International Journal of Current Engineering and Technology
©2022 **INPRESSCO**®, All Rights Reserved

E-ISSN 2277 – 4106, P-ISSN 2347 – 5161
Available at http://inpressco.com/category/ijcet

*Research Article*

# Development and exergy analysis of a multi-temperature combined compression/ejection refrigeration cycle suitable for dual PVT off-grid energy source

**Didier ZEH NDOH[1], Francklin G. NYAMI[2], Brice SANDONG OMGBA[3] and Frederic LONTSI[4]**

[1,2,3]Laboratoire E3M, EDOSFA/UFD SI, Université de Douala, 2701 Douala, Cameroun
[4]National Higher Polytechnic School of Douala, University of Douala, 2701 Douala, Cameroon

Received 18 July 2022, Accepted 10 Aug 2022, Available online 15 Aug 2022, **Vol.12, No.4 (July/Aug 2022)**

---

## Abstract

*This work deals with the development and exergy analysis of a hybrid multi-temperature combined vapor compression and ejection refrigeration system that can be powered by a dual energy source such as solar PVT, in the context of off-grid energy access. A simulation model has been developed considering the environment friendly refrigerants R134a, R152a and R290. The simulation results carried out under the defined operating conditions showed the proportions of exergy destruction in every component of the system. Based on the obtained result, an improved system has been proposed and analysed. The simulation results obtained with the latter have shown an increase of exergy efficiency of about 7.7; 6.8 and 6.6 when the system operates based on refrigerant R152a, R290 and R134a respectively.*

**Keywords:** *Exergy analysis, combined-cycle refrigeration system, multi-temperature, solar PVT, off-grid energy access*

---

## 1. Introduction

Production of cold both for refrigeration and for air conditioning requires the consumption of electrical energy. Vapor compression refrigerating systems are the most widespread because of their high performance, but they work thanks to electrical energy which can be a source of indirect pollution when it is produced in power plants based on fossil fuels. Moreover, in the context of off-grid and rural energy access, particularly in developing countries, this type of installation is often absent or simply expensive to operate, while renewable energy resources such as biomass and solar energy are abundant, and the refrigeration under-equipment leads to serious losses in agricultural production, which is an important and sometimes only source of income for the populations concerned. In these countries the cold storage potential is, in a large number of situations, of the order of 10% of that available to industrialized countries, while populations suffer from malnutrition and undernourishment and perishable foodstuffs, produced locally, are lost at 50% and very often more (Gac A, 2000). In these conditions, the use of locally available solar energy (thermal or photovoltaic) for the production of cold for the purpose of preserving perishable foodstuffs and pharmaceuticals in rural and off-grid areas appears therefore to be a serious alternative (Zeh *et al*, 2017).

The development of hybrid refrigeration systems combining the ejection cycle and the vapor compression cycle, with a view to production of cold for refrigeration and freezing based on thermal and/or electrical energy is experiencing renewed interest because of the advantages it offers through the quality and type of energy it consumes, and especially in relation to the preservation of the environment. The refrigeration systems combining the ejector cycle and the vapor compression cycle form a family of hybrid refrigeration systems which are part of a classification elaborated by Farah *et al*. (2016) and which have many advantages when they are powered by solar energy. Several research works are listed in the literature, concerning combined compression/ejection cycles (Kairouani *et al*., 2009, Sakar 2010, Yu Gao *et al*., 2020) some of which are focused on multi-temperature applications in particular for refrigeration and freezing (Lontsi *et al*., 2016). Moreover, some recent review publications dealing with solar PVT installations (Sandeep *et al*.,2018, Amal *et al*., 2020) show that these systems appear to be a good option in terms of

---

*Corresponding author's ORCID ID: :0000-0000-0000-0000
tel.: +237 677 60 42 87; mail: lontsi@yahoo.fr (Frederic LONTSI)
DOI: https://doi.org/10.14741/ijcet/v.12.4.9

energy sources likely to supply combined compression/ejection refrigeration systems with electrical energy and heat; these two forms of energy produced upstream being necessary for the operation respectively of the compressor and the generator of the combined refrigeration system.

Lontsi *et al* (2016) proposed and studied a hybrid compression-ejection refrigeration system intended to produce cold simultaneously in refrigeration and freezing mode. The energy analysis of said system made during this study for different ecological refrigerants, namely R134a, R152a and R290, made it possible to quantify the energy flows involved and to evaluate their performance in terms of COP. However, such an analysis does not take into account the weight of irreversibilities within the various components of the system, even less the quality of the various energy flows in relation to the conditions of the ambient environment.

The present study aims to carry out an exergy analysis of the system proposed by lontsi and to develop an optimized refrigeration cycle suitable for dual PVT off-grid energy source.

## 2. System description

The multi-temperature combined compression/ ejection refrigeration cycle consists in combining an ejector refrigeration cycle with a two-stage vapor compression refrigerating cycle with two evaporators, the low-pressure compressor of the latter having been replaced by the ejector.

The compressor and the ejector of such a system can be powered by a dual source solar PVT system. A detailed description of this system, its operation and energy analysis have been carried out by Lontsi *et al.* (2016) according to figure 1.

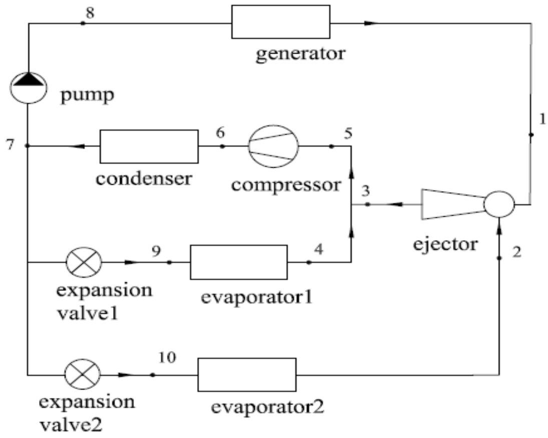


**Figure 1** : System principle diagram (Lontsi *et al.*, 2016)

## 3. Exergy analysis of the system

Considering the control volume of each component of the system, the exergy balance in steady state is expressed by the following equation (Mahmood *et al.*, 2013):

$$\Delta E_{x/dest} = \sum_{int} \dot{W} - \sum_{out} \dot{W} + \sum_{int} \dot{E}_Q - \sum_{out} \dot{E}_Q + \sum_{int} \dot{m}e - \sum_{out} \dot{m}e \quad (1)$$

The specific exergy due to the flow in (1) is given by :

$$e = h - h_0 - T_0(s - s_0) \quad (2)$$

And the exergy related to heat transfer is calculated according to (3).

$$\dot{E}_Q = \dot{Q}\left(1 - \frac{T_0}{T}\right) \quad (3)$$

According to the above mentionned equations, the exergy destruction in each component will be calculated below. the quantities of heat and work exchanged in each component result from the energy analysis carried out in (lontsi *et al.*, 2016).

### 3.1. Evaporator

By applying the exergy balance on evaporators 1 and 2 the following equations can be derived:

$$\Delta E_{x/dest\_ev1} = \dot{m}_9[(h_9 - h_4) - T_0(s_9 - s_4)] + \dot{Q}_{ev1}\left(1 - \frac{T_0}{T_{ev1}}\right) \quad (4)$$

$$\Delta E_{x/dest\_ev2} = \dot{m}_{10}[(h_{10} - h_2) - T_0(s_{10} - s_2)] + \dot{Q}_{ev2}\left(1 - \frac{T_0}{T_{ev2}}\right) \quad (5)$$

### 3.2. Condenser

Condensation is done by evacuating energy in the form of heat to the outside. Applying the exergy balance to the condenser gives:

$$\Delta E_{x/dest\_c} = \dot{m}_6[(h_6 - h_7) - T_0(s_6 - s_7)] - \dot{Q}_c\left(1 - \frac{T_0}{T_c}\right) \quad (6)$$

### 3.3. Expansion valves

The expansion process is supposed to be isenthalpic without exchange of work and heat through the control volume. The exergy destruction applied to each of the two expansion valves is expressed as:

$$\Delta E_{x/dest\_val1} = \dot{m}_9 T_0(s_9 - s_7) \quad (7)$$

$$\Delta E_{x/dest\_val2} = \dot{m}_{10} T_0(s_{10} - s_7) \quad (8)$$

### 3.4. Refrigerant pump

Exergy destruction in the circulating pump is calculated as follows:

$$\Delta E_{x/dest\_p} = \dot{m}_8(h_7 - h_8 - T_0(s_7 - s_8)) + \dot{W}_P \quad (9)$$

### 3.5. Generator

The generator requires an input of heat with no exchange of work. The application of the exergy balance to the latter gives the exergy destroyed in the generator by the relation :

$$\Delta E_{x/dest\_g} = \dot{m}_1[\,(h_8 - h_1) - T_0(s_8 - s_1)] + \dot{Q}_g\left(1 - \frac{T_0}{T_g}\right) \quad (10)$$

### 3.6. Compressor

The compression process is assumed to be irreversible and adiabatic. Considering the mass flow and the work input to the controle volume of the compressor, the exergy destruction in this component is calculated as follows:

$$\Delta E_{x/dest\_comp} = \dot{m}_5(h_5 - h_6 - T_0(s_5 - s_6)) + \dot{W}_{com} \quad (11)$$

### 3.7. Ejector

The ejector exchanges neither work nor heat through its control volume. Therefore, exergy destruction in this component is given by the relation:

$$\Delta E_{x/dest\_ej} = \dot{m}_1[h_1 - h_0 - T_0(s_1 - s_0)] + \dot{m}_2[h_2 - h_0 - T_0(s_2 - s_0)] - \dot{m}_3[h_3 - h_0 - -T_0(s_3 - s_0)] \quad (12)$$

The mass balance in the ejector is given by:

$$\dot{m}_3 = \dot{m}_1 + \dot{m}_2 \quad (13)$$

The energy balance in the ejector

$$\dot{m}_3 h_3 = \dot{m}_1 h_1 + \dot{m}_2 h_2 \quad (14)$$

The ejector entrainment ratio:

$$u = \frac{\dot{m}_2}{\dot{m}_1} \quad (15)$$

Thus the expression of the destruction of exergy in the ejector as a function of its entrainment ratio $u$ leads to:

$$\Delta E_{x/dest\_ej} = \dot{m}_1\begin{pmatrix} u[h_2 - h_0 - T_0(s_2 - s_0)] + [h_1 - h_0 - T_0(s_1 - s_0)] - \\ (1+u)[h_3 - h_0 - T_0(s_3 - s_0)] \end{pmatrix} \quad (16)$$

### 3.8. Total exergy loss of the system

Given the equations (4), (5), ..., (12), the total exergy destruction in the system is given by the relation:

$$\Delta E_{x/dest\_total} = \textstyle\sum_i E_{x/dest\_i} \quad (17)$$

### 3.9. Relative irreversibility

The relative irreversibility is defined as the percentage of exergy destruction of each component compared to the total destruction of the system as follows (Joybari *et al.*, 2013):

$$IR_i = \frac{\Delta E_{x/dest\_i}}{\Delta E_{x/dest\_total}} \quad (18)$$

### 3.10. Exergy efficiency

Considering the total exergy destruction and the total exergy input, the exergy efficiency of the system can be calculated as follows (Yu Gao *et al.*, 2020):

$$\eta_{ex} = 1 - \frac{\Delta E_{x/dest\_total}}{\sum \dot{E}_{in}} \quad (19)$$

In equation (19) the total exergy input is calculated as follows:

$$\sum \dot{E}_{in} = \dot{Q}_g\left(1 - \frac{T_0}{T_g}\right) + \dot{W}_P + \dot{W}_{com} \quad (20)$$

## 4. Computation methodology

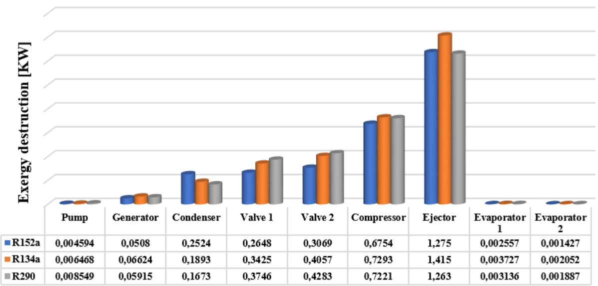
The set of equations presented above made it possible to write the simulation program which also integrates the model of the energy analysis of the system, developed by [lontsi *et al.*, 2016] with the same input operating parameters and the same simplifying assumptions. The simulation programs are written based on Engineering Equation Solver (EES) package (Klein and Beckman, 2009). The thermodynamic properties of all the considered refrigerants are obtained from the same software data base. Solving the model equations involves an iterative process that helps determine the ejector entrainment ratio and thereafter, the exergy destruction and the relative irreversibility.

## 5. Results and discussions

Refrigerants R134a, R290 and R152a are the three candidate refrigerants selected in the energy analysis carried out in lontsi *et al.*, 2016 with regard to system performances and operation conditions. These environmentally friendly refrigerants are considered in this study. During the simulations, the temperature of the generator is maintained at 70°C so as to better correspond to applications where the combined multitempearature compression/ejection refrigeration system is powered by a dual PVT solar source.

### 5.1. Exergy destroyed by each component

Figure 2 shows the simulation results of exergy destruction in each system component for the three considered fluids under the same operating conditions. In decreasing order, the exergy destruction is mainly observed in the ejector, the compressor, the expansion valve 2, the expansion valve1, the condenser, the generator, the two evaporators, and finally in the pump which has almost zero exergy destruction.



| | Pump | Generator | Condenser | Valve 1 | Valve 2 | Compressor | Ejector | Evaporator 1 | Evaporator 2 |
|---|---|---|---|---|---|---|---|---|---|
| R152a | 0,004594 | 0,0508 | 0,2524 | 0,2648 | 0,3069 | 0,6754 | 1,275 | 0,002557 | 0,001427 |
| R134a | 0,006468 | 0,06624 | 0,1893 | 0,3425 | 0,4057 | 0,7293 | 1,415 | 0,003727 | 0,002052 |
| R290 | 0,008549 | 0,05915 | 0,1673 | 0,3746 | 0,4283 | 0,7221 | 1,263 | 0,003136 | 0,001887 |

**Figure 2.** Exergy destroyed by each component

When taking into account the effect of refrigerants, there is a disparity in the levels of exergy destroyed when switching from one component to another. But globally, the total exergy destruction is predominant with refrigerant R134a, lower when the system operates with R152a and intermediate with R290. Figure 3 illustrates the relative irreversibility for R152a which appears as the fluid with the best potential for energy conversion in the system.

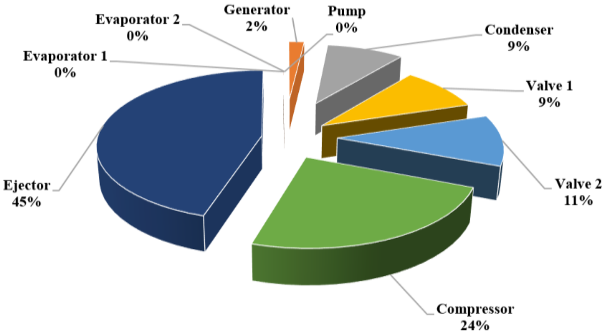


**Figure 3.** Relative irreversibility of each component when the system operates based on R152a

The high values of exergy destruction in the ejector and in the compressor are explained by the irreversibilities which take place in these components. There are heat transfers in the compressor with high flow while the ejector entrainment ratio remains low. The level of exergy destroyed in the expansion valves is explained by the fact that the fluid upstream of these components has a potential energy that is not converted and valued during the expansion process.

### *5.2. Influence of operating conditions on exergy efficiency*

Some operating parameters such as condensation temperature, cooling capacities ratio and generator temperature are likely to influence the exergy performances of the combined compression-ejection refrigeration system.

- **Influence of the condensation temperature**

The condensation temperature is determined by the cooling medium. Simulation of the effect of this temperature when it varies within the reasonable range for the ambient medium shows an increase in exergy destruction with increasing condensation temperature as depicted in the figure 4. In fact, a rise in condensation temperature leads to an increase of the compression ratio. This has the effect of increasing the compression work and consequently, a drop in system performance.

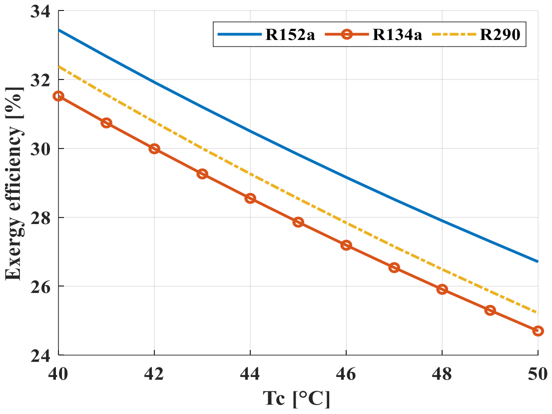


**Figure 4.** Influence of condensation temperatureon exergy efficiency

- **Influence of cooling capacities ratio on exergy efficiency**

It has been established in lontsi *et al*,. (2016) that the combined refrigeration system performance depends on the ratio $\psi$ between the cooling capacities of refrigeration and freezing. An increase in this ratio leads to an increase of fluid flow rate through the evaporator of the vapor compression refrigeration sub-cycle, while the flow rate of fluid sucked by the ejector into the ejector refrigeration sub-cycle decreases, but with an entrainment ratio which remains unchanged.

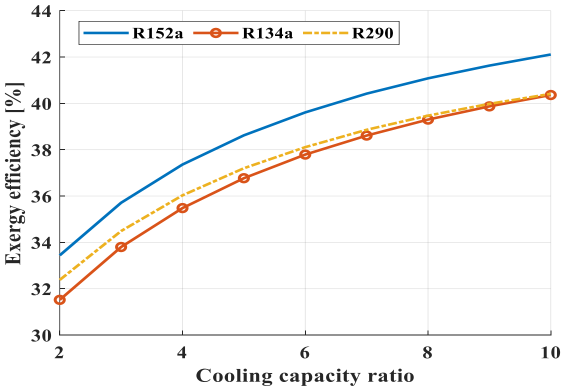


**Figure 5.** Influence of cooling capacities ratioon the exergy efficiency of the system

Vapor compression cycle becomes predominant with less exergy losses, compared to ejector refrigeration sub-cycle. This results in an increase in exergy efficiency of the combine refrigeration system when cooling capacities ratio increases according to figure5. This trend is more accentuated for R152a than for the two other working fluids whose representative curves approach each other when $\psi$ >8.

## 6. Improved proposed system

The exergy analysis having shown that the destruction of exergy is greater in the ejector, in the compressor and in the expansion valves, a new configuration of the system is proposed in order to improve both the energy and exergy performances of the system. This new scheme includes two recuperation heat exchangers. The first is mounted between the compressor and the condenser so as to preheat the fluid before it enters the generator, and the second is mounted between the condenser and the evaporator 2 so as to preheat the fluid which is sucked in by the ejector. The principle diagram is illustrated in figure 6.

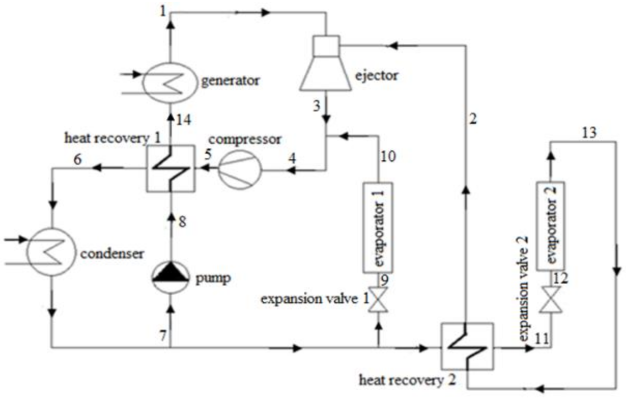


**Figure 6.** New hybrid compression-ejection refrigeration system proposed

The governing first law equations of recuperators in the new configuration of the combined compression/ejection refrigeration system are given as follows :

Recuperator 1:

$$\dot{m}_5(h_5 - h_6) = \dot{m}_1(h_{14} - h_8) \tag{21}$$

Recuperator 2:

$$\dot{m}_{11}(h_7 - h_{11}) = \dot{m}_{13}(h_2 - h_{13}) \tag{22}$$

By considering the same operating conditions, a simulation of the proposed new system was carried out for the three refrigerants. The simulation results of the two systems as illustrated in Figure 7 show an improvement in the exergy efficiency of the new system compared to that of the initial installation.

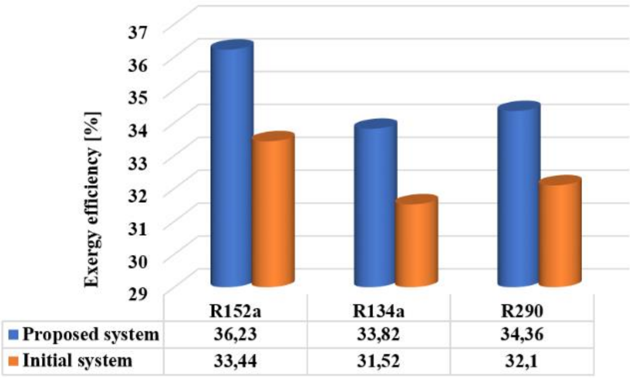


**Figure 7**. Comparison of exergy performances

Indeed, the presence of heat exchangers will have contributed to the reduction of exergy destruction in the relevant components of the installation. Globally, a decrease of around 7.7; 6.8 and 6.6 is observed when the system operates with R152a, R290 and R134a refrigerant respectively.

## Conclusion

The evaluation of the exergy destructions in each element of a multi-temperature combined vapor compression and ejection refrigeration system previously proposed by by F. Lontsi *et al.*(2016) was carried out, which made it possible to highlight on the one hand the total exergy losses and on the other hand the exergy efficiency of the said system. The ejector, the compressor and the expansion valves appear respectively as being the components where the exergy destructions are predominant.

The influence of operating parameters such as generator temperature, condenser temperature, and cooling capacities ratio was also investigated based on environmentally friendly refrigerants such as R134a, R290 and R152a. The simulation results showed that the exergy efficiency of the system decreases with increasing condensation temperature; but increases with the rise of the cooling capacities ratio.

Two recovery heat exchangers have been incorporated to the initial system in such a way as to obtain a new system with improved exergy performances. The simulation results obtained from the new system showed an increase in exergy efficiency of about 7.7; 6.8 and 6.6 when the system operates with R152a, R290 and R134a respectively.

## References

[1]. GAC André, (2000). Optimisation de la conception et de la gestion des entrepôts frigorifiques. Edition Pyc livres S.O.

[2]. Didier ZEH NDOH, Frederic LONTSI, Thomas DJIAKO, Robert ZENGWA, Engelbert NGWA (2017). Dual source solar powered combined-cycle multi-temperature refrigeration system for cold production in the context of off-grid and rural energy access. International Journal of Thermal Technologies. Vol.7, N°1, pp29-36.

[3]. Farah Kojok, Farouk Fardoun, Rafic Younes, Rachid Outbib (2016). Hybrid cooling systems: A review and an optimized selection scheme. *Renewable and Sustainable Energy Reviews.* 65, pp57–80

[4]. Kairouani L, Elakhdar M, Nehdi E, Bouaziz N, 2009. Use of ejectors in a multi-evaporator refrigeration system for performance enhancement. International Journal of Refrigeration 32, 1173-1185

[5]. Sarkar J, 2010. Performance characteristics of multi-evaporator transcritical CO2 refrigeration cycles with hybrid compression/ejection. In: Proc. Inst Mech Engrs, Part A: Journal of Power and Energy 224, 773-780.

[6]. Yu Gao, Guogeng He, Dehua Cai, Mingjing Fan (2020). Performance evaluation of a modified R290 dual-evaporator refrigeration cycle using two-phase ejector as expansion device. Energy. 2012, pp118614

[7]. F. Lontsi, O. Hamandjoda, O. T. Sosso Mayi, A. Kemajou (2016). Development and performance analysis of a multi-temperature combined compression/ejection refrigeration cycle using environment friendly refrigerants. *International Journal of Refrigeration*. 69, pp 42-50.

[8]. Sandeep S. Joshi, Ashwinkumar S. Dhoble (2018). Photovoltaic-Thermal systems (PVT): Technology review and future trends. Renewable and Sustainable Energy Reviews. 92, pp848-882.

[9]. Amal Herez, Hicham El Hage, Thierry Lemenand, Mohamad Ramadan, Mahmoud Khaled (2020). Review on pho tovoltaic/thermal hybrid solar collectors: Classifications, applications and new systems. Solar Energy. 207, s-1347.

[10]. Mahmood Mastani Joybari , Mohammad Sadegh Hatamipour, Amir Rahimi, Fatemeh Ghadiri Modarres (2013). Exergy analysis and optimization of R600a as a replacement of R134a in a domestic refrigerator system. International Journal og Refrigeration. 36, pp1233-1242.

[11]. M. M. Joybari, M. S. Hatamipour, A. Rahimi et F. G. Modarres, «l'Analyse exergétique et optimisation du R600a comme frigorigène de remplacement du R134a dans le système frigorifique d'un réfrigérateur domestique,» *International Journal of Refrigeration,* pp. 1233-1242, 2013.

## Nomenclature

| | | |
|---|---|---|
| $E_x$ | *Exergy* | *[KJ]* |
| $e$ | *Flow-related exergy* | *[KJ/kg]* |
| $h$ | *Enthalpy of the fluid* | *[KJ/Kg]* |
| $IR$ | *Relatitive irreversibility* | *[.]* |
| $\dot{m}$ | *Mass flow rate of the fluid* | *[Kg/s]* |
| $P$ | *Fluid pressure* | *[KPa]* |
| $\dot{Q}$ | *Calorific power* | *[KW]* |
| $s$ | *Entropy* | *[KJ/Kg. K]* |
| $T$ | *Fluid temperature* | *[K]* |
| $U$ | *Ejector entrainment ratio* | *[.]* |
| $\dot{W}$ | *Mechanical power* | *[KW]* |

***Greek symbols***

| | | |
|---|---|---|
| $\eta$ | *Efficiency* | *[.]* |
| $\psi$ | *Cooloing capacity ratio* | *[.]* |

### *Indices*

| | |
|---|---|
| *0* | *Index relating to the ambient environment* |
| $1, 2, \ldots, 14$ | *System points* |
| *c* | *Condenser* |
| *com* | *Compressor* |
| *dest* | *Destroyed* |
| *ej* | *Ejector* |
| *ev1* | *Evaporator 1* |
| *ev2* | *Evaporator 2* |
| *ex* | *Exergy* |
| *g* | *Generator* |
| *i* | *System components* |
| *int* | *Entering* |
| *out* | *Outgoing* |
| *val1* | *Expansion valve 1* |
| *val2* | *Expansion valve 2* |
| *p* | *Pump* |