World Academy of Science, Engineering and Technology
International Journal of Electronics and Communication Engineering
Vol:10, No:1, 2016

Production of Ultra-Low Temperature by the Vapor Compression Refrigeration Cycles with Environment Friendly Working Fluids

Sameh Frikha, Mohamed Salah Abid

***Abstract*---**We investigate the performance of an integrated cascade (IC) refrigeration system which uses environment friendly zeotropic mixtures. Computational calculation has been carried out by varying pressure level at the evaporator and the condenser of the system. Effects of mass flow rate of the refrigerant on the coefficient of performance (COP) are presented. We show that the integrated cascade system produces ultra-low temperatures in the evaporator by using environment friendly zeotropic mixture.

***Keywords*---**Coefficient of Performance, Environment friendly zeotropic mixture, Integrated cascade, Ultra low temperature, Vapor compression refrigeration cycles.

NOMENCLATURES

COP:	Coefficient of performance	(-)
h:	Enthalpy	(J kg^{-1})
IC:	Integrated cascade	(-)
$\dot{m}_L$:	Liquid mass flow rate	(kg s^{-1})
$\dot{m}_t$:	Total mass flow rate	(kg s^{-1})
$\dot{m}_V$:	Vapor mass flow rate	(kg s^{-1})
P:	Pressure	(Pa)
$\dot{Q}$:	Heat rate	(W)
$\bar{T}$:	Average temperature	(K)
U:	Circulation ratio	(-)
$\dot{W}$:	Compressor power	(W)
x:	Liquid composition	(-)
y :	Vapor composition	(-)
Z:	Initial composition	(-)
y-x :	Difference in composition	(-)

Greek Symbols

ΔT_{bp}:	Difference between the boiling point temperatures
ΔT_r:	The refrigerant temperature glides (difference between dew point and bubble point) in the heat exchanger

Subscripts

B:	Bottle
C:	Condenser
Cp:	Compressor
E :	Evaporator
E-C:	Evapo-condenser
H:	Height
L:	Low
V:	Valve

I. INTRODUCTION

A worldwide interest is considered to develop low cost vapor compression systems at cryogenic refrigeration. It consists to the integrated cascade system that can reach temperatures as low as -200°C in a single stage, with acceptable pressure ratio, using a mixture of refrigerants. These systems are also known as "auto-cascading" systems, and sometimes they are referred to as one-flow cascade or mixed refrigerant cascade systems. The refrigerant working fluid is a zeotropic mixture, normally between 2 and 5 refrigerants, with progressively low normal boiling points related to the temperature difference between the cold source and the hot sink of the considered system [1]. The specific characteristic of the zeotropic refrigerant mixtures is the occurrence of temperature pinch points in condensers and evaporators. The pinch point is due to the temperature difference between the mixture's isobaric dew points and bubble points [2]. The main characteristic of the integrated cascade (IC) system is the difference between the composition of the mixture charged into the system and the refrigerant mixture flows (liquid formed and residual vapor) through the complete cycle. The compositions of the residual vapour and liquid formed are identified at the partial condenser witch is considered as a fractional composition part with one inlet and two outlet. The range of mass composition fraction is related to the pressure and temperature levels at the partial condenser. There will be three different compositions of the working fluid of the IC system, the vapor charged with composition z, the liquid formed at the condenser enriched with the lowest volatile component with composition x and the residual vapor enriched with the more volatile component with composition y. A little range of works has been concerned by the performances investigation of IC cycles with or without phase separators [1], [3]-[13]. Missimer [1] presented a brief history of auto-cascading systems. He described auto-refrigerating cascade systems converted from a multi-component zeotropic CFCs working fluid to a CFC free mixture. Clodic [3] presented the design of an integrated cascade system permitting the low temperature CO_2 frosting. The energy

Sameh Frikha is with the Physics Department, Faculty of Science - Al-Jouf University, KSA and with the Department of Mechanical, Electro-Systems Laboratory, Engineering National School of Sfax, Street of soukkra BP W. 3038 SFAX, Tunisia (corresponding author, phone: 00966547108869; 0021693404851e-mail: samehfrikha14@yahoo.fr).

Mohamed Salah Abid is with the Department of Mechanical, Electro-Systems Laboratory, Engineering National School of Sfax, Street of soukkra BP W. 3038 SFAX, Tunisia.

consumption and the coefficient of performance of this refrigerating system are calculated. Dewitte [4] performed an integrated cascade system with two refrigerants. Kim and Kim [5] investigated the performance of an auto-cascade refrigeration system using zeotropic refrigerant mixtures of R744/R134a and R744/R290. The effect of the high-boiling component mass fraction, on the cooling capacity, the compressor power and the coefficient of performance (COP) of the cycle are presented. It was found that the agreement between the theory and experiment was perfect and that the auto-cascade refrigeration cycle has a merit of low operating pressure as low as that in a conventional vapour compression refrigeration cycle. In our precedent works, a performance analysis of combined refrigeration cycles was established [6], [7]. Indeed, we presented a theoretical survey, which was based on finite time thermodynamic (FTT) analysis. The operating performance of two different combined vapor compression cooling cycles, the conventional cascade (CC) and the integrated cascade (IC), was investigated. It was founded that, at fixed condensing and evaporating temperatures and for same intermediate heat-exchanger temperature ratio, the IC is more efficient than the CC system. Q. Wang et al. [8] proposed a new approach to investigate the performance of a single-stage auto-cascade refrigerator operating with two vapor–liquid separators and environmentally benign binary refrigerants. They show that the main factors affecting COP are the pressure ratio and the composition of mixed refrigerants. Three stage auto refrigerating cascade (ARC) system was studied by [9]. The zeotropic mixture of environment friendly refrigerants (HC's and HFC's) was studied using two combinations (R290/R23/R14, R1270/R170/R14). Several performances of the system among them the Coefficient of Performance (COP), exergy lost and exergic efficiency were investigated for different mass fractions in order to verify the effect of mass fraction on them. G. Yan et al. [10] proposed an internal auto-cascade refrigeration cycle (IARC) operating with the zeotropic mixture of R290/R600a or R290/R600 for domestic refrigerator-freezers. Performances of the IARC are evaluated by using a developed mathematical model, and then compared with that of the conventional refrigeration cycle. Zhang et al. [11] proposed a small-sized auto-cascade refrigeration cycle using CO_2/propane as refrigerant. The effect of fractionation heat exchanger on the performance of the cycle was analyzed. The theoretical results are compared with the experimental data which validates the precision of numerical simulation. X. Xu et al. [12] investigated theoretically and experimentally the effect of throttle valves opening on the working refrigerant composition of auto-cascade refrigeration system. The variation of refrigerant composition under different valves opening was obtained. A new ejector enhanced auto-cascade refrigeration cycle (EARC) using R134a/R23 refrigerant mixture is proposed in [13]. The performance of the EARC and the basic auto-cascade refrigeration cycles is compared by the simulation method, in terms of energetic and exergy aspects.

This paper reports the modelling of an integrated cascade (IC) system. Heat and materiel balances are developed for the considered cycle. Then, the performance investigation of an integrated cascade refrigeration system using refrigerant mixtures of R744/R134a, R23/134a, and R170/R290 is presented. The study of the coefficient of performance of the IC system for an operating point source/sink (-60°C/20°C) is presented.

II. A TWO STAGE VAPOR COMPRESSION PLANT WITH ENVIRONMENT FRIENDLY ZEOTROPIC MIXTURES

The integrated cascade (Fig. 1) is similar to the conventional cascade system.

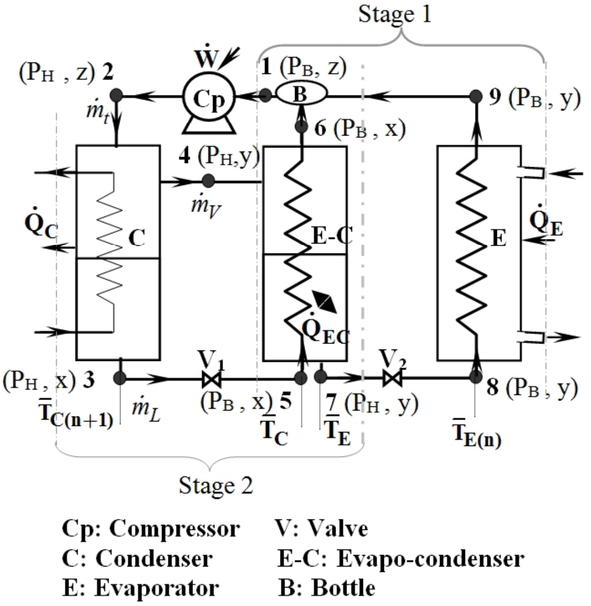

Fig. 1 Integrated cascade system with two stages

The IC system is divided into two stages and the number of stages is related to the temperature difference between the cold source and the hot sink. Fig. 1 illustrates an integrated cascade with two fluids. The integrated cascade architecture is composed by six elementary components which are: a compressor Cp, an evaporator E, a partial condenser C, an evapo-condenser E-C (the main component), a Freezer B, and tow throttling valves V_1 and V_2.

An example of binary fluid (R23/R134a) integrated cascade cycle is represented, in Fig. 2, by a temperature- composition diagram for the most volatile pure fluid.

An important integrated cascade (IC) system characteristic, which must not be overlooked, is the difference between the composition of the mixture charged into the system and the refrigerant mixture flows through the complete circuit.

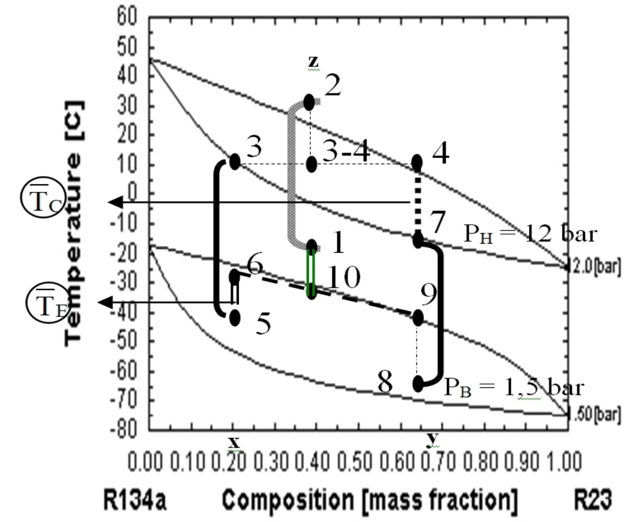

Fig. 2 Representation of an integrated cascade cycle by a T-x diagram using the R23/R134a mixture. (10→1 Freezer, 3→5 and 7→8 Trotting valve, 8→9 Evaporator, 5→6 Evapo-condenseur (Evaporation), 4→7 Evapo-condenser (Condensation), 6→10 and 9→10 Bottle, 1→2 Compressor, 3→3-4 and 4→3-4 Condenser)

III. INTEGRATED CASCADE CYCLE SIMULATION

The refrigerated efficiency of a bi-fluid IC system COP is defined as:

$$COP = \frac{\dot{Q}_B + \dot{Q}_E}{\dot{W}} \tag{1}$$

Another important parameter for the IC working is the circulation ratio:

$$U = \frac{\dot{m}_V}{\dot{m}_t} \tag{2}$$

Expressions of U and COP have been established by matter and energy balances applied on the quasi-totality of the IC cycle components. These balances and the necessary relations for the calculation are summed up in Table I.

Table I shows that the COP expression depends on the specific refrigerating effect and circulation ratio. The behavior of the COP is analyzed billow.

IV. NUMERICAL APPRECIATION

A. Working Conditions and IC Characteristics

The binary zeotropic fluid is supposed evolving between the source temperature -60°C and the sink temperature 20°C.

The working conditions of the IC (refrigerated power, COP, intermediated heat exchanger temperatures, etc) depend on the following parameters:

- Average condensing temperature of the evapo-condenser,
- Average evaporating temperature of the evapo-condenser,
- Nature and composition of the refrigeration mixture.

The influence of these parameters on working conditions of the IC system is developed subsequently in next paragraph.

B. Simulation Results of the Integrated Cascade Operation

The simulation results of an integrated cascade with three different mixtures R744/R134a, R23/R134a, and R170/R290 are shown in Figs. 3-5. Thermodynamic properties were computed using the database NIST REFPROP 6.01 [14]. The variations of coefficient of performance (COP) are shown in Fig. 3 according to the total molar fraction of pure most volatile.

TABLE I
ENERGY AND MATTER BALANCES OF IC SYSTEM

Matter balances		
Condenser		
Global balance	$\dot{m}_V + \dot{m}_L = \dot{m}_t$	(3)
Balance related the higher refrigerant		
	$y\,\dot{m}_V + x\,\dot{m}_L = \dot{m}_t\,z$	(4)
Energy balances		
Evaporator		
Courant (8-9)	$\dot{Q}_E = \dot{m}_V(h_9 - h_8)$	(5)
Bottle Courant (10-1)		
	$\dot{Q}_B = \dot{m}_t(h_1 - h_{10})$	(6)
Compressor Courant (1-2)		
	$\dot{W} = \dot{m}_t(h_2 - h_1)$	(7)
Evaporator-condenser Courant (4-5-6-7)		
	$\frac{(y-z)}{(z-x)} = \frac{(h_4 - h_7)}{(h_6 - h_5)}$	(8)
Circulation ratio		
	$U = \frac{(z-x)}{(y-x)}$	(9)
Coefficient of performance		
	$COP = \frac{(z-x)}{(y-x)}\frac{(h_9 - h_8)}{(h_2 - h_1)}$	(10)

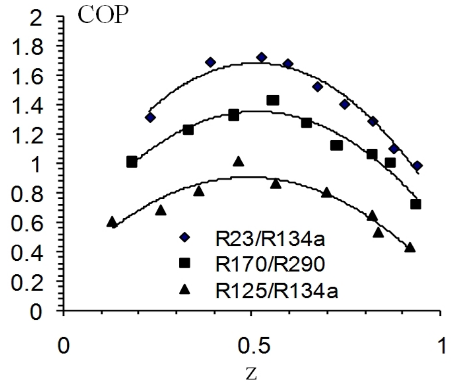

Fig. 3 Variations of the coefficient of performance (COP) with composition z for three binary mixtures R744/R134a, R23/R134a and R170/R290 at T_L=-60°C and T_H=20°C.

Table II presents the maximum COP values for three different binary mixtures. It shows that maximum COP is reached at nearly equal concentration of both fluids. The performed refrigerant mixture is R744/R134a which has the high boiling point temperature difference and the greatest difference in composition (y-x) in the partial condenser. The performance of the evapo-condenser heat exchanger is qualitatively measured by the difference ($\overline{T}_C - \overline{T}_E$) which must be low to improve the efficiency.

Variations of COP are shown in Fig. 3 according to the total mass fraction of the more volatile component. Fig. 3 and Table II show that the binary mixtures studied can be classified into two categories:

(a) The first category includes mixtures with a high glide ΔT_r (strongly zeotrope): R23/R134a and R170/R290. The maximum COP of the IC system is obtained with the refrigerant mixture R23/R134a. This COP_{max} reaches 1.722 with initial composition z of 0.526 as showing in Fig. 3 and Table II. Whereas with the refrigerant mixture R170/R290 the COP_{max} (1.431) is obtained for a composition z of 0.556 in R170.

(b) The second category consists of slightly zeotropic mixtures (low glide temperature ΔT_r). Fig. 3 shows that the mixture formed from 50% of R125 and 50% of R134a leads to the maximum coefficient of performance of 1.012.

TABLE II
VALUES OF COP_{MAX} FOR THE THREE DIFFERENT BINARY MIXTURES

Binary mixtures	ΔT_{bp} [K]	ΔT_r [K]	z	x	$\overline{T}_C - \overline{T}_E$ [K]	(y-x) max	COP max
R23/R134a	56,03	27	0,526	0,348	9,5	0,405	1,722
R170/R290	46,51	18	0,556	0,353	28,5	0,311	1,431
R125/R134a	22,07	3.4	0,464	0,612	55,5	0,128	1,012

The working of the integrated cascade is studied for three types of mixtures for different conditions (T, P, x). The results indicate that for the three binary mixtures the maximum value of COP is reached approximately at the maximum difference in composition between the vapor and liquid phases in partial condenser (y-x). Table II shows that the maximum value of the COP system R23/R134a is reached for a total composition of about 0.526. This feature of COP due to the minimum compression ratio ($R_P = P_{aval}/P_{amont}$) is not reached for the maximum value of (y-x), but it is reached for a value of (y-x) slightly below the maximum value (Fig. 4).

C. Influence of the Zeotropic Mixture Composition on the Occurrence of Pinch Point

The temperature distribution patterns in the evapo-condenser according to the total composition for refrigeration systems R23/R134a and R170/R290 are presented in Fig. 5.

Fig. 5 shows that the temperature profile in the intermediate heat exchanger is strongly influenced by the composition of the mixture. The pinch point at the evapo-condenser is lower with R23/R134a mixture than with the R170/R290 one. For both systems the pinch point (minimum $\overline{T}_C - \overline{T}_E$) is obtained with nearly equal concentrations of both fluids.

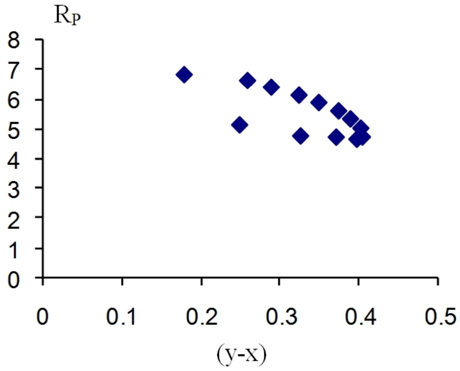

Fig. 4 Variation of compression ratio R_P versus the difference in composition (y-x) for R23/R134a system

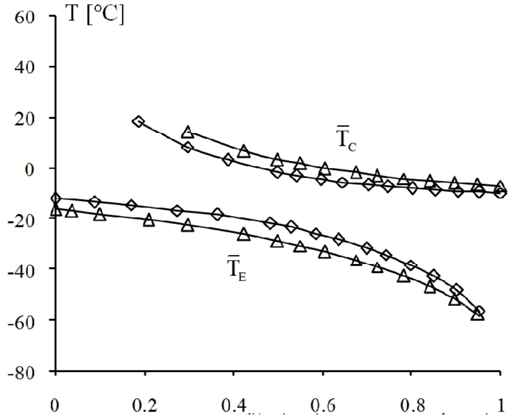

Fig. 5 Temperature profile in the E-C as a function of the total composition (z) for refrigerant mixtures: (◊) R23/R134a and (Δ) R170/R290

IV. CONCLUSION

The integrated cascade system is modeled from the mass and energy balances. This model leads to the coefficient of performance and to the simulation of integrated cascade cycle. We simulated the working of the integrated cascade system by varying the liquid composition at constant temperatures of condensation and evaporation for three refrigerant mixtures (R23/R134a), (R170/R290) and (R125/R134a). This study shows that the most efficient mixture is R23/R134a which has a large boiling point temperature difference with highest temperature glide. The efficient (R23/R134a) system conditions are reached with important partial separation composition (y-x) and lowest intermediate temperature difference at the evapo-condenser. The maximum coefficient of performance is obtained when (y-x) is approximately maximum and with a total composition z of around 0.5. The minimum temperature difference in the Evapo-Condenser is obtained with nearly equal concentrations of the two concerned mixture components. The study of the glide matching (minimization of the temperature difference) of the zeotropic mixtures in the condenser and evaporator of the integrated cascade cycle is therefore necessary to improve the performance of this cycle. This work is under way.

ACKNOWLEDGMENTS

The research is supported by the Faculty of Science, Al-Jouf University, KSA.

REFERENCES

[1] D. J. Missimer, Refrigerant conversion of Auto-refrigerating Cascade (ARC) systems, Int. J. of Refrig., Vol. 20, n. 3, pp. 201-207, (1997).

[2] Didion, D. and Bivens, D.B., Role of Refrigerant Mixtures as Alternatives to CFCs, Int. J. of Refrig., Vol. 13, pp. 163-175, (1990).

[3] D. Clodic, M. Younes, CO2 frostinn/defrosting process at atmospheric pressure. FR 01 01 232, 2001.

[4] P. Dewitte, Etude et modélisation d'une cascade intégrée à deux fluids (study and modeling of integrated cascade system with two refrigerants). Thèse de doctorat (P. h. D), Energétique, Ecole des Mines de Paris, 4 janvier (1995).

[5] S.G. Kim, M.S. Kim, Experiment and simulation on the performance of an autocascade refrigeration system using carbone dioxide as a refrigerant, International Journal of refrigeration vol. 25, p.p. 1093-1101, (2002).

[6] S. Frikha, M.S. Abid.: Performance Analysis of an Irreversible combined Refrigeration Cycles Based on Finite Time Thermodynamic Theory, International Review of Mechanical Engineering (I.RE.M.E.), Vol. 2, N. 2, pp 325-335, March (2008).

[7] S. Frikha and M. S. Abid, Performance optimization of irreversible combined Carnot refrigerator based on ecological criterion. International Journal of Refrigeration, article in press (Available online 11 November 2015), doi:10.1016/j.ijrefrig.2015.10.013

[8] Q. Wang, D.H. Li, J.P. Wang, T.F. Sun, X.H. Han, G.M. Chen, Numerical investigations on the performance of a single-stage auto-cascade refrigerator operating with two vapor–liquid separators and environmentally benign binary refrigerants, Applied Energy, vol. 112, p.p. 949-955, (2013).

[9] M. Sivakumar, P. Somasundaram, Exergy and energy analysis of three stage auto refrigerating cascade system using Zeotropic mixture for sustainable development, Energy Conversion and Management, vol. 84, p.p. 589-596, (2014).

10] G. Yan, H. Hu, J. Yu, Performance evaluation on an internal auto-cascade refrigeration cycle with mixture refrigerant R290/R600a, Applied Thermal Engineering vol 75, p.p. 994-1000, (2015).

11] L. Zhang, S. Xu, P. Du, H. Liu, Experimental and theoretical investigation on the performance of CO2/propane auto-cascade refrigerator with a fractionation heat Exchanger, Applied Thermal Engineering vol 87, p.p. 669-677, (2015).

12] X. Xu, J. Liu, L. Cao, Mixed refrigerant composition shift due to throttle valves opening in auto cascade refrigeration system, Chinese Journal of Chemical Engineering, vol. 23, p.p. 199-204, (2015).

13] G. Yan, J. Chen, J. Yu, Energy and exergy analysis of a new ejector enhanced auto-cascade refrigeration cycle, Energy Conversion and Management, vol. 105, p.p. 509-517, (2015).

14] O. M. Mark, A. K. Sanford, W.L. Eric and P. P. Adele, Nist Thermodynamic and Transport Properties of Refrigerants and Refrigerant Mixtures-REFPROP Version 6.01, National Institute of Standards and Technology Physical and Chemical Properties Division Boulder, Colorado, July (1998).