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Comparison of Thermodynamics Analysis of cascade Refrigeration System for refrigerant pairs R23/R404A and R41/R404A

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***Abstract*— This study presents a comparative analysis of thermodynamics performance of cascade refrigeration systems(CRSs) for refrigerants pairs R23/R404a and R41/R404a to discover whether R41is suitable substitute for R23.The discharge temperature, coefficient of performance(COP), exergy loss(x),and exergy efficiency are chosen as objective functions. The operating parameters considered in this paper include condensing temperature, evaporating temperature in both high-temperature cycle (HTC)and low temperature cycle(LTC).The results indicate that overall R41/R404a has a better performance than R23/R404a in cascade refrigeration system.**

***Index Terms*— cascade refrigeration system, Thermodynamic analysis, Exergy, COP**

1. INTRODUCTION

Refrigeration applications vary from domestic refrigerators to industrial and cold storage refrigeration systems with power requirements up to several megawatts and containing thousands of kilograms of refrigerant. Refrigeration system, with ultra-low temperature freezers employing the cascade refrigeration system can bring down temperature to a range of -80 °C

A refrigeration cycle consists of a source at low temperature, a sink at high temperature, and a device to produce the work done to transfer heat from the source to sink. For the complete circulation, the refrigeration cycle should have an expansion device to circulate the refrigerant to the source. A cascade refrigeration system is a vapor-compression refrigeration system (VCRS) with two circuits, operate with a lower evaporating temperature, smaller compression ratio and higher compressor volumetric efficiency when compared with a single-stage refrigeration system.

CRS has a Cooling system that uses two kinds of refrigerants having different boiling points, which run through their own independent cooling cycle and are joined by a heat exchanger. The lower temperature cycle provides the desired refrigeration effect at a relatively low temperature. The condenser in the lower-temperature cycle is thermally coupled to the evaporator in the higher-temperature cycle. Thus, the evaporator in the higher cycle only serves to extract the heat released by the condenser in the lower cycle. Then this heat is rejected into the ambient air or a water stream in the condenser of the higher cycle.

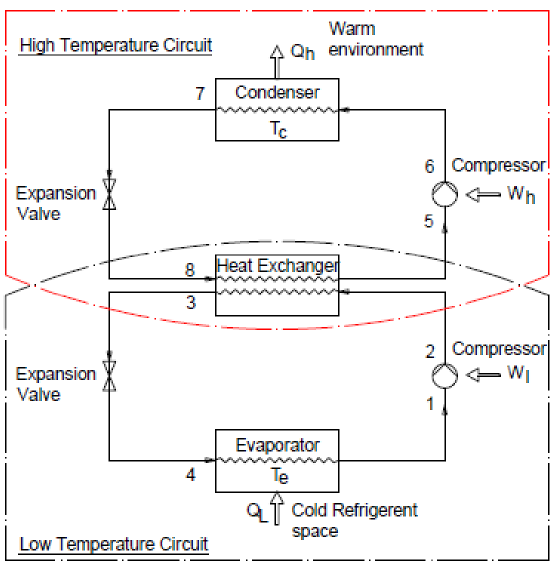
All major refrigeration systems including vapor-compression refrigeration system (VCRS) require large amount of refrigerants. The design of refrigeration equipment depends strongly on the properties of the selected refrigerants and efficiency. The refrigerant selection is based on safety and durability of refrigerants, focusing on stratospheric ozone protection and global warming effects.

In 1987, the Montreal protocols banned production and consumption of ozone depleting compounds, initiated actions to phase out CFC and HCFC in order to reduce ozone depletion. In 1997, The Kyoto protocol laid down goals for the reduction of global warming substances and subsequently the industry has been forced to look for substitutes of CFCs and HCFCs.

Even today the conventional refrigerants CFCs and HCFCs remain as refrigerant fluids of choice for many industries. Now the world scientific community is concentrating on inventions of environment friendly refrigerants, and energy efficient equipments.

2. THERMODYNAMIC MODELING

There are two cycles in a cascade refrigeration system; the high temperature cycle (HTC) is used to absorb the energy released by the low temperature cycle (LTC) during the condensation process (in the heat exchanger). In this way, cascade refrigeration system can reach the low-temperature cooling requirement range from 35°C to 80 °C. For the present studies, R23 and R41 are used as LTC refrigerant and R404A as HTC refrigerant.



CASCADE REFRIGERATION SYSTEM

SCHEMATIC DIAGRAM

Fig :a

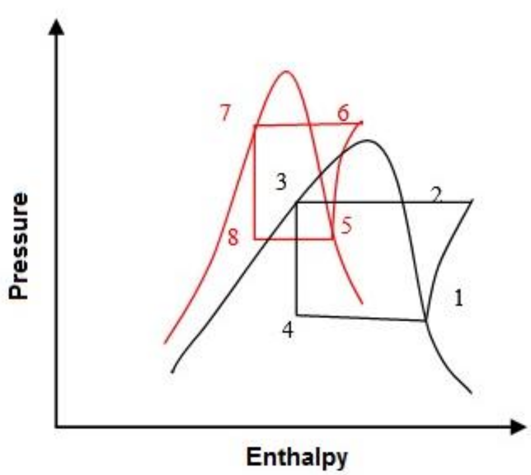


Fig : b

Refrigerant R-23 also known as Fluoroform is used in diverse applications in organic synthesis. It is not an ozone depleting refrigerant but is a greenhouse gas. Refrigerant R41 also known as Freon 41 is a non-toxic, liquefiable, and flammable gas at standard temperature and pressure. R41 is an environment friendly refrigerant with similar physical properties to R23 and not destructive to the ozone layer. R404A ternary mixture consisting of R-125, R-143a and R-134a. R-404A is characterized by a remarkable chemical stability and low glide temperature 0.7 ° C.

Thermo physical Properties of R41, R23 and R404A

Refrigerant	Molecular mass (gm /mole)	Critical temperature (°C)	Boiling Point (°C)	safety	ODP	GWP
R41	34.03	44.1	-78.1	A2	0	97
R23	70	25.6	-82	A1	0	12,000
R404A	97.6	72.1	-46.6	A1	0	3800

Figure (a) & (b) shows the schematic diagram of a typical cascade refrigeration system pressure enthalpy curve of a CRS. Two basic vapour compression refrigeration cycles, LTC and HTC are coupled with each other by means of a cascade condenser (heat exchanger). The cascade condenser behaves like a condenser in the LT Circuit and an evaporator in the HT Circuit. Refrigerant R41 is chosen to be the LTC refrigerant, whereas R404A is considered as the working fluids separately in HTC. Comparisons of different thermo physical and environmental properties of the three refrigerants used in this investigation are shown in above table. In CRS pair R41/R404A, R23 is the refrigerant in the Low temperature circuit and R404A is in the High temperature circuit.

Engineering equations solver

The mathematical modeling and thermodynamic comparison analysis is performed with Engineering equations solver (EES). EES can solve differential equations, equations with complex variables, thermodynamic problems, do optimization, provide linear and non-linear regression, generate publication-quality plots, simplify uncertainty analyses and plot graphs.

The library of mathematical and thermal physical property functions in EES is extensive. The large data bank of thermodynamic and transport properties built into EES is helpful in solving problems in thermodynamics and heat transfer analysis. The properties of refrigerants used in this analysis are inbuilt in EES.

3. MATHEMATICAL FORMULATIONS

System description

A mathematical model has been developed based on the following assumptions. Pressure drop and heat loss in all the pipe lines are neglected. Negligible heat interaction in the cascade heat exchanger with surrounding. Negligible changes in kinetic and potential energy. No sub cooling is considered and superheating is taken as effective heating. All the CRS components are at steady state condition. Other basic input parameters values considered for the present analysis are presented in table below.

Parameters	Values	Parameters	Values
ηC,LTC	70%	TC	40ºC
ηC,HTC	70%	ΔT	3ºC
TE	-60ºC to -30ºC	T0	25ºC

Equations

Mass balance

$$\sum_{in} \dot{m} = \sum_{out} \dot{m}$$

Energy balance:

$$\dot{Q} - \dot{w} = \sum_{out} \dot{m}h - \sum_{in} \dot{m}h$$

Capacity of the evaporator

$$X_{Lost} = \sum_{out} (1 - \frac{T_0}{T_1})\dot{Q}_i - \dot{w} + \sum_{in} \dot{m}\varphi - \sum_{out} \dot{m}\varphi$$

Capacity of the evaporator

$$\dot{Q}_E = \dot{m}_i (h_1 - h_4)$$

Compressor isentropic efficiency for low-temperature circuit

$$\eta isen, L = \frac{h_{2s} - h_1}{h_2 - h_1}$$

Compressor isentropic efficiency for high-temperature circuit

$$\eta isen, H = \frac{h_{6s} - h5}{h_2 - h5}$$

Compressor power consumption for low-temperature circuit is given as

$$\dot{W}_1 = \dot{m}_i (h_2 - h_1)$$

Compressor power consumption for high-temperature circuit is given as

$$\dot{W}_h = \dot{m}_h (h_6 - h_5)$$

Total work done or Actual work done:

$$W_{act} = \dot{W}_h + \dot{W}_1$$

The rate of heat transfer in the cascade condenser is determined from

$$\dot{Q}_{CC} = \dot{m}_i (h_2 - h_3) = \dot{m}_h (h_5 - h_6)$$

The rate of heat rejection by the air-cooled condenser is given as

$$\dot{Q}_H = \dot{m}_h (h_6 - h_7)$$

COP compression system is given by

$$COP_L = \frac{QE_1}{WC_1} = \frac{(h_1 - h_4)}{(h_2 - h_1)}$$

$$COP_H = \frac{QE_2}{WC_2} = \frac{(h_5 - h_8)}{(h_6 - h_5)}$$

Where,

COP_L - COP of lower compression system

COP_H - COP of higher compression system

COP of the cascade system is given as

$$COP_{CAS} = \frac{QE}{WC_1 + WC_2}$$

$$COP_{CAS} = \frac{COP_1 \times COP_H}{1 + COP_L + COP_H}$$

Exergetic efficiency or Second law efficiency is given by

$$\eta_{Exergy} = \frac{\dot{w}_h + w_L - \dot{X}_{Total}}{\dot{w}_h + w_L}$$

4. RESULTS AND DISCUSSIONS

A parametric study was conducted to evaluate the performance of the CRS and to determine the optimum operation parameters. The cascade heat exchanger is the most important component connecting Low temperature and high temperature circuits, which serves as the condenser of LTC and evaporator of HTC. The variation of evaporation temperature (Te) of HTC has a significant effect on operation of both HTC and LTC. Therefore, the variation of COP, the discharge temperature of the compressor in HTC and LTC, the compressor input power, the exergy efficiency of the system, the exergy loss of system and the proportion of exergy loss in each component of the system with evaporation temperature (Te) are analyzed respectively.

The COP is the ratio of cooling provided to work required, an important parameter to evaluate the performance of the refrigeration system. It can be also noted that the COP of R41/R404A CRS is higher than that of R23/R404A CRS, especially for a higher condensing temperature of LTC. The difference is higher at -30c to -5C.The main reason for this phenomenon is that the LTC efficiency of R41/R404A system is higher than that of R23/ R400A system. There exists a maximum COP at optimum condenser temperature of LTC. R41/R404A is a more potential refrigerant couple than R23/R404A in CRS.

Tables and graphs are given below:

Table 1: Results obtained with varying evaporator temperature (R23-R404A refrigerant pair)

1..10	T_1	COP	η_{exergy}	W_{total}	X_{total}
Run 1	-80	0.8974	1.022	148253	-3194
Run 2	-72	1.059	1.023	128437	-2892
Run 3	-64	1.251	1.023	110907	-2584
Run 4	-56	1.482	1.024	95309	-2267
Run 5	-48	1.762	1.024	81374	-1939
Run 6	-40	2.106	1.023	68894	-1595
Run 7	-32	2.537	1.021	57713	-1230
Run 8	-24	3.085	1.018	47715	-835.6
Run 9	-16	3.794	1.01	38827	-403.4
Run 10	-8	4.724	0.9973	31014	82.26

Table 2: Results obtained with varying evaporator temperature (R41-R404A refrigerant pair)

1..10	T_1	COP	η_{exergy}	W_{total}	X_{total}
Run 1	-80	1.075	1.089	300.4	-26.62
Run 2	-72	1.289	1.101	254.9	-25.71
Run 3	-64	1.553	1.115	214.8	-24.78
Run 4	-56	1.884	1.133	179.4	-23.86
Run 5	-48	2.31	1.155	148	-22.94
Run 6	-40	2.877	1.184	119.9	-22.01
Run 7	-32	3.666	1.222	94.71	-21.06
Run 8	-24	4.829	1.278	72.18	-20.07
Run 9	-16	6.693	1.365	52.13	-19.05
Run 10	-8	10.11	1.522	34.41	-17.97

Table 3: Results obtained with varying condenser temperature (R23-R404A refrigerant pair)

1..10	T_6	COP	η_{exergy}	W_{total}	X_{total}
Run 1	25	0.8974	1.022	148253	-3194
Run 2	30	0.876	1.025	151883	-3771
Run 3	35	0.8564	1.028	155366	-4358
Run 4	40	0.8383	1.031	158706	-4958
Run 5	45	0.8218	1.034	161907	-5574
Run 6	50	0.8065	1.038	164972	-6211
Run 7	55	0.7924	1.041	167906	-6878
Run 8	60	0.7794	1.044	170717	-7591
Run 9	65	0.7672	1.048	173412	-8392
Run 10	70	0.7559	1.054	176004	-9468

Table 4: Results obtained with varying condenser temperature(R41-R404A refrigerant pair)

1..10	T_6	COP	η_{exergy}	W_{total}	X_{total}
Run 1	25	1.075	1.089	300.4	-26.62
Run 2	30	1.063	1.089	304	-27.2
Run 3	35	1.051	1.09	307.5	-27.79
Run 4	40	1.039	1.091	310.8	-28.39
Run 5	45	1.029	1.092	314	-29
Run 6	50	1.019	1.093	317.1	-29.64
Run 7	55	1.009	1.095	320	-30.31
Run 8	60	1.001	1.096	322.8	-31.02
Run 9	65	0.9923	1.098	325.5	-31.82
Run 10	70	0.9845	1.1	328.1	-32.9

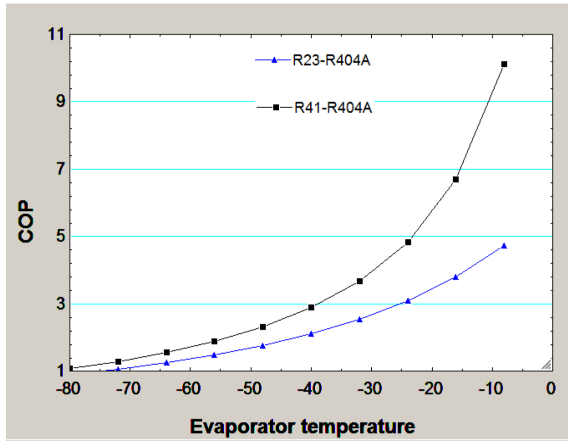


Fig:1 Effect of evaporator temperature on cop.

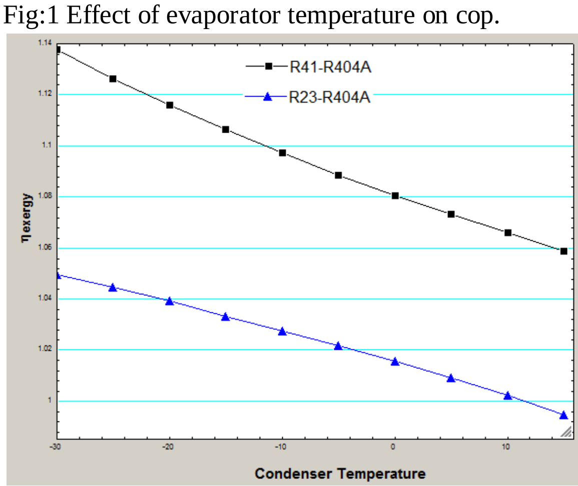


Fig:2 Effect of Condenser temperature on exergy efficiency.

5. CONCLUSIONS

The conclusions we obtained are as follows:

1. It can be noted that the refrigerant R41 can be used as an alternative refrigerant for R23 in the application of cascade refrigeration system.
2. R41/R404A has a better performance than R23/R404A in cascade refrigeration system.

3. Both R41/R404A and R23/R404A CRSs have an optimal condenser temperature of low-temperature circuit (T4opt) at which the COP achieves the maximum value.
4. The exergy loss of R41/R404A is lower than that of R23/R404 and the maximum exergy efficiency of R41/R404A is higher than R23/ R404A

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