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# Parametric assessment and multi-objective optimization of an internal auto-cascade refrigeration cycle based on advanced exergy and exergoeconomic concepts

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ABSTRACT

This research deals with the advanced exergy and exergoeconomic analyses and multi-objective optimization of an internal auto-cascade refrigeration cycle. Butane is used as the refrigerant and all heat exchangers are modeled by considering pressure drops. Sensitivity study is carried out to assess the variation of exergetic and economic improvement potentials; namely, total avoidable exergy destruction, total avoidable exergy destruction cost and total avoidable investment cost rates to the compressor mass flow rate, condenser, refrigerator evaporator and freezer evaporator inlet temperatures. Parametric study indicates that the condenser inlet temperature growth improves the total avoidable exergy destruction within 88.19%, the total avoidable investment cost rate increases by about 126.92% and 3.68% as compressor inlet mass and refrigerator evaporator inlet temperature rise, respectively and the increment of refrigerator evaporator inlet temperature shows a positive effect on the total avoidable exergy destruction cost rate. In addition, improvement potentials are maximized by applying Non-dominated Sort Genetic Algorithm-II. The multi-objective optimization indicates 76.78%, 38.66% and 103.38% improvements in total avoidable exergy destruction rate, total avoidable investment and total avoidable exergy destruction cost rates, respectively relative to the base design point.



## 1. Introduction

More recently, studies on the auto-cascade refrigeration cycles (ACRCs) have been carried out in various aspects, such as the cycle characteristics of the system, exergy analysis of the system and the system modifications.

ACRCs show more advantages in comparison with traditional cascade refrigeration cycles (CRCs); as a result, more investigations have been focused on ACRC. It is suggested that adding a fractionation device in the phase separator or reducing separation stages may sharply cut down the cost of system [1].

Kim and Kim [2] studied the performance of an ACRC using zeotropic refrigerant mixtures of R744-R134a and R744-R290 as working fluid. It was found that ACRC had a merit of low operating pressure as low as that of a conventional vapor compression refrigeration cycle. Yu et al. [3] proposed a novel ACRC with an ejector with refrigerant mixture of R23/R134a to recover available work and to investigate the effects of major design parameters on the desired system performance. The results showed the decrement in the pressure ratio of compressor as well as the increment in the coefficient of performance (COP). Nayak and Venkatarathnam [4] studied an ACRC operating with optimized R22/R404A mixtures and various cascade heat exchangers. In this research, the optimum stages of cascade heat exchangers were suggested for different operating temperatures. Wang et al. [5] assessed the performance of ACRC operating with two vapor-liquid separators and six binary refrigerants, i.e. R23-R134a, R23-R227ea, R23-R236fa, R170-R290, R170-R600a and R170-R600, with a new approach at the temperature level of −60 °C. Sivakumar and Somasundaram [6] performed an exergetic analysis of three stage ACRC using two combinations of R290/R23/R14 and R1270/R170/R14. COP, exergy loss, exergic efficiency, efficiency defect and the evaporating temperature were evaluated for various mass fractions.

Tan et al. [7] proposed and analyzed thermodynamically an ejector enhanced ACRC to obtain lower refrigeration temperature.

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**Nomenclature**

| | |
|---|---|
| A | heat transfer area ($m^2$) |
| Bo | boiling number |
| c | cost per unit of exergy ($/kJ) |
| $\dot{C}$ | cost rate ($/year) |
| $D_h$ | hydraulic diameter (m) |
| $dP_A$ | accelerational pressure drop (Pa) |
| $dP_F$ | frictional pressure drop (Pa) |
| $dP_G$ | gravitational pressure drop (Pa) |
| $dP_M$ | pressure loss at the entry and exit (Pa) |
| $dP_{tot}$ | total pressure drop (Pa) |
| $\dot{Ex}$ | exergy flow rate (kW) |
| f | frictional factor |
| G | mass flux ($kg/m^2s$) |
| g | gravitational acceleration ($m/s^2$) |
| h | specific enthalpy (kJ/kg) |
| $h_C$ | cold side convection heat transfer coefficient (W/K $m^2$) |
| $h_H$ | hot side convection heat transfer coefficient (W/K $m^2$) |
| L | length between the centers of entry and exit tubes (m) |
| $r_c$ | compressor pressure ratio |
| P | pressure (kPa) |
| *Pr* | Prandtl number |
| $\dot{Q}$ | heat transfer rate (kW) |
| T | temperature (°C) |
| $\dot{m}$ | mass flow rate (kg/s) |
| *Nu* | Nusselt number |
| *Re* | Reynolds number |
| U | heat transfer coefficient (W/K $m^2$) |
| V | velocity of fluid (m/s) |
| $\dot{W}$ | compression power (kW) |
| X | quality |
| $\dot{Z}$ | investment cost rate of components ($/year) |

*Greek letters*

| | |
|---|---|
| $\beta$ | chevron angle |
| $\eta_{is}$ | isentropic efficiency |
| $\Delta$ | difference |
| $\delta_{plate}$ | plate thickness (m) |
| $\lambda_{plate}$ | plate thermal conductivity (W/m K) |
| $\rho$ | density ($kg/m^3$) |
| $\upsilon$ | specific volume ($m^3/kg$) |
| $\upsilon_{fg}$ | difference of specific volume between gas and liquid phase ($m^3/kg$) |

*Superscripts*

| | |
|---|---|
| AV | avoidable |
| EN | endogenous |
| EX | exogenous |
| UN | unavoidable |

*Subscripts*

| | |
|---|---|
| C | cold side |
| Cond | condenser |
| Comp | compressor |
| D | destruction |
| F | fuel |
| H | hot side |
| HE | heat exchanger |
| in | inlet stream |
| k | kth component |
| l | liquid phase |
| L | loss |
| LMTD | logarithmic mean temperature difference |
| out | outlet stream |
| P | product |
| tot | total |
| V | vapor phase |
| 1–13 | state points of refrigerant |

The R32/R236fa zeotropic mixture was applied as a refrigerant. The results showed that refrigerant mixture composition, condenser outlet temperature and evaporation pressure had considerable effects on the performance of ACRC. Yan et al. [8] designed and investigated a new ejector enhanced ACRC applying R134a/R23 refrigerant mixture to recover the work loss in the throttling process. The performance comparison of the new proposed system with a basic ACRC was performed from the first and the second laws of thermodynamics and the effect of substantial parameters were evaluated on system performance.

Rui et al. [9] proposed R600a/R23/R14 mixture for a modified ACRC. The performance of the mixture, the effects of composition ratio and bypass scheme were evaluated in the desired system. Results implied the feasibility of the mixture as an environmental benign alternative for the system.

Chen et al. [10] modified an ACRC by adding an additional evaporating subcooler to provide a good use of temperature glide characteristic of R23/R134a zeotropic mixture. Results indicated that under the considered operating conditions, COP, volumetric cooling load and exergy efficiency of the modified cycle could be improved compared to that of the basic cycle.

In 2015, Yan et al. [11] proposed and evaluated the performance of an internal auto-cascade refrigeration cycle (IARC). In this research, R290/R600 or R290/R600a was used as a working fluid and its performance was compared with the conventional refrigeration cycle. There was a main advantage of the IARC in comparison to CRC. This advantage is that the heat transfer irreversibility within refrigerator evaporator would be smaller due to the reduction in average temperature difference across the refrigerator evaporator. Therefore, IARC gave the drastic enhancement of overall efficiency. Moreover, using refrigerant R290/R600 in IARC indicated that COP, volumetric refrigeration capacity and pressure ratio of compressor were further improved. The performance characteristics of the IARC showed its promise in domestic refrigerator-freezers applications.

The conventional exergy and exergoeconomic analyses are the powerful tools to estimate the location, magnitudes and causes of inefficiencies and costs related to these irreversibilities in the energy systems. However, this is not always effective because the conventional analyses are not able to estimate the interaction among the components or to reveal the real improvement potential of the system. Therefore, optimization strategies for energy systems can be misguided. Advanced analyses attempt to address this weakness. Splitting the exergy destruction rate and cost rates into avoidable (the part of the exergy destruction that can be avoided by improving the performance of the component itself) and unavoidable (the part of the exergy destruction that cannot be reduced with improvement of the component itself due to the technological limitations) subdivisions provides a realistic measure of improvement potential of each component. Moreover, splitting the exergy