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# Thermodynamic analysis and optimization of a novel dual-evaporator system powered by electrical and solar energy sources

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ABSTRACT

A novel dual-evaporator system with dual-source (renewable and electrical energies) is proposed to provide negative and positive evaporator temperatures. The system is a combination of the generator–absorber heat exchange (GAX), ejector-expansion transcritical $CO_2$ refrigeration (EETC), Organic Rankin Cycle (ORC) and supercritical $CO_2$ power cycles. The system is analyzed and optimized thermodynamically in detail. It is found that allocating the lower temperatures (−25 to −45 °C) for EETC evaporator and higher temperatures (5–10 °C) for GAX evaporator is more suitable. Detailed exergy analyses reveal that 19.89% and 5.92% of total input exergy, are useful in EETC evaporator and GAX evaporator, respectively. The ejector is found to be the highest source of irreversibility in the system. Moreover, the system performs better than dual-evaporator systems recently reported in literature.



## 1. Introduction

Nowadays, carbon dioxide, as a natural refrigerant, has been paid more attentions in account of its spectacular thermal characteristics, such as low viscosity, high heat transfer coefficient, no toxicity, and no inflammability. This refrigerant has also some other advantages such as having a zero ODP (Ozone depletion potential) and negligible GWP (Global warming potential), being inexpensive and widely available [1,2]. Practical applications involving its use in railways, automobile air conditioning and in supermarket refrigeration have already been reported in the literature [3–5].

An interesting point about this refrigerant is having a low value of critical temperature which is 30.85 °C. Therefore, using $CO_2$ as a refrigerant necessitates a transcritical process in the condenser (gas cooler) of the refrigeration cycle [6,7]. In spite of all the above-mentioned advantages, the higher expansion loss of $CO_2$ can be accounted as a disadvantage for the transcritical $CO_2$ cycles. In this respect, a lot of effort has been made by researchers such as employing two stages compression [8,9], employing a vortex tube [10] or an expander instead of expansion valve [11] and making use of an ejector [12–17]. Among these modifications using the ejector seems to be more appropriate as this component has low cost and no moving parts. In the transcritical $CO_2$ refrigeration cycle (TRCC), a considerable amount of comparatively high-grade heat is dissipated and therefore, there is a potential to drive some bottom cycles to produce a useful form of energy. Some research works have been published in the literature attempting to capture this energy for heating purposes [18,19] and power production [17]. Nevertheless, published work on the utilization of this waste heat to drive a refrigeration system is sparse. Arora et al. [20] proposed a combined cycle to use a single effect LiBr/water absorption refrigeration system to recover some part of the rejected heat in the gas cooler of the transcritical $CO_2$ compression refrigeration cycle to produce cooling. They reported enhancements of 14.2% and 3.67% in the first and second law efficiencies of the cycle compared to those in the transcritical $CO_2$ compression refrigeration system.

The generator–absorber heat exchange (GAX) cycle, in which some part of the rejected heat from absorber is utilized internally in the generator, is an interesting configuration of absorption refrigeration cycles [21]. The temperature in the GAXD (lower temperature part of the generator) of this cycle is in the range of 80–120 °C [22,23]. Therefore, there is a potential of heat utilization in GAXD. On the other hand, producing cooling at different temperatures, through introducing multi-evaporator systems, has been practiced

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**Nomenclature**

| | |
|---|---|
| $T$ | temperature [°C] |
| $P$ | pressure [bar] |
| $h$ | enthalpy [kJ kg$^{-1}$] |
| $\dot{m}$ | mass flow rate [kg s$^{-1}$] |
| $\dot{Q}$ | heat transfer rate [kW] |
| $\dot{W}$ | power [kW] |
| $\dot{E}$ | exergy rate [kW] |
| $s$ | entropy [kJ kg$^{-1}$K$^{-1}$] |
| $D_x$ | degassing range, $X_{\text{strongsolution}}-X_{\text{weaksolution}}$ |
| $A$ | area [m$^2$] |
| $\overline{T}_{\text{wf}}$ | average collector working fluid temperature [K] |
| $T_{\text{d}}$ | compressor discharge temperature [°C] |
| $r_{\text{p}}$ | compressor pressure ratio [−] |

*Abbreviations and subscripts*

| | |
|---|---|
| 0 | ambient |
| COP | coefficient of performance [−] |
| TRCC | transcritical $CO_2$ |
| EETC | ejector-expansion transcritical $CO_2$ |
| GAX | generator–absorber heat exchange |
| GAXA | GAX absorber |
| GAXD | GAX desorber |
| DEDS | dual-evaporator dual-source |
| GEN | generator |
| Rec | rectifier |
| COND | condenser |
| RHX | condensate pre-cooler |
| EVAP | evaporator |
| SEP | separator |
| EJ | ejector |
| T | turbine |
| C, COMP | compressor |
| IHE | internal heat exchanger |
| P | pump |
| EV | expansion valve |
| ABS | absorber |
| OCDPR | optimum compressor discharge pressure ratio |
| PIR | performance increasing ratio |
| SIR | second law efficiency increasing ratio |
| CCR | cooling capacity ratio |
| gc | gas cooler |
| D | destruction |
| ut | utilized |
| i, in | input |
| out | output |
| av | available |
| rq | required |
| $G$ | direct solar irradiance [Wm$^{-2}$] |

*Greek symbols*

| | |
|---|---|
| $\eta_{\text{II}}$ | second law efficiency [%] |
| $\eta_{\text{n}}$ | ejector nozzle efficiency [%] |
| $\eta_{\text{d}}$ | ejector diffuser efficiency [%] |
| $\varepsilon$ | effectiveness [%] |
| $\psi$ | flow exergy [kJ kg$^{-1}$] |
| $\omega$ | entrainment ratio [−] |
| $\delta$ | defect efficiency [%] |
| $\eta_{\text{IND300}}$ | collector efficiency [%] |

by some researchers [24,25]. These authors employed ejectors for system performance enhancement.

In the present work, a new dual-evaporator combined refrigeration cycle with dual source (DEDS), consisting of a GAX, an Organic Rankin Cycle (ORC), an ejector-expansion transcritical $CO_2$ refrigeration (EETC) cycle and a supercritical $CO_2$ power cycle, is proposed and analyzed in detail. In the proposed system, renewable energy sources such as solar energy play an important role in driving the system. In fact, the proposed system is a combination of the heat driven and vapor-compression refrigeration systems. In the system, the waste heat recovery has been accomplished in three stages; in the GAXD, in the ORC evaporator and in the supercritical $CO_2$ power vapor generator (gas cooler of the EETC). To our knowledge, this system has not been studied so far and the present work is an attempt to do so.

A parametric study is performed on the proposed cycle performance considering the effects of some important parameters such as; gas cooler pressure, gas cooler outlet temperature, evaporators' temperature and GAX generator temperature on the COP (coefficient of performance) and second law efficiency. Finally, the proposed system is optimized thermodynamically using the EES (Engineering Equation Solver) software [26]. As the R1234yf has a zero Ozone Depletion Potential and a 100-year time horizon Global Warming Potential (GWP) of 4 and it has lower toxicity according to the ASHRAE, it is selected as the working fluid in the ORC [27,28].

## 2. System description

Fig. 1 shows a schematic of the proposed dual-evaporator dual-source refrigeration (DEDS) system. Referring to this figure, four different cycles including, the GAX absorption refrigeration, the transcritical $CO_2$ refrigeration, the supercritical $CO_2$ power and the ORC with an internal heat exchanger are combined with each other. The input energy to the combined system is in the forms of heat (solar energy) and electricity and the system output is the cooling effects which are obtained from two evaporators as shown in Fig. 2, clearly. Fig. 2 also indicates the energy flows among the four above-mentioned cycles.

Referring to Fig. 1, the saturated $CO_2$ vapor in the EETC is compressed in the compressor (state2) and then cools to some stage in the GAXD of the GAX cycle. The high pressure $CO_2$ is further cooled in vapor generator (ORC evaporator) to a temperature of around 85 °C to run the ORC. The $CO_2$ exiting the vapor generator then flows to the gas cooler (supercritical $CO_2$ vapor generator) to run the supercritical $CO_2$ power cycle before entering the ejector as the primary flow. The secondary flow of the ejector is the low pressure vapor coming from the evaporator of the EETC (EVAP1). The ejector mixed flow discharges to the separator which feeds the compressor. The details of flows in the GAX cycle, supercritical $CO_2$ power cycle and ORC can be seen in our previous works [17,25,29–31].

## 3. Thermodynamic modeling

### 3.1. Assumptions

Table 1 summarizes the input parameter values for the DEDS system shown in Fig. 1. Also the basic assumptions in the modeling of system are as follows;

(1) The system is simulated under steady state conditions.
(2) The pressure drops in all heat exchangers and pipelines are neglected.