Third International Conference on Energy, Materials, Applied Energetics and Pollution.
ICEMAEP2016, October 30-31, 2016, Constantine,Algeria.
M.KADJA, A.ZAATRI, Z.NEMOUCHI, R.BESSAIH, S.BENISSAAD and K. TALBI (Eds.).

USE OF THERMAL ENERGY SOURCES FOR COMBINED POWER AND COOLING PRODUCTION SYSTEMS

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ABSTRACT

Air-conditioning, refrigeration and electricity are useful forms of energy products, usually produced using separate energy conversion technologies. Further, most end-users need at least dual energy products: typical example could be building's applications where space air-conditioning and electricity for various purposes are in need. Therefore the combined production of power and cooling using efficient thermally-driven systems is one of the suitable technological solutions. This study presents a brief review of some combined absorption power and cooling cycles and expander technology. The performance indicators used to evaluate combined power and cooling cycles have also been discused.

Key Words: *Absorption Power Cycle, Expander, Absorption Refrigeration, Thermal Energy*.

NOMENCLATURE

Symbols :		**Subscripts :**			
$\dot{Ex}$	exergy rate, kW	chill	chiller	I / II	first / second law
W	power, kW	des	desorber	net	net
$\dot{Q}$	heat rate, kW	eff	efficiency	rfg	refrigerator
Greek Letters:		ex	exergetic	sh	super-heater
η	efficiency, [-]	exp	expander	sp	solution pump

1. INTRODUCTION

The combined production of power and cooling using efficient thermally-driven systems is one of the suitable technological solutions to address the current global energy-related challenges. These challenges include energy supply uncertainty, rising price of fuels and adverse environmental impact. Air-conditioning, refrigeration and electricity are useful forms of energy products, usually produced using separate energy conversion technologies. Further, most end-users need at least dual energy products: typical example could be building's applications where space air-conditioning and electricity for various purposes are in need. In such a case the life cycle cost of the combined system is enhanced because there is an increase in the number of running hours for periods in which there is no cooling demand for but a power demand is still essential.

The objectives of this research work is to present a new class of absorption systems, capable of producing mechanical power and cooling simultaneously and/or alternatively by using a single thermal energy source available at low temperatures (below 200°C). Typical thermal energy sources available in this range include solar, geothermal and industrial waste heat. The dual-output nature of such kind of systems makes it difficult to evaluate their energetic and exergetic performances therefore various performance indicators used to evaluate the performance of such cycles will be presented.

2. COMBINED POWER AND COOLING CYCLES

2.1. Performance indicators

In order to explain and compare the behaviour of the cycle, the following performance indicators have been chosen: net mechanical power, cooling capacity and effective first law and exergetic efficiencies

The net mechanical power of the cycle ($\dot{W}_{\mathrm{net}}$) is the result of subtracting the mechanical power provided to the solution pump ($\dot{W}_{\mathrm{sp}}$) from the mechanical power produced by the scroll expander ($\dot{W}_{\mathrm{exp}}$).

According to Vijayaraghavan and Goswami [1], an accurate definition of the first law efficiency for a combined power and cooling cycle must account for the quality of the cooling output. Therefore the first law effective efficiency ($\eta_{\mathrm{I,eff}}$) is represented as:

$$\eta_{\mathrm{I,eff}} = \frac{\dot{W}_{\mathrm{net}} + \left(\dot{E}x_{\mathrm{chill}} \big/ \eta_{\mathrm{II,rfg}} \right)}{\dot{Q}_{\mathrm{des}} + \dot{Q}_{\mathrm{sh}}} \tag{1}$$

The effective exergetic efficiency ($\eta_{\mathrm{ex,eff}}$) is defined as the exergy output of the combined system divided by the exergy change in the heat source as shown:

$$\eta_{\mathrm{ex,eff}} = \frac{\dot{W}_{\mathrm{net}} + \left(\dot{E}x_{\mathrm{chill}} \big/ \eta_{\mathrm{II,rfg}} \right)}{\dot{E}x_{\mathrm{hs,in}} - \dot{E}x_{\mathrm{hs,out}}} \tag{2}$$

The term $\dot{E}x_{\mathrm{chill}}$ represents the exergy flow associated with the cooling output while $\eta_{\mathrm{II,rfg}}$ is the second law efficiency of a vapor compression refrigeration system.

2.2. Combined absorption Cycles

One of the suggestions for a combined absorption power and refrigeration design is accredited to Goswami [2]. To generate both shaft power and refrigeration, the coupling of an absorption refrigeration cycle and a traditional Rankine cycle was suggested as shown in Figure 1. Initial studies on the Goswami cycle were performed with an ammonia-water mixture as the working fluid however the research was extended to study the application working fluids consisting of organic fluid mixtures. The ammonia-water mixtures produced a better performance as compared to binary mixtures of organic working fluids. Mendoza et al. [3] highlight that ammonia-water absorption cooling cycles require a costly rectification process. This disadvantage also exists in the combined absorption cycles since the combined absorption cycles with ammonia-water working fluid also require rectification process for their cold production. Therefore, low or non-volatility of the absorbent is of great importance in order to reduce or eliminate rectification. Consequently, when absorbents which are soluble solid (non-volatile), as lithium nitrate (LiNO3) and sodium thiocyanate (NaSCN) or liquids which have very low (negligible) vapor pressure like Ionic Liquids are utilized then the need for a rectifier (REC) is completely eliminated.

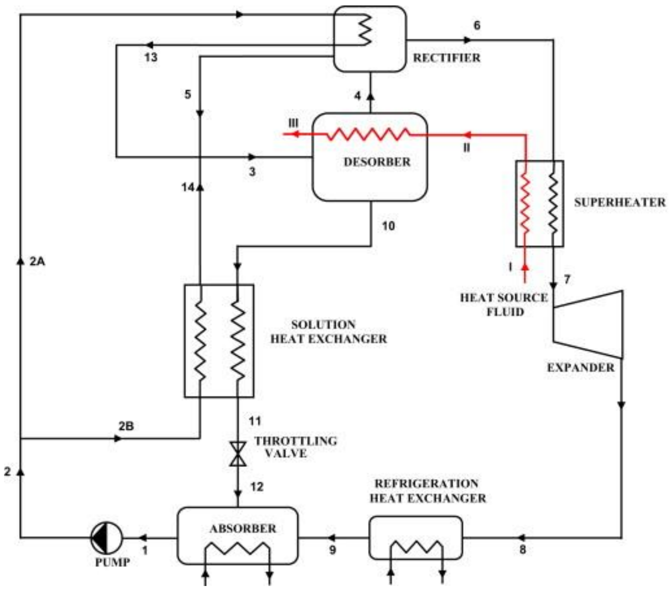
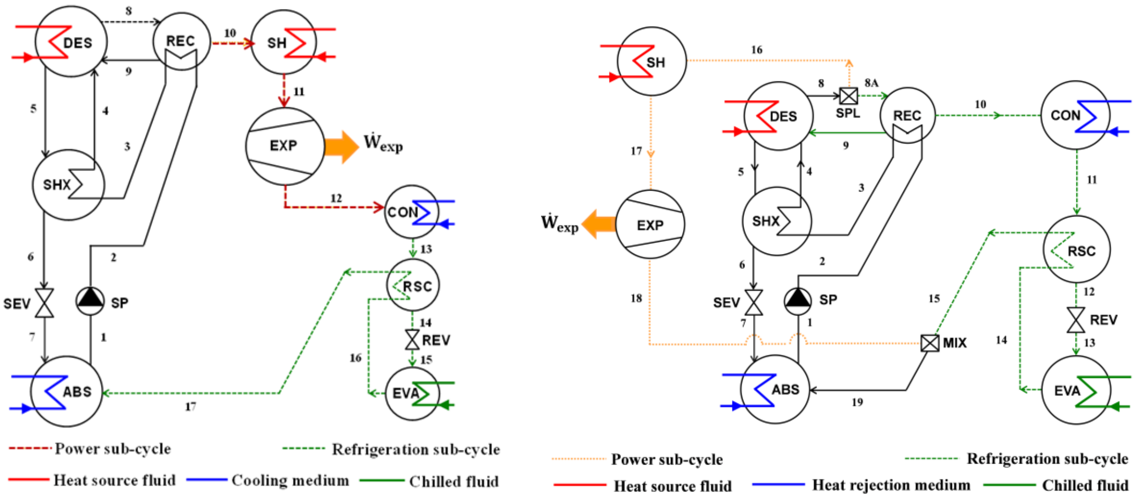


FIGURE 1. Schematic diagram of the Goswami cycle [1]

Generally, the combined absorption cycles presented in literature can be divided into two groups: those producing cooling using sensible heat (Goswami cycle) and those based on latent heat. The single-stage combined absorption cycle with series flow arrangement (SSAPRC-S) shown in Figure 2a can be viewed as the Goswami cycle except the sensible refrigerant heat exchanger (Cooler) is replaced by a refrigeration sub-cycle, comprising of several components, with a capability of producing latent cooling output. The single-stage combined absorption cycle with parallel flow arrangement (SSAPRC-P) shown in Figure 2b incorporates a splitter which facilitates the ability to cover varying demand profiles from only cooling to only power and intermediate dual outputs with various power/cooling ratios. A comparison of the performance of the three configurations (Goswami, SSAPRC-C and SSAPRC-P) revealed that the SSAPRC-S configuration offered the best performance. Application of low heat-source temperatures below 200°C is one of the characteristics of the Goswami cycle. For a heat source temperature of 87°C and optimal conditions, both power and refrigeration outputs were achieved. However at a source temperature of 167°C, optimum conditions do not provide any refrigeration output. The cooling output of the Goswami cycle is very low compared with the other proposed cycle configurations (SSAPRC-P and SSAPRC-S) however its power output is superior than the SSAPRC-S but not the SSAPRC-P cycle configuration with high split ratios [4-5].

A particular feature of the SSAPRC-P cycle configuration is its capability of producing a whole range of power and cooling. This combined power and cooling cycle configuration can produce 18 kW of mechanical power and 150 kW of cold with effective first-law and exergy efficiencies of 10% and 47% respectively, when the heat source, heat sink and, chilled fluid inlet/outlet temperatures are 120°C, 32/37°C and 12/7°C respectively with vapour split ratio of 0.5. For the same thermal boundary conditions the cycle produces 32 kW of mechanical power with thermal and exergy efficiency of 9.0% and 42.0% when it operates in only power-mode. For only cooling-mode of operation it produces 293 kW of cooling effect at a COP of 0.626. A unique feature of the SSAPRC-S configuration is it can produce more power and cold by using heat sources at relatively higher temperature (150 to 200°C). This combined cycle configuration can produce 32 kW of mechanical power and 320 kW of cold with effective first-law and exergy efficiencies of 17% and 66% respectively, when the heat source, heat sink and, chilled fluid inlet/outlet temperatures are 150°C, 32/37°C and 12/7°C respectively [5].



(a) (b)

FIGURE 2. Schematic diagram of single-stage combined absorption cycle with: (a) series flow arrangement (SSAPRC-S) and (b) Parallel flow arrangement (SSAPRC-P) [5]

The single-stage combined absorption cycles presented here tend to exhibit a poor performance at heat source temperatures above 200°C. Therefore to achieve an improved performance at these relatively high heat source temperatures, the adoption of multi-stage multi-effect combined absorption cycle configurations is suggested.

3. EXPANDERS

The expander plays an integral role in the performance of the whole system. Two types of expanders could be used in these kind of cycles: dynamic and volumetric machines. The first ones (such as axial turbines and radial flow turbines) have been successfully used for large capacity, however for small capacity (below 50 kW) their application is still a challenge since ammonia has a low molecular weight and high sound speed which considerably increases the machine rotor speed and the internal leakages thereby reducing the effective operating pressure ratio. Volumetric devices include: scroll expanders, screw expanders, piston expanders and rotary vane expanders. Volumetric technology, specifically scroll machines, has proven to have a promising future for small capacity absorption systems for cooling and power applications. Scroll compressors are simple in design, reliable, possess a compact structure, have fewer moving parts, lower level of noise and vibration. They are also easy to access because they are widely applied in the HVAC industry. Consequently, researchers have been experimenting on scroll expanders modified from scroll compressors and reporting satisfactory results [6-7].

In scroll units, lubrication is employed to reduce friction and wear between mobile parts and surfaces in contact. An additional feature of the lubrication is also the reduction of the internal leakages; however the use of a mixture of ammonia-water provides a new challenge: water contained in ammonia will be mixed with the lubricant creating water-oil emulsions which in turn reduces the capacity of lubrication damaging the machine. Furthermore any amount of lubricant returning to the absorption sub-cycle will reduce the global performance of the system since it reduces the heat transfer coefficients of the heat exchangers [8].

4. INTERGRATION OF SCROLL EXPANDERS IN COMBINED CYCLES

Demirkaya [8] performed an experimental analysis of an ammonia-water Goswami cycle utilizing an off-the-shelf open drive scroll compressor modified to operate as an expander. Expander performances of between 30-50% were recorded. Following a similar procedure, Mendoza et al. [9] experimentally characterized and modeled a scroll expander (modified from an open drive scroll compressor) with air and ammonia as working fluid. They studied how the main operating variables (supply pressure and temperature, pressure ratio, rotational speed and lubrication) influence the performance of the scroll expander and used a semi-empirical model to determine the scroll expander performance. The results obtained further confirmed that the modified scroll device can be used in absorption power cycles. The maximum overall isentropic efficiency and net mechanical power achieved in the tests with ammonia were 61% and 958 W, at a supply pressure of 1400 kPa, a supply temperature of 335 K, a rotational speed of 50 Hz, a pressure ratio of 1.95 and a lubrication mass percentage of 2%.

Iglesias and Favrat [10] developed an oil-free co-rotating scroll compressor–expander for small-scale compressed air energy storage applications. The same scroll device was studied by Mendoza and Schiffmann [11] to determine its technical feasibility in a power cycle. They reported that an overall isentropic efficiency between 54.7% and 60.5% could be achieved through the integration of the co-rotating scroll prototype into a Kalina cycle. Therefore they deduced that the implementation of co-rotating scroll expander is technically feasible and most importantly, adopting this scroll device eliminates the inherent complications of lubricated scroll expanders.

Next, Muye et al. [12] performed a theoretical study of a combined absorption cycle for power and cooling production (SSAPRC-S) using the novel oil-free co-rotating scroll expander. Figure 3 shows the working principle of the co-rotating scroll prototype. The SSAPRC-S cycle configuration utilizing an oil-free co-rotating scroll expander produced 87 kW of mechanical power and 162 kW of cold with effective first-law and exergy efficiencies of 19% and 59% respectively, when the heat source, heat sink and, chilled fluid inlet/outlet temperatures are 180°C, 32/37°C and 12/7°C respectively.

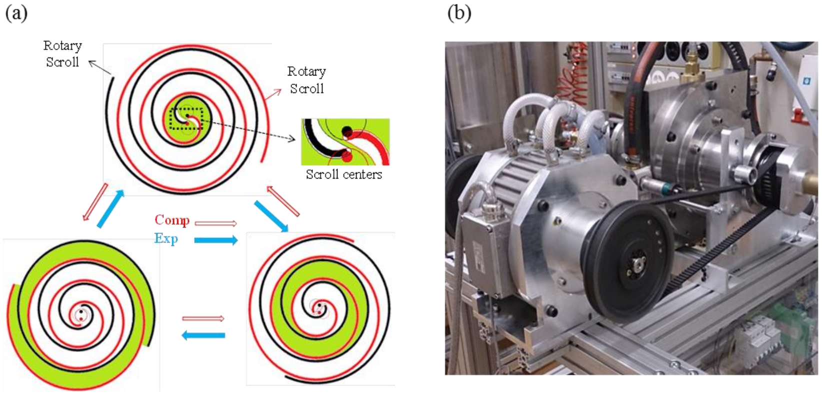


FIGURE 3. Working principle of the co-rotating scroll prototype and (b) mechanical transmission of one of the two scrolls [12]

Recently, the first results of the experimental performance of a combined power and cooling production system designed for a cooling capacity of 35 kW when operated under refrigeration mode and power generation of 3.5 kW when operated during power generation mode have been presented [13]. The set-up incorporates an oil-less scroll expander derived from an Anest Iwata air compressor. In the combined cooling and power generation mode, the system is capable of producing a cooling capacity of 11 kW and net power output of 2 kW at a sink temperature of 32°C and generator temperature of 140°C.

3. CONCLUSIONS

A brief review of some combined absorption power and cooling cycles and expander technology has been performed. The low cooling output of the Goswami cycle could be improved by introducing latent cooling as adopted by the SSAPRC-S configuration. To address the lack of flexibility inherent in serial designs (Goswami and SSAPRC-S), the parallel configuration (SSAPRC-P) is suggested. A drawback of the parallel configuration is the low cycle performance; for the serial designs it is the low cooling output at high heat source temperatures. Converting lubricated open drive scroll compressors into expanders is a technically and economically viable option for power generation. However in absorption systems using ammonia-water working fluid provides a new challenge: water contained in ammonia will be mixed with the lubricant creating water-oil emulsions which in turn reduces the capacity of lubrication damaging the machine. Furthermore any amount of lubricant returning to the absorption sub-cycle will reduce the global performance of the system since it reduces the heat transfer coefficients of the heat exchangers. Therefore the use of effective oil separation procedures is advised if a lubricated scroll device is to be used in an ammonia-water absorption systems. Experimental and theoretical studies prove that the novel oil-free co-rotating scroll expander prototype and adopting oil-less scroll compressors are feasible options for use in combined power and cooling cycles.

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