Evaluation of the Energy efficiency of new cogeneration systems based on Kalina and ORC cycles

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***Abstract*— Innovative thermodynamic cycles are critical for maximizing the efficiency of low-temperature heat sources such as solar, geothermal, and waste heat. A mixed working fluid composition optimization model for ORCs (Organic Rankine cycles) and Kalina cycles was developed in this study. This work presents a comparative study between two cogeneration systems, the first based on a modified Kalina cycle to ensure the production of electricity and refrigeration simultaneously by adding an evaporator in the configuration. The second system, which is based on an Organic Rankine Cycle, is set up for a low-energy heat source cogeneration installation that uses an ejector and an internal heat exchanger as an energy recuperator. New thermodynamic parameters arose as a result of these two configurations, allowing the system's performance to be improved. For Organic Rankine Cycles, various refrigerants such as R124, R236fa, R1234yf, and R1234ze have been tested. The results revealed that R1234yf has the maximum system efficiency of 55% and the highest ORC cycle efficiency of 26%. Moreover, For Kalina cycle system the use of a binary mixture as a work fluid exhibit different boiling temperature, resulting in a good thermal match between the heating fluid and the working fluid for efficient heat source use. Results have shown that with a steam generator temperature of 145°C and a mass fraction of ammonia of 0, 8, the thermal efficiency of power production for the Kalina cycle reaches roughly 21%, which is regarded a more economical benefit.**

Keywords*— *Cogeneration System, Thermal efficiency, Kalina cycle, ORC, Refrigeration, Solar energy

I. INTRODUCTION

The enormous consumption of energy and the emission of greenhouse gases have encouraged researchers to exploit and further enhance renewable energy sources for the development of a sustainable society. The participation of renewable energies in electricity generation is also increasing because of increased awareness of global warming and therefore it is essential to abandon the use of fuels in the energy field. The alternative is the recovery of waste heat and the development of renewable energy. One of the major challenges facing scientists today is to focus on the development of efficient and economical power plants using renewable energy sources and environmentally friendly working fluids.

ORC technology, which uses thermal energy to generate electricity, is attracting a lot of attention. Even with low-temperature heat sources, the ORC system is regarded a good energy converter. When compared to other dynamic energy conversion systems, the Rankine cycle was initially determined as having the highest efficiency system [1]. Steam, the traditional Rankine cycle's working fluid, had several advantages, including low cost, nonflammability, and nontoxicity [2]. However, when it comes to low-temperature heat sources, steam as a working fluid has a low efficiency. The (Organic Rankine Cycle) ORC and the Kalina cycle are two alternatives to the Rankine cycle for increasing efficiency in low-temperature applications. The selection of proper working fluids is the ORC's main challenge. Aside from the working fluid, the device used to expand the fluid to generate power is a key distinction between the traditional Rankine cycle and the ORC.

This technology has also been used in a variety of applications, including solar energy [3, 4], low-quality waste heat [5], and biomass [6]. Solar energy, in particular, is recognized as an environmentally friendly energy source [7].

Kalina cycle technology was introduced in 1983 as an alternative to the Rankine cycle, especially for low-quality heat sources such as solar resources and industrial waste heat. This new cycle has challenged conventional power generation technology through improved performance and environmentally friendly use. The binary properties of the mixture produce non-isothermal evaporation and condensation in the cycle, which contributes to higher efficiency compared to pure working fluids [8].

Therefore, the main difference between the Kalina cycle system and the Rankine cycle is that the KCS condensation process is completed by the absorption (absorber) and distillation (separator) process. In the ORC and Rankine steam cycle, there is no separator. In addition, high-concentration turbine expansion requires a very low condensation temperature. Under these conditions, the condenser needs a very low cooling water temperature [9].

The objective of this paper is to study the performance of working fluids for the ORC cycle and Kalina for low temperature applications.

II. FLUID SELECTION

The fluid of choice is mostly determined by the temperature delivered by the heat source [10, 11]. The ORC system proposed in this study operates at a low temperature. Because refrigerants are considered dry fluids, they are highly recommended [12]. The working fluids in this study are R124, R236fa, R1234yf, and R1234ze. Because of their low ODP and GWP, they are less damaging to the environment and help to protect our ecosystem [13, 14].

TABLE I. CHARACTERISTICS OF CHOSEN FLUIDS

	T_c (°C)	P_c (bar)	Safety Group	GWP	ODP
R124	122.5	36.6	Al	609	0
R236fa	124.92	32.192	Al	9810	0
R1234yf	94.7	33.82	A2L	4	0
R1234ze	109.36	36.62	A2L	6	0

The water-ammonia mixture is the basic working fluid for the Kalina cycle, it has the vital blood of this cycle. This mixture has considerable characteristics compared to pure water and also pure ammonia [15].

The water-ammonia mixture is characterized by a variable boiling and condensation temperature. The thermophysical properties of a water-ammonia mixture can be changed by changing the concentration of ammonia. Because of these physical thermal properties, the water-ammonia mixture had the power to modify the temperature of the mixed fluid without a change in the heat content. Table II shows the melting point and boiling point of the two pure substances forming the binary mixture as well as the temperature and the critical pressure.

TABLE II. THERMODYNAMIC PARAMETERS OF THE PURE WORKING FLUIDS CONSIDERED

	Melting Point (°C)	Boiling point (°C)	Critical temperature (°C)	Critical pressure (bar)
Water	0	100	373.946	220.64
Ammonia	-77.7	-33.4	132.500	112.8

III. PRPPOSTION OF THE CONFIGURATIONS

In the context of this work two configurations are proposed, the fig. 1 presents a cogeneration system based on Kalina cycle. For a system that uses pure ammonia as a working fluid, the process of condensing ammonia vapor at the turbine outlet is difficult because of its higher concentration, which requires a very low condensation temperature. The difficulty of condensation is overcome, in the KCS, by the dilution of the steam released at the outlet of the turbine. Consequently, the concentration of the fluid is reduced by mixing the weak solution with turbine steam. Hence the fluid produced is known as a strong solution. The absorption process continues by discharging heat into the absorber. The role of the absorber is the same as that of the condenser.

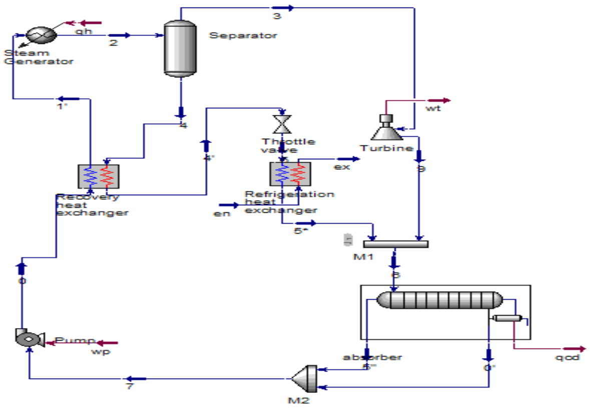

Fig. 1. Schematic of the Kalina Cycle

An ORC system with an internal heat exchanger and a refrigeration cycle is the second option as presented in Fig.2. The ejector, a very important organ, is responsible for this connection. This configuration is seen in subcritical and transcritical regimes, and it is designed to create both power and cold. The ejector connects the two cycles and serves a critical function in improving system performance. It compresses the gas released by the turbine, preheating the fluid entering the steam generator via the internal heat exchanger. The ejector activates thermal compression of the gas. It's termed a thermo-compressor for this reason.

These are cogeneration systems using heat as a source of energy from concentrated solar collectors operating at a temperature in the region of 120°C.

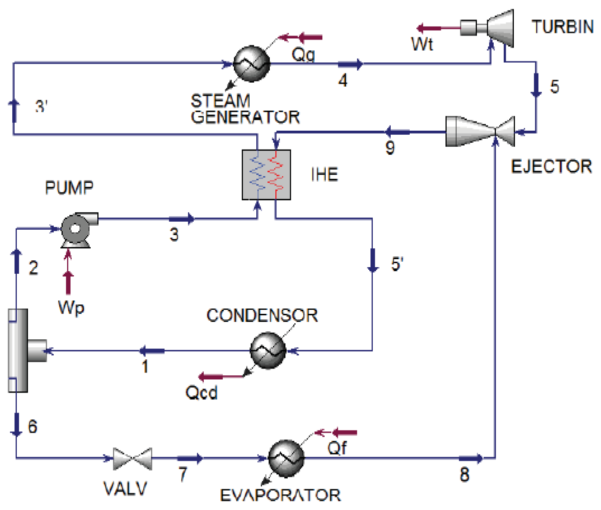

Fig. 2. Schematic of the ORC Cycle

IV. THERMODYNAMIC MODELING

Energy evaluations for cogeneration plants were simulated using Aspen Hysys software. Peng-Robinson equation is an excellent thermodynamic model for calculating liquid-vapor equilibrium.

$$P = \frac{RT}{v-b} - \frac{a(T)}{(v^2+2bv-b^2)}$$

This section of this study focuses on the system's energy efficiency as a function of several parameters. we presented a thermodynamic analysis based on the thermal efficiency of the cycles, the cold coefficient performance of the refrigeration cycle and the thermal efficiency of the cogeneration [16]. The energy equations for all of the components used in the Kalina and ORC cycles are listed in table III and table IV.

TABLE III. KALINA CYCLE ENERGY EQUATIONS

Component\Efficiency	Equation
HRVG	$\dot{Q} = \dot{m}_1(h_2 - h_1)$
Separator	$\dot{m}_1 h_2 = \dot{m}_3 h_3 + \dot{m}_4 h_4$
Turbine	$W_t = \dot{m}_3(h_3 - h_6)$
Regenerator	$\dot{m}_1(h_1 - h_{10}) = \dot{m}_4(h_4 - h_{4\prime})$
Throttle valve	$\dot{m}_{4\prime} h_{4\prime} = \dot{m}_0 h_0$
Pump	$W_P = \upsilon_{10}(P_{10} - P_7)$
Absorber	$\dot{Q}_A = \dot{m}_7 h_7 + \dot{m}_5 h_5 - \dot{m}_{10} h_{10}$
Thermal Efficiency	$\eta = \frac{W_t - W_p}{\dot{Q}} = \frac{W_{net}}{\dot{Q}}$
COP of the refrigeration Cycle	$COP = \frac{Q_f}{Q_g}$

TABLE IV. ORC CYCLE ENERGY EQUATIONS

Component\Efficiency	Equation
Vapor Generator	$Q_g = m_1(h_4 - h_3)$
Evaporator	$Q_E = m_2(h_8 - h_7)$
Condenser	$Q_{CD} = m(h_1 - h_9)$
Turbine	$W_T = m_1(h_5 - h_4)$
Pump	$W_P = m_1(h_3 - h_2)$
Ejector	$m \cdot h_9 = m_1 \cdot h_5 + m_2 \cdot h_8$
Valve	$h_7 = h_6$
Thermal efficiency of the ORC cycle	$\eta_{ORC} = \dfrac{W_T - W_P}{Q_G}$
Refrigeration Coefficient of performance	$COP_R = \dfrac{Q_E}{Q_G}$
Thermal efficiency of the cogeneration system	$\eta_{CG} = \dfrac{W_T - W_P + Q_E}{Q_G}$

V. RESULTS AND DISCUSSIONS

A. *Performance Study of the Kalina Cycle*

The analysis of the performance of configuration A under different concentration conditions shows the evolution of the thermal efficiency, for a heat source temperature between 50°C and 170°C.

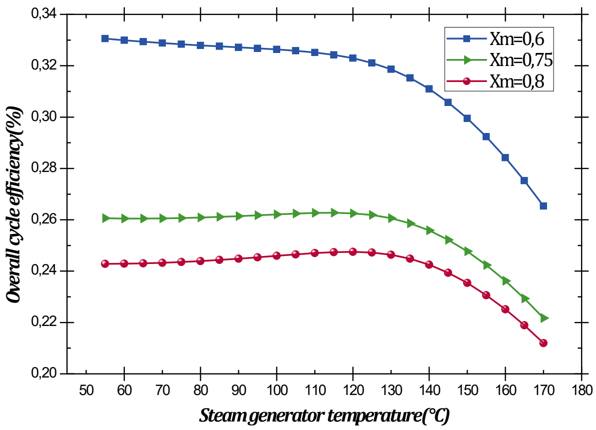

Fig. 3. The variation of the overall cycle efficiency as a function of the steam generator temperature for different mass fractions

The Fig. 3 demonstrates that all of the overall cycle efficiency improvements are made at temperatures below 120°C, and that the lower the ammonia concentration, the higher the overall efficiency. Indeed, the increase in the vapor fraction is responsible for the decrease in efficiency at the system level. And this is because of the amount of heat required for cooling that decreases because of the decrease in the liquid fraction.

The next figure shows the COP coefficient of performance variation as a function of the temperature at the outlet of the evaporator operating with different ammonia concentrations.

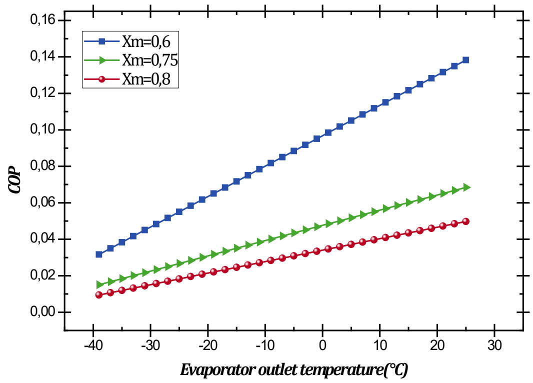

Fig. 4. Evolution of the coefficient of performance as a function of the evaporator temperature

It should be remembered that the evaporator outlet temperature T increases linearly with the coefficient of performance COP. The COP values for each curve grow as the evaporator outlet temperature rises. The cycle running with mass fraction equal to 0.6 provides the best performance for evaporator temperatures between -40°C and 25°C.

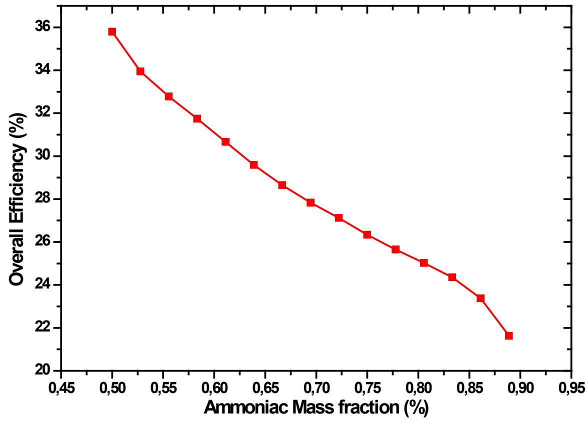

Fig. 5. Evolution of the Overall efficiency with ammonia concentration

It can be seen in Fig. 5 that as the ammonia concentration increases, the overall efficiency begins to increase and reaches a maximum value at a concentration of about 83%. This analysis provided an understanding of the effect of the concentration of mixed ammonia on the performance of the Kalina cycles. It's worth noting that, because the stability of the water-ammonia mixture at high temperatures and pressures is unknown, a high concentration of ammonia-water mixture could induce system instability, which explains this decrease.

B. *Performance Study of the ORC Cycle*

This part of work concerns the variation of the energy efficiency of the ORC system as a function of several parameters. the steam generator temperature characterizes the heat consumed by the system and it is considered as the most important factor in the optimization of the system performance. Fig. 6 displays the variation of the thermal efficiency of the cogeneration system as a function of the steam generator temperature.

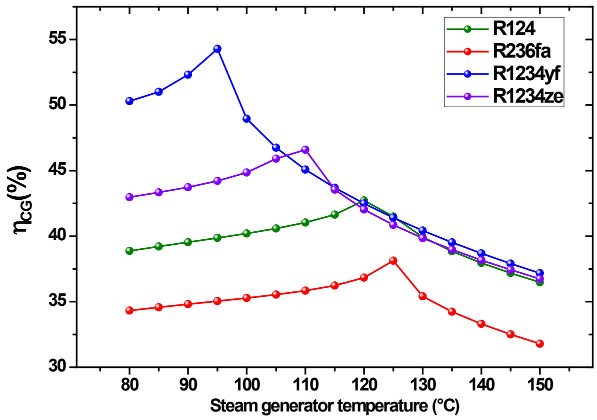

Fig. 6. Variation of the Overall efficency of the ORC cycle as a function of the steam generator temperature

Each of the curves presented by Fig. 6 shows an interesting peak where the system performance is optimal at this particular point. This temperature represents the critical temperature TC of the working fluid, which explains the increase and decrease of the global performance of the system around this point. In fact, the cycle makes a transition from subcritical to transcritical regime. In this transition, the heat consumption for each refrigerant is minimal. That is why the system performance is optimal.

Beyond the critical temperature, results showed that the thermal efficiency of the cogeneration system decreases despite the increase in the efficiency of the ORC cycle.

This is explained by the increase of the heat consumed and consequently the refrigeration performance is reduced.

On the other hand, the evaporator temperature affects directly the pressure ratio of the ejector. Fig. 7 displays the variation of the refrigeration performance as a function of the evaporator temperature for each working fluid.

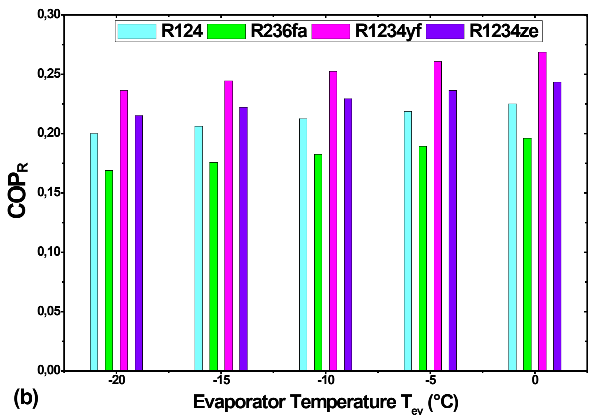

Fig. 7. Influence of the evaporator temperature on the refrigeration coefficient of performance of the ORC cycle

As observed in fig. 7, the refrigeration performance is increasing as the evaporator temperature increases. In fact, the thermal power consumed by the vapor generator is stable while the refrigeration power is increasing to reach its maximum at a temperature equal to 0°C.

Besides these temperatures, the parameters of the gas ejector can be used to optimize the system performance. The influence of motive ratio and the entrainment ratio on the system energy efficiency is plotted in fig. 8.

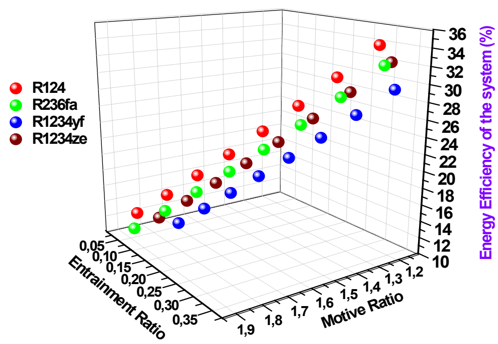

Fig. 8. Overall efficiency of the system as a function of the Entrainment ratio and the Motive ratio of the ORC Cycle

According to fig. 8, the energy efficiency of the system is optimized by increasing the entrainment ratio and decreasing the motive ratio. In fact, results showed that entrainment ratio is affecting only the refrigeration coefficient of performance which is related by the primary and secondary flows. However, by decreasing the motive ratio, the outlet gas pressure of the turbine is decreasing. Therefore, the mechanical power produced by the turbine is enhanced.

Consequently, the motive ratio has influence only on the ORC cycle efficiency. Furthermore, results showed that R124 presents the highest efficiency compared to the chosen fluids and its efficiency reaches about 35%.

VI. CONCLUCIONS

The thermal efficiency of the Kalina and ORC cycles were investigated using the results of the numerical simulation of the proposed configurations according to the varied operating parameters of the systems, which is the focus of this study. The results of the impact of the different parameters which significantly affects the thermodynamic performance of the two systems made it possible to conduct a comparative study. The best performance of the Kalina cycle was around 21% as thermal efficiency and 0.14 as COP. However, the thermal efficiency of the ORC cycle has reached around 26% and the COP was around 0.26 with the refrigerant R123yf. Moreover, by using the gas ejector, new thermodynamic parameters allowed optimizing more the cycle performance.

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