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Improving liquefaction process of microgrid scale Liquid Air Energy Storage (LAES) through waste heat recovery (WHR) and absorption chiller

Emiliano Borri[a], Alessio Tafone[b], Gabriele Comodi[a,*], Alessandro Romagnoli[c]

[a] *Università Politecnica delle Marche, Via Brecce Bianche, Ancona, Italy*
[b] *Energy Research Institute @ NTU, ERI@N, Interdisciplinary Graduate School, Nanyang Technological University, Singapore*
[c] *School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore*

Abstract

Liquid air energy storage systems (LAES) store liquid air produced by a liquefaction cycle and convert it into electric/cooling power when needed. A small-scale Liquid air energy storage system represents a sustainable solution in microgrid and distributed generation, where small energy storage capacities are required. The main drawback of these systems though, is the low round trip efficiency due to a high specific consumption of the liquefaction cycle. In this work, a single-effect absorption chiller using a Water-Lithium Bromide solution is integrated with a small air liquefier with a liquid air production capacity of 0.834 t/h. In the proposed solution, the waste heat of the compression phase of the liquefaction cycle is recovered and used to drive the absorption cycle, where the resulting cooling power is used to decrease the specific consumption and improving the exergy efficiency of the system. The operative parameters of the absorption chiller reflect the specifications of the most common commercial models available in the market and the size has been selected to maximize the heat power recovered. The results of simulation of the absorption chiller integration show a reduction of the specific consumption of around 10% (537 kWh/t to 478 kWh/t) and an increase of exergy efficiency of around 11.5%.

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Keywords: liquid air energy storage; small scale LAES; waste heat recovery; absorption chiller; WHR

* Corresponding author. Tel.: +390712204761
E-mail address: g.comodi@univpm.it

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1. Introduction

Energy storage has a fundamental role to overcome the problem related with the availability of the renewably energy and shaping the energy demand. A solution to store energy is represented by Liquid Air Energy Storage (LAES) whose benefits, compared to other energy storage systems, are reported by Comodi et al. (2017) and Chen et al (2009). In these system, the air is liquefied during the off-peak period by means of a cryogenic cycle and then stored in vessels. When the power is needed, the liquid air is pumped at high pressure and then expanded in a power producing device. A microgrid scale LAES plant is particularly suitable in the context of microgrid and distributed generation. When scaling down the size of the LAES, the critical point lies in the low efficiency of liquefaction cycle used to charge the system that results in a low round trip efficiency. Borri et al. (2017) conducted a preliminary study on the configuration of an air liquefaction cycle for a microgrid LAES application estimating for a Kapitza cycle with a pressurized phase separator, a specific consumption around 500kWh/t. This address the research to further improvements as the recovery of the waste heat of compression. Guizzi et al. (2015) integrates in a LAES plant a hot storage section where the heat of compression is stored and then used to reheating the air in the expansion process on the discharge side of the LAES plant increasing the work output extracted from the power producing device. In this work part of the heat of the aftercooling process in the compression phase of the liquefaction cycle is used to drive a single effect water-Lithium Bromide (LiBr) absorption chiller where the chilled water is then used directly to cool down the air at the inlet of the two main compressors below the ambient temperature thus reducing the work of compression and the specific consumption of the cycle with the improve of the exergy efficiency.

Nomenclature

Ex	exergy [kW]
ex	specific exergy [kJ/kg]
m	mass flow rate [kg/s]
P	Power [kW]
Q	Thermal Power [kW]
s'	characteristic parameter [kW °C^{-1}]
r,a,e	characteristic parameter
t	external arithmetic mean temperature [°C]
W	work [kWh]
$\Delta\Delta t'$	characteristic temperature difference [°C]

Greek

η_{ex}	exergy efficiency

Subscripts

amb	ambient
comp	compression
cond	condenser
evap	evaporator
exp	expander
gen	generator
Liq	liquid

Abbreviations

Abs	Absorption chiller
AFTC	Aftercooler
HEX	Heat exchanger for liquefaction cycle
H	Heat exchanger for WHR
J-T	Joule Thompson valve
LAES	Liquid Air Energy Storage
PS	Phase Separator
WHR	Waste Heat Recovery

2 Materials and Methods

2.1 Kapitza liquefaction cycle with pressurized phase separator

Figure 1 shows a schematic of the Kapitza cycle with pressurized phase separator. Ambient air is first pre-compressed (C-3) at the phase separator (PS) pressure and then cooled at ambient temperature before being mixed with the return air (11). The total air flow (1) is compressed by a two-stage compressor (C-1, C-2) and cooled down at almost ambient temperature before entering in the high temperature heat exchanger (HEX-1) where is cooled down and then divided in two streams (5a and 5b). The first stream passes through the low temperature heat exchanger (HEX-2) before being expanded (6a-7a) in the Joule-Thompson valve (J-T). The resulting two phase mixture is then separated in the phase separator and the liquid air (Liq) is extracted. The cold vapor is mixed with the vapor coming from the expander (6a) and used to cool down the air in the two heat exchangers (HEX-1, HEX-2). The second stream (5b) is expanded through an expander resulting in a temperature drop and a work output. The ratio between the mass flow going through the J-T valve and the total mass flow of compressed air is defined by the recirculation fraction that is determinant on the cycle performance.

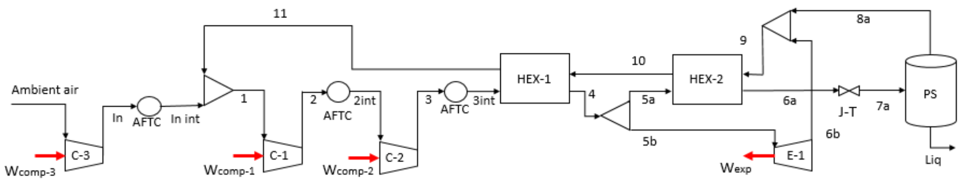
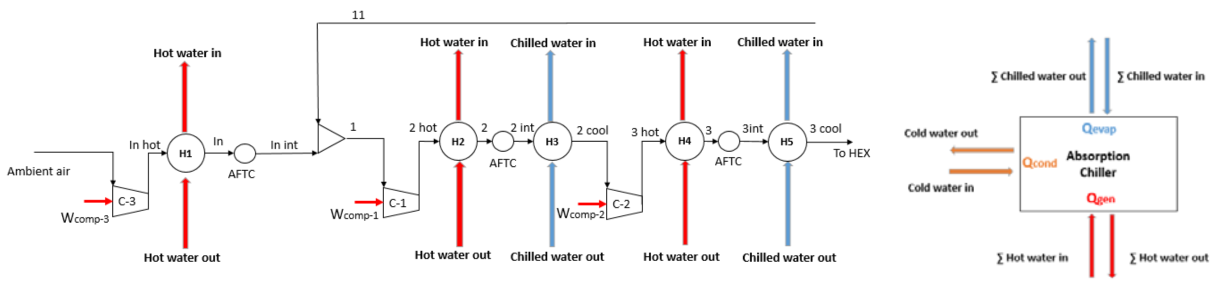


Fig.1 Schematic of the Kapitza liquefaction cycle with pressurized phase separator (PS)

2.2 Proposed solution

In the proposed solution, the waste heat of the compression is partially recovered to drive a single stage 105.5 kW water-LiBr absorption chiller. The size of the absorption chiller has been chosen based on the results presented in Borri et al. (2017) thus to maximize the heat recovery of a Kapitza cycle with 40 bar operating pressure and phase separator pressure of 6 bar. Figure 2a shows the schematic of the compressor phase of the Kapitza cycle in Figure 1, with the integration of the absorption chiller (Figure 2b).



(a) (b)

Figure 2. compression phase of the Kapitza cycle with pressurized phase separator with absorption chiller integrated (a) absorption chiller (b)

In this case, the waste heat of the compression is recovered by means of three heat exchangers (H1, H2, H4) to rise the temperature of the hot water that drives the absorption chiller. After the heat recovery, the aftercoolers (AFTC) cool down the air at nearly ambient temperature, then the chilled water coming from the absorption chiller is used to further cool down the air below the ambient temperature by means of two heat exchangers (H3 and H5). The first (H3) is used to cool down the air before entering the second compressor (C-2) thus reducing its specific work. The second heat exchanger (H5) is used to cool down the air before entering the high temperature heat exchanger (HEX-1). This results in a lower temperature of the return stream (11) that mixes with the inlet air (In int) thus reducing the specific work of the first compressor (C-1).

2.3 Absorption chiller modelling

The single stage water-LiBr absorption chiller is modelled considering the system made up of three main components as shown in Figure 2b:

- Generator (Q_{gen})
- Evaporator (Q_{evap})
- Absorber-Condenser (Q_{cond})

These components are modelled using the characteristic equation method to fit the technical data of a commercial single effect water-LiBr model with a cooling capacity of 105.5 kW. The characteristic equation method is based on the approach of Kühn and Ziegler (2005). In this method, the thermal power (Q_k) of each k-component of the absorption chiller is calculated by a linear correlation with an arbitrary characteristic temperature function defined as:

$$Q_k = s' \cdot \Delta\Delta t' + r \tag{1}$$
$$\Delta\Delta t' = t_{gen} - a \cdot t_{ac} + e \cdot t_{evap} \tag{2}$$

Where t [°C] represents the average temperature of the medium fluids of the chiller and the four parameters (*a, s', r, e*) of equation (1) and equation (2) are the constant parameters estimated by multipole regression from the technical data.

2.4 Simulation assumptions

The analysis of the integration of the absorption chiller in the Kapitza cycle with pressurized phase separator has been made with the following assumptions:

- Cryogenic cycles are considered in steady flow conditions
- The size of the liquefaction plant is assumed to be a microgrid scale with a liquid air production rate of 0.834 t/h (i.e 10 t/day considering an operating period of 12 h)

Table 1 reports the boundary conditions for both the Kapitza cycles with pressurized phase separator with or without the absorption chiller.

Table 1. Boundary conditions for the simulation of the Kapitza cycle with pressurized phase separator (PS) with absorption chiller (Abs) and without heat recovery

	Kapitza pressurized PS	***Kapitza pressurized PS+ Abs***
AFTC outlet temperature	30 °C	-
AFTC pressure loss	0.0 bar	0.0 bar
HEX pressure loss	0.0 bar	0.0 bar
Compressor adiabatic Efficiency	85%	85%
Expander adiabatic Efficiency	70%	70%
Recirculation Fraction	0.2	0.2
Minimum pinch point temperature difference		
HEX-1	5°C ± 0.5	5°C ± 0.5
HEX-2	3°C ± 0.3	3°C ± 0.3
Absorber HEX (H1, H2, H3, H4, H5)	-	5°C ± 0.5
Absorption chiller boundary conditions	-	
Hot Water		
Mass flow rate [m^3/h]	-	26
Max allowed temperature [°C]	-	95
Chilled Water		
Mass flow rate [m^3/h]	-	16.5
Inlet temperature [°C]	-	7
Cold Water		
Mass flow rate [m^3/h]	-	55
Inlet temperature [°C]	-	31
Absorption chiller input Power [W]	-	310

In the Kapitza liquefaction cycle with pressurized phase separator, the outlet pressure of the pre-compressor (C-3) is assumed to be the same of the phase separator pressure and the outlet of the expander. The pressure ratio of the two main compressors (C-1, C-2) is then assumed to be the equal to reduce the specific consumption. In the case of the liquefaction cycle with the absorption chiller integrated, the AFTC temperature is a variable calculated during the simulation to maintain a constant value of the chiller water temperature. The mass flow rate of the hot water and the chiller water is distributed equally along the heat exchangers.

The performances of the liquefaction cycle are calculated and compared by means of the specific consumption defined as:

$$Specific\ consumption\ \left[\frac{kWh}{t}\right] = \frac{\sum W_{comp} - W_{exp} + W_{Abs}}{(hourly\ liquid\ air\ produced)} \tag{3}$$

where W_{comp} and W_{exp} are the work of the compressor and expander respectively and W_{abs} represents the work input of the absorption chiller.

2.5 Exergy Analysis

The exergy analysis has been carried out to compare the exergy efficiency η_{ex} that can be calculated for both configuration as follows:

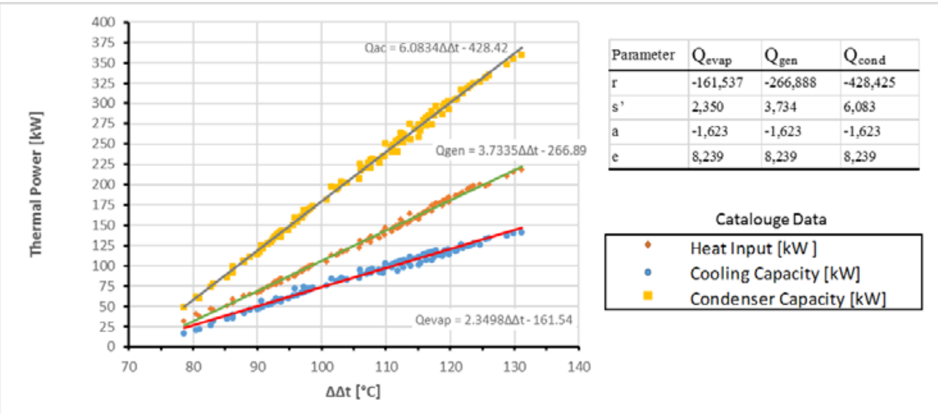
$$\eta_{ex} = \frac{m_{liq}(ex_{liq} - ex_{amb})}{P_{net}} \tag{4}$$

Where m_{liq} is the mass flow rate [kg/s] of the liquid air produced by the plant, ex_{liq} and ex_{amb} are the specific exergy [kJ/kg] of the liquid air and the ambient air respectively. P_{net} [kW] represents the net power electrical or mechanical supplied to the system.

3 Results

3.1 Absorption chiller model

Figure 3 reports the results of the cooling capacity, the heat input and the condenser capacity related with the characteristic temperature difference for a single stage 105.5 kW water-LiBr absorption chiller modelled with the method proposed by Kühn and Ziegler (2005). The results show a good agreement between the technical data and the relation proposed can be considered a valid solution for the absorption chiller model.



Parameter	Q_{evap}	Q_{gen}	Q_{cond}
r	-161,537	-266,888	-428,425
s'	2,350	3,734	6,083
a	-1,623	-1,623	-1,623
e	8,239	8,239	8,239

Figure 3. Results of the Kühn and Ziegler (2005) characteristic equation method and the parameters used for equation (1) and (2) applied for a 105.5 kW single stage water-Li-Br absorption chiller

3.2 Kapitza cycle with pressurized phase separator + Absorption chiller

Table 2 shows the results of the specific consumption of the Kapitza cycle with pressurized phase separator (PS) with the integration of a 105.5 kW single stage water-LiBr absorption chiller compared to the case without heat recovery.

Table 2. Results of the simulations for Kapitza cycle with pressurized phase separator (PS) with absorption chiller (Abs) and without heat recovery.

		Specifc Consumption [kWh/t]			***Exergy Efficiency [%]***		
Pressure	**Pressure PS**	**Kapitza**	**Kapitza+ Abs**	**%**	**Kapitza**	**Kapitza + Abs**	**%**
40	6	537.03	477.80	11.02	14,91	16.63	11.52
	8	520.53	463.91	10.87	14.94	16.78	12.36
	10	514.89	-	-	14.82	-	-
50	6	508.51	-	-	15.68	-	-
	8	490.72	439.68	10.41	15.85	17.68	11.58
	10	482.20	432.16	10.41	15.83	17.69	11.73
60	6	513.74	-	-	15.52	-	-
	8	487.41	440.32	9.66	16.01	17.68	10.46
	10	471.02	425.52	9.66	16.18	17.95	10.92

The results show that for all the operating conditions considered is not possible to integrate the absorption chiller proposed (40-10 bar, 50-6 bar and 60-6 bar)). Therefore, the size of the absorption chiller has to be optimized according to the operating conditions of the liquefaction cycle. However, this temperature can be reduced increasing the mass flow ratio of the hot water but this is limited with the size of the absorption chiller. The integration of a single stage 105.5 kW water-LiBr absorption chiller can reduce of 11% in the case of operating pressure 40 bar and a phase separator pressure of 6 bar (from 537 kWh/t to 478 kWh/t). Indeed, this corresponds to the size for which the absorption chiller has been selected to maximize the heat recovery. The exergy analysis shows that the value of exergy efficiency slightly improves (11.5% in the case of 40 bar and 6 bar of phase separator pressure) but still results in a low value. Indeed, although most of the waste heat of compression is recovered, the absorption chiller introduces a further exergy loss mainly due to the heat rejected through the condenser. However, this can be considered an interesting solution where the heat is recovered and the specific consumption is reduced in the same working period without the use of further energy storage.

5 Conclusions

In this work a 105.5 kW cooling capacity single-effect absorption chiller using a water-Lithium Bromide solution is integrated with a microgrid scale liquefier based on a Kapitza cycle with pressurized phase separator with a liquid air production capacity of 0.834 t/h. The absorber has been modelled with the characteristic equation method considering the specification of the most common commercial models available in the market resulting in a good match between the technical data and the numerical model. The results of simulation of the absorption chiller integrated with the liquefaction cycle gives a reduction of the specific consumption of around 10% (537 kWh/t to 478 kWh/t) compared with the solution proposed by Borri et al. (2017) and an increase of exergy efficiency of around 11.5%.

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