature from cold stream.

$$\dot{Q}_i = U_i \cdot A_i \cdot \frac{(T_{hot,in} - T_{cold,out}) - (T_{hot,out} - T_{cold,in})}{ln\left(\dfrac{T_{hot,in} - T_{cold,out}}{T_{hot,out} - T_{cold,in}}\right)} \tag{3}$$

The cooling tower modeling is simple and only takes account Conservation of Mass and First Law of Thermodynamics. Furthermore, psychrometry properties are required to fulfill the enthalpy properties due to relative humidity and dry bulb temperature.

The development of cold-water cooling system for UTE thermal power plant has three possible applications, the first one is applicable to cool the water stream using a heat exchanger after the radiator. The Eq. (1) to Eq. (3) are used too and the similarity rules from Fox *et al.* (2012) represented in Eq. (4), Eq. (5) and Eq. (6) are applied, where $\rho_{air}$ represents the air density, $Q_{fan}$ is the volumetric flow rate of air, $Q_{design}$ is the volumetric flow rate of design operating condition, $\omega_{fan}$ is rotating speed of the fan, $\omega_{design}$ is the design rotating speed of the fan, $\dot{W}_{fan}$ is consumed power on the radiators and $\dot{W}_{design}$ is the design operating power condition.

$$\dot{m}_{air} = \rho_{air} \cdot Q_{fan} \tag{4}$$

$$\frac{Q_{fan}}{Q_{design}} = \frac{\omega_{fan}}{\omega_{design}} \tag{5}$$

$$\frac{\dot{W}_{fan}}{\dot{W}_{design}} = \left(\frac{\omega_{fan}}{\omega_{design}}\right)^3 \tag{6}$$

HVAC systems use electrical energy to operate a cooling system on the control and low voltage rooms, thus, it is applicable to install two heat exchangers to cool the air stream of the rooms by using cold-water system from absorption chillers, then reducing the electrical energy consumption. Equation (1) to (3) are applied.

Finally, the third application is possible to be reached by installing a heat exchanger before the intake air on the engine. The ICE presents a turbocharger configuration in its structure, then cooling the air means to reach more shaft power generation and specific fuel consumption reduction. Ribeiro (2015) provides necessary data to assist this modeling, including two ISO standards; ISO 15550 and ISO 3046-1 that determine the gain in shaft power and reduction in specific fuel consumption, respectively. Besides that, the Conservation of Mass, Energy Balance and LMTD are used again, as represented in Eq. (1) to Eq. (3).

### 4.2 Economic Modeling

The development of economic modeling of all components inside the superstructure is based in Boehm (1987) methodology, as in Eq. (7), where $Z_i$ is the purchase cost of equipment, $Z_{ref,i}$ is the reference purchase cost of equipment, $X_i$ is the calculated variable, $X_{ref,i}$ is the desired reference variable and $m_i$ is the value that represents the type of equipment.

$$Z_i = Z_{ref,i} \cdot \left( \frac{X_i}{X_{ref,i}} \right)^{m_i} \tag{7}$$

For components that are heat transfer devices, the calculated variable is the heat transfer area and for cooling tower cost is used the volumetric flow rate as calculated variable. However, for pumps and electric motors, d'Accadia and Rossi (1998) give the Equation (8) to determine the purchase cost of these equipment, where $\dot{W}_i$ is the work, $\dot{W}_{ref,i}$ is the reference work, $\eta_i$ is the device efficiency, $n_i$ and $m_i$ are other constants values referent to this kind of equipment.

$$Z_i = Z_{ref,i} \cdot \left( \frac{\dot{W}_i}{\dot{W}_{ref,i}} \right)^{m_i} \cdot \left( \frac{\eta_i}{1 - \eta_i} \right)^{n_i} \tag{8}$$

The reference purchase costs of chiller's equipment are given by Misra *et al.* (2003) which used Christian's (1997) reference costs while was updated to year 2000. For cooling tower reference cost, Boehm (1987) gives some valuable data and d'Accadia and Rossi (1998) present the coefficients values for pump. Regarding to the corrected values of these reference purchase costs, it was updated to year 2017.

Boehm (1987) provides a simple and basic methodology to update the reference purchase cost by just using the Equation (9), where $CI_i$ is the cost index. In order to accomplish this updating step on reference purchase costs, it is consulted the Chemical Engineering Plant Cost Index (CEPCI) to get the corresponding values of each cost index for different referenced years.

$$Z_{ref,i}^{Current} = Z_{ref,i}^{Past} \cdot \frac{CI_i^{Current}}{CI_i^{Past}} \tag{9}$$

Finally, these economics modeling need to be corrected by the correcting factor (*CF*). For UTE thermal power plant, the acquisition of all equipment must be treated as an expansion process because the power plant already exists and it is not a new installation process. Bejan *et al.* (1996) give 6.32 and 4.16 as installation and expansion factors, respectively. Although these values were given to use on plant costs, it is best required to use a value more compatible with absorption chillers acquisition. Thus, Castillo (2007) presents an installation correcting factor on chillers of 3.73, then applying a basic mathematical proportion, the expansion correcting factor is 2.455. Therefore, the total cost investment ($TCI_{exp}$) can be calculated in Eq. (10).

$$TCI_{exp} = CF_{exp} \cdot \sum Z_i \tag{10}$$

## 5. OPTIMIZATION PROBLEM FORMULATION AND SOLUTION

The optimizations are carried out in two objective functions; chiller specific cost, as in Eq. (11), and plant's total specific profit, as in Eq. (12), respectively, where $\dot{B}_i$ are the economic specific savings, $\dot{Z}_i$ is the total specific cost and *PENALTY* is an artificial penalty which is responsible to hold the Conservation of Mass in cold-water system.

$$\dot{C}_{Chiller} = \frac{\sum Z_{i,Chiller}}{\dot{Q}_{ev}} \tag{11}$$

$$Profit_{total} = \sum \dot{B}_i - \dot{Z}_{total} - PENALTY \tag{12}$$

The artificial penalty is necessary because when all thermodynamic modeling is integrated, an artificial mass is used to supply or withdraw cold-water mass rate. Moreover, in real scenario, this artificial variable does not exist at all. Therefore, during the optimization process is important to pay for this excess or lack of cold-water mass rate. Donatelli (2002) used this strategy of using an artificial penalty to solve a high complex optimization problem.

The economic specific savings on radiator, control and low voltage rooms are well presented by Eq. (13), where $\dot{W}_{ope,i}$ is operating work, $\dot{W}_{recalc,i}$ is recalculated work and $E_{price}$ is selling electrical energy price which is provided by ONS (2017).

$$\dot{B}_i = (\dot{W}_{ope,i} - \dot{W}_{recalc,i}) \cdot E_{price} \tag{13}$$

Equation (14) determines the economic specific saving on ICE, where $\dot{W}_r$ is real shaft engine work, $b_r$ is real specific fuel consumption, $\dot{W}_{actual}$ is actual shaft engine work, $b_{actual}$ is actual specific fuel consumption and $C_{fuel}$ is fuel price.

$$\dot{B}_{ICE} = \dot{W}_r \cdot (E_{price} - b_r \cdot C_{fuel}) - \dot{W}_{actual} \cdot (E_{price} - b_{actual} \cdot C_{fuel}) \tag{14}$$

Valero *et al.* (1994) provide the necessary data and the Eq. (15) to calculate the total specific cost, where *CRF* is capital recovery factor, $\varphi_{maint}$ is maintenance factor and $t_{ope}$ is number of operating hours.

$$\dot{Z}_{total} = TCI_{exp} \cdot CRF \cdot \frac{\varphi_{maint}}{t_{ope}} \tag{15}$$

Figure 4 shows the methodology to solve the superstructure optimizations.

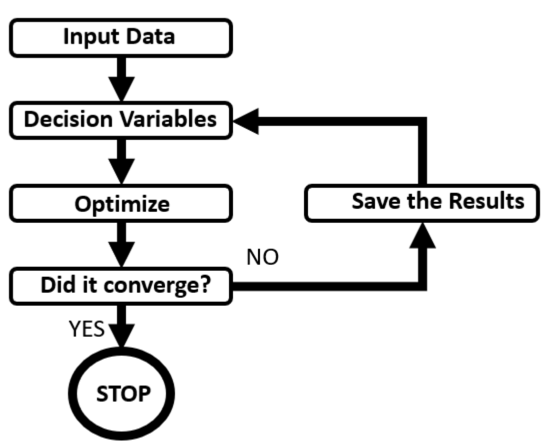


Figure 4. Optimization Methodology

The optimization mathematical tool is the genetic algorithm from EES, which presents an open and basic programming code, it is called PIKAIA (FCHART-EES, 2017). The idea of this methodology is based on mutating and crossing pair of individuals, basically the best new individuals provide the best solution during the optimization process. According to Amir (2012), there are three advantages on using Genetic Algorithm methodology in optimization problems, the first advantage is no involvement of many mathematical assumptions, the second is the periodicity on evolution operators due to its efficient global search on the solution. Finally, the third is a great flexibility on hybridizing the heuristic dependent-domain. The EES genetic algorithm method is based on PIKAIA coding, thus it is necessary to set the number of individuals, generations and mutation rate. For each superstructure optimization, it was set 32 individuals, 256 to 2048 generations depending on the improvement of optimizing process, and 0.058 of mutation rate. These values were tested several times because an issue called "infloating point" could appear during the optimizing process. The mutation rate value was based according to Dejong (1975).

## 6. RESULTS AND DISCUSSION

In this section, all optimizations results are presented and discussed. In summary, three absorption chiller superstructures integrating the cooling tower and cold-water system are optimized separately in this work.

For each superstructure, it is optimized considering, separately, two different objective functions; chiller specific cost minimization and profit maximization, respectively. Table 3 shows the main results from all three superstructures optimizations.

Table 3 – Optimized results from all absorption chillers superstructures.

| Optimization | Minimizing Chiller Specific Cost | | Maximizing Profit | | | | |
|---|---|---|---|---|---|---|---|
| - | Chiller Specific Cost (US$/TR) | Cold-water (kg/s) | Profit (US$/h) | TCI (US$) | Chiller Specific Cost (US$/TR) | Cold-water (kg/s) | Artificial Cold-water (kg/s) |
| Simple Effect (Hot Water) | 2523 | 28.649 | 4.745 | 588311 | 2593 | 23.021 | 0 |
| Simple Effect (Exhaust Gases) | 387 | 75.911 | 4.739 | 658543 | 498 | 56.171 | 0 |
| Double Effect (Exhaust Gases) | 427 | 94.079 | 4.410 | 744656 | 718 | 65.030 | 0 |

The comparison between the results in Tab 3 provide some interesting information about the behaviors of superstructures optimization. The highest profit is 4.745 US$/h, which is the Simple Effect structure driven with Hot Water, and its total cost investment is the cheapest among the optimized results with a corresponding value of US$ 588311. In addition, the lowest profit is 4.410 US$/h, which is the Double Effect structure driven with Exhaust Gases, and its total cost investment is US$ 744656. It is notable that the Simple Effect structure driven with Exhaust Gases presents the minimum chiller specific cost of 498 US$/TR when the objective function is maximizing profit.

Other relevant observation is on cold-water production, because when minimizing chiller specific cost, the cold-water mass rate is always greater than the cold-water mass rate in maximizing profit, as it is represented in Tab 3, also the chiller specific costs in all superstructures while maximizing profit is greater than the minimized specific costs. It means that the profit maximization is not resulting in a chiller specific cost that reaches its minimum value, as consequence, the cold-water mass rate is less produced. Thus, no superstructures produce its optimal cold-water mass rate capacity. Moreover, it is relevant to analyze that the artificial cold-water mass rate is successfully achieved to zero value for all optimal structures, which means that the artificial penalty worked during the optimization task. Therefore, holding the conservation of mass.

The optimized decision variables of optimal Simple Effect structures are presented in Tab 4. In summary, when maximizing the profit, the optimized results showed that both final Simple Effect optimal structures do not recover the same amount of heat while minimizing the chiller specific cost, and it is checked in the decision variable; Temperature Difference on Desorber.

In Table 5, the same thermodynamic behavior repeats again when maximizing the profit for Double Effect superstructure, the final optimal structure does not recover the same amount of heat while minimizing the chiller specific cost.

When minimizing the chiller specific cost of each superstructure, only the superstructure driven with hot water stream needed the heat exchanger in its final optimal structure. However, for maximum profit, all superstructures required the heat exchangers. Table 6 presents the effectiveness values, which are responsible to define the existence of heat exchangers in each optimal structure. If effectiveness is equal to zero, it means no existence of heat exchanger and if its value is greater than zero, the heat exchanger must appear in its structure.

Table 4 – Optimized decision variables for Simple Effect superstructures.

| Superstructure | Simple Effect (Hot Water) | | Simple Effect (Exhaust Gases) | |
|---|---|---|---|---|
| Optimization | Minimizing Chiller Specific Cost | Maximizing Profit | Minimizing Chiller Specific Cost | Maximizing Profit |
| Temperature Difference on Desorber (ºC) | 7.41 | 6.64 | 165.00 | 102.33 |
| Terminal Temperature Difference on Desorber (ºC) | 0.90 | 1.11 | 34.01 | 100.83 |
| Terminal Temperature Difference on Condenser (ºC) | 0.37 | 0.37 | 9.97 | 8.35 |
| Terminal Temperature Difference on Evaporator (ºC) | 0.51 | 0.70 | 6.99 | 6.99 |
| Mass Fraction on weak solution | 0.539 | 0.544 | 0.702 | 0.649 |
| Heat Exchanger Effectiveness | 0.721 | 0.588 | 0 | 0.499 |

Table 5 – Optimized decision variables for Double Effect superstructures.

| Superstructure | Double Effect (Exhaust Gases) | |
|---|---|---|
| Optimization | Minimizing Chiller Specific Cost | Maximizing Profit |
| Split B2 | 0.996 | 0 |
| Temperature Difference on Desorber (ºC) | 99.77 | 69.31 |
| Temperature Difference on the low Heat Exchanger (ºC) | 0 | 17.43 |
| Temperature Difference on the high Heat Exchanger (ºC) | 0 | 62.19 |
| Terminal Temperature Difference on Low Desorber/High Condenser (ºC) | 18.02 | 16.55 |
| Terminal Temperature Difference on Low Condenser (ºC) | 15.00 | 6.13 |
| Terminal Temperature Difference on Desorber (ºC) | 77.30 | 46.41 |
| Terminal Temperature Difference on Evaporator (ºC) | 4.93 | 3.44 |
| Pressure Ratio between High pressure and Medium pressure | 25.00 | 22.73 |
| Temperature of weak solution on High Pump Inlet (ºC) | 22.46 | 60.24 |
| Mass Fraction of weak solution on High Pump Inlet | 0.199 | 0.600 |
| Mass Fraction of weak solution on Absorber outlet | 0.668 | 0.599 |

Table 6 – Effectiveness of heat exchangers for each superstructure.

| Optimization | Minimizing Chiller specific cost | | Maximizing profit | |
|---|---|---|---|---|
| - | low heat exchanger Effectiveness (%) | high heat exchanger Effectiveness (%) | low heat exchanger Effectiveness (%) | high heat exchanger Effectiveness (%) |
| Simple Effect (Hot Water) | 72.1 | - | 58.8 | - |
| Simple Effect (Exhaust Gases) | 0 | - | 49.9 | - |
| Double Effect (Exhaust Gases) | 0 | 0 | 33.8 | 66.8 |

The splits inside the Double Effect superstructure are presented in Tab 7. As it can be seen, for minimum chiller specific cost, the final optimized structure is approximately the parallel flow which feeds both low and high desorbers, and the strong solution return firstly on low desorber and sequentially to absorber. When maximizing the profit, it presents a different optimized configuration, where there is a weak solution, which feeds both low and high desorbers but all strong solution return to absorber without passing through the low desorber. In other words, the final optimal structure for maximum profit is a hybrid configuration between parallel and series flow.

Table 7 – Split's values of Double Effect superstructure.

| Objective Function | Minimizing Chiller specific cost | Maximizing profit |
|---|---|---|
| Configuration | Parallel Flow | Hybrid Flow |
| B1 (%) | 99.0 | 98.6 |
| B2 (%) | 99.6 | 0 |
| B3 (%) | 14.7 | 36.9 |

Table 8 presents the cold-water mass rate distribution on all benefits. The Simple Effect optimal structure driven with hot water stream did not feed the heat exchanger after the radiator with cold-water stream. This behavior is consistent because the absorption chiller itself is recovering part of heat residue from jacket water, thus it is expected a low or almost negligible value of cold-water mass rate in the installed heat exchanger after the radiator. However, the optimal structures driven with exhaust gases feed cold-water mass rate to all possible benefits but there are some similarities and differences between their cold-water mass rate distributions. The Simple Effect optimal structure driven with exhaust gases sends more cold-water mass rate to cooling coil system, followed by radiators, low voltage and control room. The Double Effect optimal structure feeds more the radiators, secondly the cooling coil, and in sequence, low voltage and control rooms. It is interesting to note that the cold-water application in air conditioning system and cooling/dehumidifying the intake air of the engine is always necessary in all optimized results.

Table 8 – Cold-water mass rate distribution.

| Maximizing profit | | | | | |
|---|---|---|---|---|---|
| Cold-water distribution | Chiller Cold-water (kg/s) | Radiators (%) | Cooling Coil (%) | Low Voltage Room (%) | Control Room (%) |
| Simple Effect (Hot Water) | 23.021 | 0 | 63.1 | 24.9 | 12 |
| Simple Effect (Exhaust Gases) | 56.171 | 37.2 | 47.5 | 10.2 | 5.1 |
| Double Effect (Exhaust Gases) | 65.030 | 45.5 | 41.3 | 8.8 | 4.4 |

The implications of using cold-water applications must be accounted in output electrical power generation and specific fuel consumption savings in ICE, also electrical energy consumption savings in AC and radiator system. The real amount of electrical energy operating consumption in AC system and radiator are 60 and 100 kW, respectively. The Table 9 shows the savings related to these benefits mentioned before.

In Table 9, it is significantly important to analyze that the electrical energy saving in radiator is higher in Simple Effect driven with Hot Water, reminding that its structure does not send cold-water stream to the heat exchanger after the radiator because the chiller is already reusing part of the residual heat. In general, the optimization results showed scenarios that it is most suitable to distribute cold-water with the AC system and cooling coil applications. The results presented that for all optimal structures the electrical energy consumption in AC system are completely saved by the cold-water application. Moreover, the use of cold-water to cool and dehumidify the intake air of the engine is a huge advantage because all optimal structures showed gains in output electrical power generation and specific fuel consumption in ICE. Therefore, the application of using an absorption chiller with more than one single engine, allowing a scaling cold-water application, is possible.

Table 9 – Savings at UTE thermal power plant though cold-water applications.

| Benefits | Output Electrical Power Generation in ICE (kW) | Specific Fuel Consumption Saving in ICE (g/kWh) | Electrical Energy Consumption Saving in Radiator system (kW) | Electrical Energy Consumption Saving in AC system (kW) |
|---|---|---|---|---|
| Simple Effect (Hot Water) | 45.142 | 1.2822 | 39.719 | 59.267 |
| Simple Effect (Exhaust Gases) | 84.459 | 2.4288 | 21.592 | 59.991 |
| Double Effect (Exhaust Gases) | 85.066 | 2.4467 | 29.496 | 59.967 |

## 7. FINAL REMARKS

In this present work, the goal is fulfilled on finding optimal configurations of LiBr and Water absorption chillers from the structural and parametric point of view through superstructure optimization methodology. In addition, thermodynamic and economic modellings of the benefits at UTE Viana thermal power plant are developed with the chillers superstructures, including a basic cooling tower modelling. The presented results from both optimizations of minimizing specific costs and maximizing profits provided reliable information about the best structures for UTE Viana thermal power plant. When minimizing specific cost, there are not heat exchangers in the optimal absorption chillers structures and the Double Effect optimal structure is a parallel flow configuration. For maximizing profit, it is required the existence of heat exchangers in the optimal structures and the Double Effect optimal structure is a hybrid configuration. Furthermore, it is relevant to note that the study case optimization is a Mixed Non Linear Programming (MNLP) problem. It means that the splits B1, B2 and B3 for Double Effect superstructure allows hybrid configurations.

In summary, all superstructures resulted in final optimal structures that do not produce its optimal amount of cold-water capacity because for this study case in UTE Viana power plant the calculated chiller specific costs for maximum profit do not achieve its minimum value, which means less cold-water production. Moreover, the optimal parametric conditions of each final optimal structure and its distributions of cold-water mass rate for maximized profits is successfully reached and its results are consistent from the thermoeconomic point of view.

The gains of using cold-water applications are outstanding; all optimal structures showed that the electrical energy consumption savings in AC system is completely reached in the optimized results. The radiator electrical energy consumption savings is also achieved but not entirely. The most interesting results are in ICE benefits, where the use of cold-water to cool and dehumidify the intake air of the engine is considerably advantageous due to its output electrical energy generation and reduction of specific fuel consumption. Thus, it is possible to use one absorption chiller with more than one single engine, allowing a scaling application of cold-water distribution in several engines and possibly more benefits.

The best choice among the results, considering the Profit as objective function, is Simple Effect driven with Hot Water, where the maximum profit is 4.745 US$/h with a total cost investment around US$ 588311, chiller specific cost of 2593 US$/TR and a cold-water mass rate production of 23.021 kg/s. This result is the cheapest total cost investment with the greatest profit.

Therefore, the superstructure optimization methodology demonstrated itself as a powerful tool to achieve the best configuration from the structural and parametric point of view in absorption chillers with ICE. However, it is essential to confirm that depending on the complexity of the superstructure, it might take a rough computation effort to solve the optimization process. In addition, the artificial penalty worked properly and this optimization strategy is significantly useful to solve and achieve the aim of this work.

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