PERFORMANCE ANALYSIS AND ASSESSMENT OF A HIGHLY ENERGY-INTEGRATED SOLAR TRIGENERATION SYSTEM USING ADVANCED ABSORPTION CHILLERS

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Abstract: *The direct use of solar thermal energy to generate power produces a large amount of heat. Therefore, the use of thermally driven chillers is an appealing solution to make use of this heat to produce cooling replacing electric driven systems. The main objective of this paper is to provide a description of the possible designs and configurations of solar trigeneration systems, including organic Rankine cycles (ORC) and recently commercialized advanced absorption chillers. The main novelty of this study is the use of a Single-Effect Double-Lift absorption cycle (SE-DL AC) for solar trigeneration cycles and its comparison with a base case using a conventional single effect absorption cycle (SE AC). The main finding of this study highlights that working under the same conditions; the SE-DL AC uses heat more effectively than the SE AC for cooling production with a considerably higher production of power at the ORC.*

Keywords: solar trigeneration, absorption chiller, Organic Rankine Cycle, thermodynamic analysis, energy integration.

1. INTRODUCTION AND OBJECTIVES

The total energy demand is expected to increase steadily throughout the world. According to the International Energy Outlook (2021), the global energy consumption is predicted to increase by nearly 50% over the next 30 years [1]. Environmental issues, as well as the unpredictability of energy costs, are major concerns that should be addressed. Meanwhile, these issues drive the interest in developing advanced energy conversion technologies to replace or reduce fossil fuel overconsumption and greenhouse gas emissions.

In this regard, polygeneration systems such as trigeneration systems have proved to be a highly efficient and recommended technology for meeting the building and industrial sector's electricity, heating, and cooling needs [2]. One of the most common techniques for balancing overloads in building cooling and heating demands are Absorption Chillers (AC) [3]. The Organic Rankine Cycle (ORC) subsystem appears to be one of the most competitive power cycles in combination with AC. ORC is a proven and efficient technology to generate mechanical and/or electrical power. Researchers have developed and optimized many solar-driven trigeneration systems that encompass various energetic systems in order to improve the overall efficiency of trigeneration systems. The initial most innovative idea in trigeneration and polygeneration systems was the integration of renewable energy sources [4]. Different energy sources and trigeneration combinations have been exhaustively investigated, but the most common is the use of an absorption chiller as bottoming cycle to recover heat from the ORC. This is the configuration analyzed in this work but using an innovative absorption chiller known as Single-Effect Double-Lift absorption chiller (SE DL AC) that will be presented in detail later on. The results are compared with those using a more conventional single effect absorption chiller (SE AC). One of the limitations to perform this study is that in the literature there is limited numerical and/or experimental investigation on SE-DL AC chillers.

The primary goal of this paper is two-fold: in the first section, provide a brief review of the main configurations for solar thermal trigeneration systems, particularly those using ORC and AC. Later, a SE-DL AC is modeled, and simulated and its performance integrated in a trigeneration system is compared with that of a single-effect absorption chiller (SE AC).

2. SOLAR TRIGENERATION SYSTEMS

The primary motivation for coupling different energy conversion systems is to maximize energy efficiency. It is possible to define at least three types of solar trigeneration systems. The first one, could be the energy cascading which, typically uses the absorption chiller as a bottoming cycle. This setup exploits the residual rejected heat from the toping solar energy driven ORC cycle to drive the bottoming subsystem (absorption chiller). This type of combination appears to be the most commonly used. In this case, the heat release from the condenser and absorber of the chiller are rejected to the ambient or could be reused for heating applications whenever it is possible. In the second configuration, the same solar thermal plant feeds each subsystem (ORC and AC) separately at the same time according to the existing power and cooling demands. A third configuration could be the use of combined absorption cycles for the simultaneous production of power and cooling using directly solar thermal energy [5].

3. SINGLE-EFFECT DOUBLE-LIFT VS. SINGLE-EFFECT ABSORPTION CHILLER

This section compares and discusses the differences between the configuration and performance of single- effect double lift and the single-effect absorption chiller. The SE-DL chillers allow the efficient use of low- grade heat with an extensive temperature glide in the driving heat stream (> 30 K), which extracts approximately twice as much heat (~200 %) as the single-effect chiller [6]. This large temperature glide means that the SE-DL chillers are well suited for solar thermal collector installations or district heating networks where the extra driving heat coming from a larger temperature difference of the heat transfer fluid used to drive the chiller increases the cold production. Thus, the cooling capacity produced from the same heat source at a given temperature and mass flowrate can be larger than that of a single-effect chiller. This larger temperature gliding of the driving heat comes from the different configuration of the SE (shown in Figure 1) and that of the SE-DL (shown in figure 2). The driving heat is used three times inside the absorption cycle: High and low temperature generator and auxiliary generator.

Another factor that influences the preference of using the single-effect double-lift over the single effect absorption chiller is the fact that this novel configuration can operate at lower driving temperatures. Indeed, the most common commercialized absorption chillers operate with driving temperatures close to 90 °C to generate an overall energy performance of 0.7. Operating below this temperature will cause a significant drop in the chillers performance. In this regard, the SE-DL AC is more adaptable as it can operate with a narrow range of hot water driving temperatures down to 55 °C while maintaining an acceptable range of COP ranging from 0.35 to 0.7 [7]. Consequently, although its higher number of heat exchangers (figure 2) and complexity the advantages with respect to the SE absorption chiller are remarkable. A few commercial SE-DL chillers have been introduced recently in the market [6].

4. SE-DL SOLAR TRIGENERATION SYSTEMS

4.1. Description of the studied configurations

Figures 1 and 2 show the trigeneration system that was investigated in this study. It consists mainly of a basic Organic Rankine Cycle (ORC) as a power production subsystem that can be driven by a thermal source. A single-effect (SE) and a single-effect double lift (SEDL) absorption chiller using a H_2O/LiBr mixture as working fluid. Both chillers are used as a bottoming cycle to meet cooling and power demands simultaneously. The selected ORC works with n-pentane as working fluid, with an expander isentropic efficiency of 85 %, and a maximum pressure of 90 % of the fluid critical pressure to set the high pressure of the system. The outlet temperature of the ORC condenser is set to be 10 ºC higher that the return temperature from the chiller.

In the ORC thermodynamic cycle the low pressure working fluid at the condenser's outlet (Str. 1) is pumped to high pressure entering the evaporator (Str. 2) where solar heat is absorbed. The working fluid gets slightly superheated (Str. 3) and enters the expander to produce practical work. The hot stream from the expander's outlet (Str. 4) enters the condenser to reject the heat that allows to drive the absorption chillers to operate at a set temperature.

The water/lithium bromide single-effect and single-effect double-lift absorption chillers have a similar working principle. Both of them contain separated working fluid circuits, for the H_2O/LiBr mixture and for the refrigerant (water). The basic cycle of a single-effect absorption chiller is merged into a Double Lift absorption chiller in a SE-DL chiller (DL).

The SE-DL AC has two solution circuits, starting at the low absorber, low SHX, and low generator and progressing to the high SHX, which is where the first closed loops are found. The second loop is mostly made up of an auxiliary absorber that operates at a medium pressure; an auxiliary SHX is included into this solution circuit to improve the system's overall efficiency (COP). The refrigerant at the outlet of the auxiliary and high temperature generator pass forward to the condenser. In this one, heat is rejected and the refrigerant reaches finally the evaporator. At the evaporator, heat is removed and the cooling effect occurs. Finally, the refrigerant vapor gets into the low-pressure absorber and the cycle starts again. The SE-DL cycle operates at three pressure levels. The mathematical modeling of the entire trigeneration is carried out in steady-state conditions and is based on mass and energy balances on the basis of the first law of thermodynamics. The same external working conditions such as driving heat, cooling water and chilled water characteristics are applied in both chillers in order to compare them. The different production of power achieved is calculated for the trigeneration system using both chillers because the performance of the chiller has a clear impact on the performance of the ORC. The temperature at the condenser outlet of the ORC is expected to be lower for the case of the SE-DL AC, then assuming saturated conditions at this point, the low pressure of the ORC will be lower than that of the SE AC case increasing the power production. Thus the SE-DL AC will increase both the chilled water and power production.

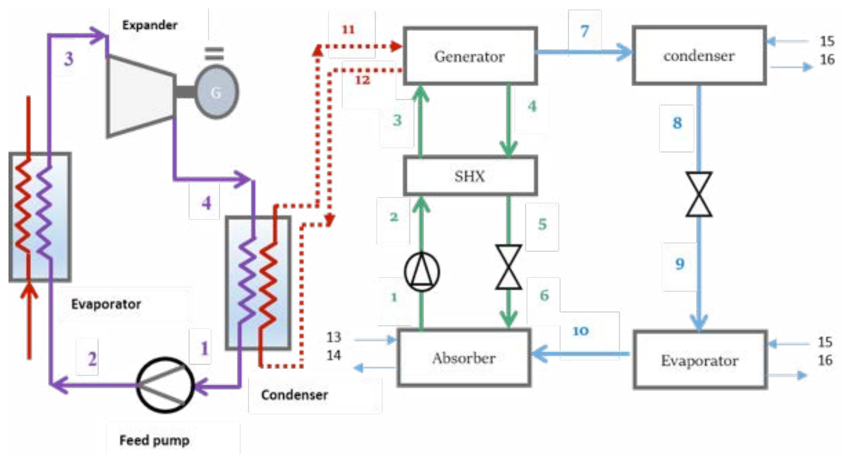

Figure 1. Schematic of the investigated ORC+ SE AC trigeneration system.

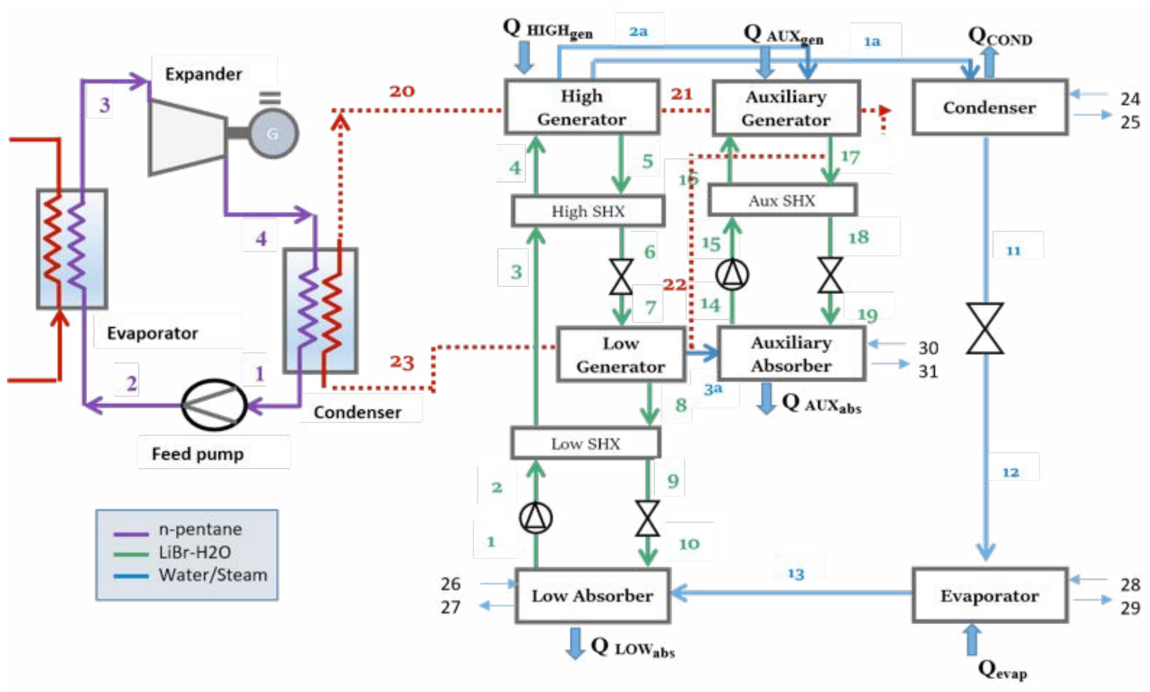

Figure 2. Schematic of the investigated ORC + SE-DL AC trigeneration system.

5. RESULATS AND DISCUSSION

The investigated trigeneration system presented in this work is a simple but advanced system with numerous variables and parameters that need to be taken into consideration for the overall analysis of both configurations (ORC+SE AC and ORC+SEDL AC). To perform a fare comparison of the SE and SE-DL AC chillers, in the simulation were considered the same boundary conditions or external streams conditions and also the same internal main temperatures to set the low and high pressure limits inside the absorption cycle for both absorption chillers (SE AC and SE-DL AC). These conditions are as follows: the internal generator temperature is 82 °C, the absorber and the condenser are assumed to work at the same temperature level of 35 °C, and the evaporator temperature was set at 4.5 °C. Furthermore, the external input temperatures of the driving heat, cooling and chilled water were set to 90, 30, and 12 °C, respectively, with a mass flow rate of 1 kg/s for the driving hot water. The thermodynamic performance of single-effect and single-effect double-lift absorption chillers are summarized in the table below based on the settings described above.

Table 1. Performance of SE and SE-DL absorption chillers

Single-effect AC		**Single-effect Double-Lift AC**	
Description	EnergyFlow	Description	EnergyFlow
Generator (Q_{gen})	14.59 kW	High Generator ($Q_{Highgen}$)	73.4 kW
Absorber (Q_{abs})	14.04 kW	Auxiliary Genarator (Q_{auxgen})	61.1 kW
Condensor (Q_{cond})	11.39 kW	Low Generator (Q_{lowgen})	11.7 kW
Evaporator (Q_{evap})	10.83 kW	Auxiliary Absorber (Q_{auxabs})	16.9 kW
Solution Heat Exchanger (Q_{shx})	2.419 kW	Low absorber (Q_{lowabs})	125.3 kW
Coefficient of Performance (*COP*)	0.742	Condenser (Q_{cond})	109.5 kW
Temperature difference (ΔT) of the generator		Evaporator (Q_{evap})	105.4 kW
T inlet_generator (T_{11})	90°C	High SHX ($Q_{highshx}$)	6.54 kW

Single-effect AC		**Single-effect Double-Lift AC**	
Description	EnergyFlow	Description	EnergyFlow
T outlet_generator (T_{12})	86.5°C	Auxiliary SHX (Q_{auxshx})	9.15 kW
		Low SHX (Q_{lowshx})	4.34 kW
		Coefficient of performance(*COP*)	0.721
		Temperature at each generator	
		T_inlet_Highgen (T_{20})	90°C
		T_inlet_Auxgen(T_{21})	72.4°C
		T_inlet_Lowgen(T_{22})	57.8°C
		T_outlet_lowgen(T_{23})	55.0°C

According to the performed analysis, and using the waste heat rejected from the ORC condenser in the form of hot water to drive the absorption chillers, the single-effect double-lift absorption chiller produces a larger amount of cooling (105.4 kW) as compared to the SE AC, which generates only 10.83 kW at the same given input parameters. Another important result is that the heat recovered to drive the three generators (low, high, and auxiliary) of the SE-DL AC is almost 90 % higher than that of the SE absorption chiller.

Furthermore, there is an important difference comparing the two configurations using a mass flow rate of 1 kg/s and a temperature of 90 °C for the driving heat. The temperature difference between the inlet and outlet temperatures of the SE AC was only 3.5 °C, thus with an outlet temperature of the driving heat of 86.5°C. Unlike the single effect, the SE-DL AC driving heat comes in at 90°C at the inlet of the high temperature generator and comes out at 55 °C at the outlet of the low temperature generator. The glide temperature has increased 10 times in comparison to the single effect chiller. A further finding that indicates that the SE-DL absorption chiller is a more viable option for utilizing waste heat from the Organic Rankine Cycle is looking at the power production. In the first configuration, where the ORC is connected to the SE AC, only 2.1 kW of electricity was produced. Using the SE-DL AC, on the other hand, has multiplied the power production 10 times higher than the SE AC, resulting in a power output of 27.6 kW. The heat recovered using the SE-DL AC systems is larges producing more cooling and also because of the lower return temperature to the condenser of the ORC, the expansion pressure ratio through the ORC expander increases and the same happens with the flow rate of the ORC working fluid. The result is a much larger production of power.

The present preliminary analysis has covered only the use of series cycles where the chiller is connected as a bottoming cycle with respect to the ORC. For the connection in parallel with respect to the solar collectors the benefits will be also interesting to calculate because the collectors will also benefit from a lower return temperature from the chiller giving a higher efficiency in the primary solar resource.

6. CONCLUSIONS

An energy-integrated trigeneration system based on an advanced absorption chiller (Single-Effect Double-Lift chiller) is investigated. The following are the main findings:

- The efficiency of the trigeneration system can be easily increased by the improvement of the heat rejected by the ORC.
- The single-effect double-lift absorption chiller has a huge potential, especially in terms of heat recovery being an efficient option as a bottoming cycle. The result is a cooling production 10 times higher for the studied conditions where the temperature glide for the driving heat for the SE-DL chiller reaches 35 ºC.
- The ORC's power output could be also increased more than 10 times when the SE-DL absorption chiller is integrated as bottoming cycle in the solar trigeneration system.

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REFERENCES

[1] EIA, *The international energy outlook 2021*, https://www.eia.gov/outlooks/ieo/pdf/IEO2021_Narrative.pdf.

[2] Kabalina N, Costa M, Yang W, Martin A, Santarelli M, Exergy analysis of a polygeneration-enabled district heating and cooling system based on gasification of refuse derived fuel, *J. Clean. Prod.*, vol. 141, pp. 760–773, Jan. 2017, doi: 10.1016/J.JCLEPRO.2016.09.151.

[3] Bataineh K, Taamneh Y, Review and recent improvements of solar sorption cooling systems, *Energy Build.*, vol. 128, pp. 22–37, 2016, doi: 10.1016/j.enbuild.2016.06.075.

[4] Suleman F, Dincer I, Development of an Integrated Renewable Energy System for Multigeneration. *Energy*, no. November, 2014, doi: 10.1016/j.energy.2014.09.082.

[5] Ayou DS, Bruno JC, Coronas A, Combined absorption power and refrigeration cycles using low- and mid-grade heat sources, Science and Technology for the Built Environment, 21, 934-943, 2015.

[6] Ayou DS, Coronas A, New Developments and Progress in Absorption Chillers for Solar Cooling Applications, Applied Sciences 2020, 10(12), 4073.

[7] X. Wang and H. T. Chua, “Absorption Cooling: A Review of Lithium Bromide-Water Chiller Technologies,” Recent Patents Mech. Eng., vol. 2, no. 3, pp. 193–213, 2010, doi: 10.2174/1874477x10902030193.