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에탄을 사용한 2원 냉동 시스템의 성능 평가

Study of Ethane Performance at Two-Stage Cascade Vapor Compression System

루비 라하디얀 · 김영근 · 정효민 · 정한식
Lubi Rahadiyan, Y. G. Kim, H. M. Jeong and H. S. Chung

Key Words : Cascade vapor compression, high stage, low stage

Abstract : 세계적인 환경 보호 정책에 따라 할로겐화탄소 냉매를 대체할 환경 친화적인 초저온 냉매의 개발과 연구가 활발히 진행되고 있다. 일반적으로 캐스캐이드 2원 냉동 시스템에서 아직까지 할로겐화탄소 냉매가 널리 사용되고 있다. 탄화수소 화합물의 한 종류인 에탄은 낮은 지구 온난화 지수와 낮은 오존층 파괴지수를 가진 친 환경적인 자연 냉매이다. 본 연구는 지구 온난화 지수가 높은 R-23 냉매와 비교하여 캐스캐이드 2원 냉동 시스템에서 에탄의 성능 시험을 목적으로 수행 하였다. 1원측에는 R-22를 사용하였으며, 증발 온도에 따른 성능은 R-23 보다 에탄(R-170)이 더 높게 나타났다.

NOMENCLATURE

Symbol	Description [unit]
COP	Coefficient of performance
GWP	Global warming potential [per 100 yr]
h	Enthalpy [kJ/kg]
Hs/Ls	High/low stage cycle
LFL	Lower flammability limit [%]
$\dot{m}$	Refrigerant mass flowrate [kg/s]
T	Temperature [℃]
TLV	Threshold limit value [ppm]
ODP	Ozone depletion potential
P	Pressure [bar]
Pr	Compression ratio
Q	Heat transfer rate [kW]
W	Compressor work [kW]
Greek	
ε	Cascade effectiveness
η_{is}	Isentropic efficiency
Subscript	
amb	Ambient
c	Condenser
cr	Critical
e	Evaporator
in	Inlet flow
out	Outlet flow
SC	Sub-cool
SH	Super-heat
tot	Total
1	Hs evaporator outlet/compressor Inlet
tot	**Total**
1	**Hs evaporator outlet/compressor Inlet**
2	**Hs compressor outlet/condenser inlet**
3	**Hs condenser outlet/exp. valve inlet**
4	**Hs exp. valve outlet/ evaporator Inlet**
5	**Ls evaporator outlet/compressor Inlet**
6	**Ls compressor outlet/condenser inlet**
7	**Ls condenser outlet/exp. valve inlet**
8	**Ls exp. valve inlet/evaporator Inlet**

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정효민(책임저자) : 경상대학교 · 해양산업연구소
E-mail : hmjeong@gsnu.ac.kr Tel. 055-640-3184
김영근, 루비라하디얀, 정한식 : 경상대학교 · 해양산업연구소

1. INTRODUCTION

Our recently, within few decades, we realized that humanity significantly influences the global environment, in the early 1800s, atmospheric measurement confirm basic concept developed a decade earlier. This basic concept showed that human activities were affecting the ozone layer(1. This threat is followed by international concern, several agreement have been issued to reduce

Table 1 Ozone tritles and their effective dates

Treaty	Date when treaty was agreed	Effective Date (Entry into force)
Vienna Convention	22 March 1985	22 September 1988
Montreal Protocol	14-16 September 1987	1 January 1989
London Adjustment	27-29 June 1990	7 March 1991
London Amandment		10 August 1992
Copnehagen Adjustment	23-25 November 1992	23 September 1993
Copenhagen Amendment		14 June 1994
Vienna Adjustment	5-7 December 1995	5 August 1996
Montreal Adjustment	15-17 September 1997	4 June 1998
Montreal Amendment		10 November 1999
Beijing Adjustment	29 November - 3 December 1999	28 July 2000
Beijing Amendment		25 February 2002

environmental impact causes ozone depleting (see table 1). The 1987 Montreal protocol(2 is widely seen as a global environmental accord that has produced tangible results in terms of reductions in ozone-depleting substances(3. For over 50 years, chlorofluo-rocarbons (CFCs) were thought of as miracle substances, they are stable, non-flammable, low toxicity, and inexpensive to produce(4. Overtime, CFC found many uses in aerosol, foam, fire extinguisher agent, solvent, air conditioning, and refrigeration(5. Since the Montreal protocol is in place, the production and consumption of chlorofluorocarbons (CFCs), of halons as well as other ozone depleting chemicals have been almost completely phased out in industrialized countries; furthermore, a schedule has been introduced to eliminate the use of methyl bromide, a pesticide, and agricultural fumigant with particularly devastating ozone depleting effect. Chemical and equipment manufacturers mounted aggressive research and development programs to introduce alternative and transition refrigerants, associated lubricants, desiccants, and redesigned equipment. The already difficult criteria became even more complex, with subsequent linkage of chemical emissions from human activities to global climate change. Therefore, researches of natural friendly refrigerant are being carried out to meet the industrial demand for new replacement of refrigerant. Hammad et al(6 and Somchai et al(8 have studied carbon mixtures (propane-butane-isobutane) in the domestic refrigerators, the refrigerator work satisfactory with this refrigerant mixture without need for any modification or adjustment. Ismail Kul et al(9 investigate vapor pressure data below the normal boiling point, liquid density data and the critical parameters are reported for equimolar mixtures, RE218/ R134a/ R161, RE125/ R32/ R152a, and RE125/ R32/ R134a, which are judged to have a high potential as R22 alternatives based on their boiling point and critical temperature. Yang Zhao(10 et al found that the cooling capacities, energy efficiencies, compressor discharge temperatures, and pressures of alternatives have been compared with R22. R32/125/152a mixtures were found to be the most effective coolants. Others large number of zeotropic mixtures may be formed with the refrigerants that are suitable for compression type heat pumps(11. Several refrigerants can be utilized for the lower temperature refrigeration. R13, R23 are the most preferable refrigerant for low temperature application. Due to the Montréal protocol, R13 was included on the controlled substances. R23, which is hydrofluorocarbons (HFC), are chlorine free and ozone safe. Chemically inert, but due to a long chemical lifetime, they cause a considerable contribution to the greenhouse effect(12. Therefore, even the HCFCs once viewed as the long-term replacement for CFCs, the application is now under question. Although the production and use of hydro-fluorocarbons (HFC) refrigerants are not regulated by Montreal protocol(13, several country has already issued regulation relating with this refrigerant. Denmark has announced a ban of R23 from the beginning of 2006(14, and there are reports that Austria and Switzerland may follow suit(15,(16. Therefore, because of several ban of this refrigerant, new alternatives refrigerant must be studied and developed. This study is aimed to investigate performance of ethane on the low of 2-stage cascade refrigerating system under the various evaporating temperature at the lower stage cycle. R22 will be employed on the high stage to cool down the low-pressure cascade condenser. Similar study will be conducted to the R22/ R23. Therefore, by the end of this study, the relationship among the compression ratio, evaporating temperature and evaporating pressure to the characteristics of the cycle (COP and work of compression) of R22/ R170, and compare to those of R22/ R23.

2. REFRIGERANT

It has long being considered that hydrocarbon refrigerant could become retrofit of the non-environmentally friendly refrigerant. It has zero ODP, since there is no presence of the chlorine, and low GWP, because it is not contain fluorine that is contribute GWP to the refrigerant. Because of the its operating range pressure, in the hydrocarbon group only ethane can be applied in the low stage cycle of cascade refrigeration system. At ambient pressure, saturated ethane can reach temperature down to -88.9 ℃. Critical temperature of ethane is 32.2 ℃ at 4.87 MPa (see table 2), this thermophysical properties is very suitable for low temperature application as drop-in of R13 and R23. Ethane is a colorless, flammable, and odorless gas. The chemical formula is C2H6 or CH3CH3, and the refrigerant number is 170. Ethane is classified as A3 refrigerant in the ASHRAE Standard 34-Safety group(17. It means that ethane is non-toxic compound and high flammability gas. Thus, careful handling must be notified. Properties of refrigerants are highly influenced by the element that constitutes the refrigerant. Fig. 1 illustrates the triangle trade-off of refrigerant. Properties of refrigerants are highly influenced by the element that constitutes the refrigerant. Fig. 1 illustrates the triangle trade-off of refrigerant. Adding fluorine to the substance (moving to the lower right corner of the triangle) tends to increase the GWP of the substance. Therefore, R23, which has more fluorine atom, has highest GWP. Increasing the fluorine also tends to reduce toxicity(19. Increasing chlorine improves lubricant miscibility but also ODP and toxicity. Increasing carbon generally increases the molecular weight and boiling point. Increasing hydrogen generally reduces atmospheric lifetime, which good for GWP and ODP, but increases flammability. Since ethane does not contain either chlorine or fluorine, it is natural friendly refrigerant. Nevertheless, ethane is flammable refrigerant, it does not need heat of combustion to ignite, once the LFL value is reach, auto-ignition will be occur, thus careful handling to ethane in the refrigeration system must be considered. Ethane has lower normal boiling point compare than R23. Thus, at the atmospheric pressure, lower temperature can be obtained.

Table 2 Thermophysical Property of Refrigerants

Parameters	R-22	R-23	R-170
Molecular mass	86.47	70.01	30.07
Normal boiling point	-40.8	-82	-88.9
Critical temperature (T_{cr})	96.2	25.9	32.2
Critical pressure (P_{cr})	49.9	48.4	48.7
TLV	1000	1000	1000
LFL	none	none	2.9
Heat of combustion	2.2	-12.5	-
Atmospheric life [yr]	11.9	260	-
ODP	0.034	0.000	0.000
GWP	1700	12000	~20

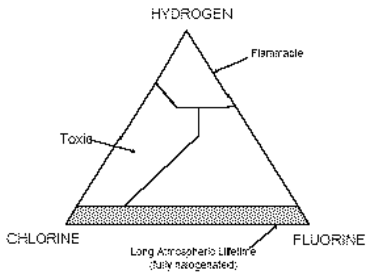

Fig. 1 Trade-off in varying F, Cl and H in Refrigerants

3. THEORETICAL ANALYSIS

To compare performance of two refrigerants, mathematical model can be used. This calculation includes coefficient of performance and evaporation temperature of cascade system. Assuming a steady state cyclic operation of two-stage cascade vapor-compression cycle, with no pressure drop occur on each process. Therefore, P-h diagram of cascade system will be same as fig. 2. Low stage refrigerant gains heat from evaporator, this evaporation heat changes liquid-vapor refrigerant at state 8 to superheat refrigerant (state 5) before it enters compressor.

Amount of the heat transferred to low stage evaporator (heat of evaporation) is:

$$Q_e = \dot{m}_{Ls}(h_5 - h_8) \tag{1}$$

This super heat refrigerant of low stage cycle subsequently compressed to higher pressure of compression outlet at state 6. The compression work of two cycles is:

$$W = \dot{m}(h_{out} - h_{in}) \tag{2}$$

In addition, the isentropic work is:

$$W_{Ls} = \dot{m}(h_{out,Ls} - h_{in}) \tag{3}$$

Where isentropic efficiency of the compressor is:

$$\eta_{Ls} = \frac{\Delta h_{Ls}}{\Delta h} \tag{4}$$

At this point, the state of compressor outlet can be determined by using P-h diagram. This superheat refrigerant of low stage then will be cooled down by high stage evaporator to state 7 at condenser outlet.

Heat rejected by low stage condenser is:

$$Q_{c,Ls} = \dot{m}_{Ls}(h_6 - h_7) \tag{5}$$

Alternatively, it can be written as:

$$Q_{c,Ls} = Q_e + W_{Ls} \tag{6}$$

Moreover, heat absorbed by high stage evaporator is :

$$Q_{e,Hs} = \dot{m}_{Hs}(h_1 - h_4) \tag{7}$$

Since the heat of condensing is not completely transferred to high stage evaporator, therefore, heat exchanger effectiveness (ε) is introduced to describe relationship between Qc and Qe,Hs

$$\varepsilon = \frac{Q_{e,Hs}}{Q_c} \tag{8}$$

Compression work by high stage cycle, which is operating at specific evaporation and condensing temperature, can be calculated by equation 2 and 3.

Finally, performance of cascade system is:

$$COP = \frac{Q_e}{Q_{Ls} + W_{Hs}} \tag{9}$$

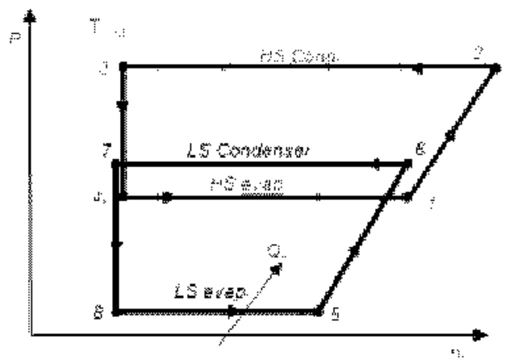

Fig. 2 Ideal P-h diagram of two-stage cascade vapor compression cycle

4. RESULT AND DISCUSSION

Table 3 shows operational condition of cascade system as fundamental state for calculation. This calculation base on assumption that the processes occur in the Ideal condition, with steady flow condition and no pressure drop, therefore, temperature and pressure in the each line (suction line, discharge line, liquid line) will be constant. Thus, temperature and pressure of evaporator outlet will be same as compressor inlet and so on. High stage cycle of R22 is operated at constant evaporation and condensing pressure. Condensing temperature is 30 ℃ with 5 ℃ of subcool degree, thus, liquid refrigerant leave condenser (T3) at 25 ℃. In the expansion valve, adiabatic throttling process is occur, therefore, enthalpy of expansion valve inlet and outlet are at the same quantity. Having absorbed heat from low stage condenser at cascade heat exchanger, HS refrigerant evaporate and reach superheat state (T1). Since mass flowrate and evaporation pressure of high stage refrigerant is kept constant, superheat degree will directly depend on the evaporation heat transferred by low stage condenser; higher evaporation heat, higher degree of superheat at high stage, therefore, higher the compressor outlet temperature. At low stage, constant evaporation heat (Qe) is supplied to evaporator. Mass flow-rate of refrigerant is constant. Evaporation temperatures of low stage cycle are increased, from -100 ℃ to -60 ℃. Effect of this variation will lead this analytical result. Meanwhile condensing temperature is always maintained at same degree that is ~5℃ above the evaporation temperature of high stage evaporator to ascertain heat transfer process from low stage to high stage. Increasing evaporation temperature (Te,Ls) in low stage circuit means increase of the evaporation pressure (Te,Ls). At lowest temperature conducted (-100 ℃), R23 shows lower pressure than R170 (Fig. 3). Low vacuum condition is not desired for operational condition. Therefore, R170 has advantage that it can reach lower temperature with relatively higher evaporating pressure compare to those of R23. Since evaporating pressure increases but condensing

Table 3 Operational condition of cascade system

	Quantity
Ambient temperature, Tamb [℃]	20
cascade effectiveness, ε	0.7
Degree of sub-cool , ΔT_{SC} [℃]	5
High Stage	
isentropic efficiency , η_{is}	0.7
High Stage Condensing temperature [℃]	30
Evaporation temperature $T_{e,Hs}$ [℃]	-40.8
Evaporatio Pressure, $P_{e,Hs}$ [bar]	1
Condensing Temperature, $T_{c,Hs}$ [℃]	30
Condensing Pressure, $P_{c,Hs}$ [bar]	11.9
Mass flowrate of refrigerant, $\dot{m}_{Hs}$ [kg/s]	0.007
Low Stage	
Isentropic efficiency, η_{Ls}	0.7
Heat of Evaporation, Q_e [kW]	1.5
Condensing temperature, $T_{c,Ls}$ [℃]	-35
Condensing Pressure, $T_{c,Ls}$ [bar]	
R23	8.5
R170	9.2
Mass flowrate of refrigerant, $\dot{m}_{Hs}$ [kg/s]	0.004
Evaporation temperature, $T_{e,Ls}$ [℃]	-100~-60

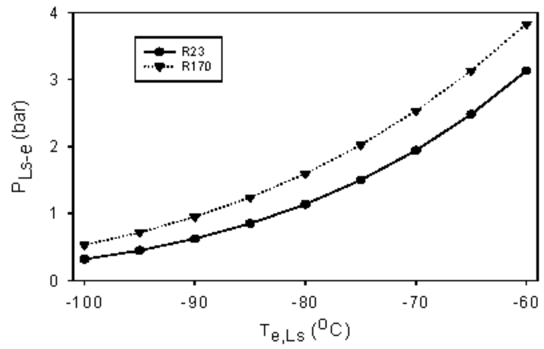

Fig. 3 low stage compression ratios versus low stage evaporation temperature

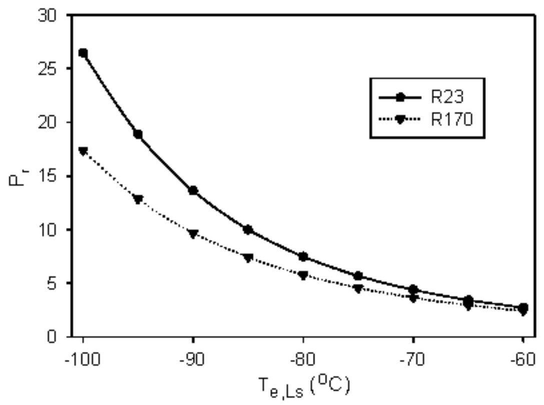

Fig. 4 low stage compression ratios versus low stage evaporation temperature

-pressure is steady, compression ratio will decreases as temperature of evaporation increases. In Fig. 4, comparison of low stage compression ratio can be seen. R23 gives higher compression ratio in every evaporation temperature. High compression ratio implies high compression power. Fig. 5 describe compression power of low stage cycle, R23 system consume higher compression power than those of R170 system. Performance of single cycle of low stage is displayed by Fig. 6. This graph shows COP of single R170 cycle is higher than R23. This is simply because with same evaporating heat rate (Qe), R170 has lower compression power. By equation 6, 7 and 8 it can be said that more heat rate will be transferred by R23 to R22 compare to that of R170. Therefore, in theR22 of R23 cycle, R22 leave evaporator with higher superheat degree. With the same pressure ratio, high superheat degree refrigerant will cause higher compression work. This is why in Fig. 7, R22 of R22-R23 require higher compression work. Total power consumes by two stage cascade system is equal to summation of by high stage and low stage cycle; the result can be seen in Fig. 8. For the same evaporating load, R22-R23 system shows higher power consumption to those of R22-R170. Fig. 8 show result of COP calculation for both systems. R22-R170 shows better performance than R22-R23. COP increases as evaporation temperature increases, higher evaporation temperature, better COP of R22-R170.

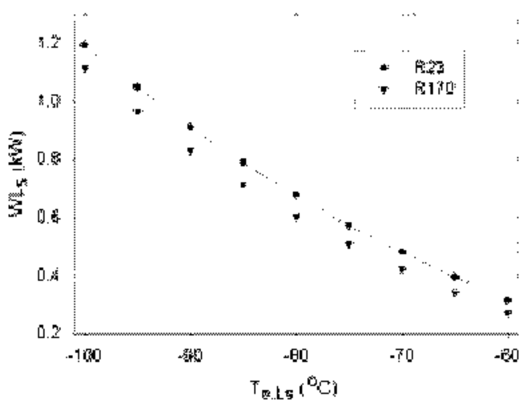

Fig. 5 low stage compression powers versus low stage evaporation temperature

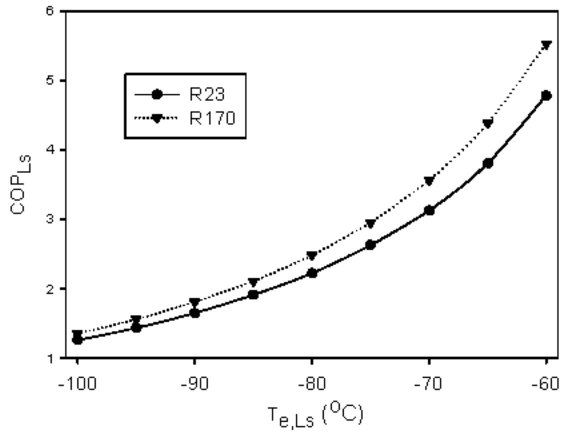

Fig. 6 Coefficient of Performance of low stage cycle versus Ls evaporation temperature

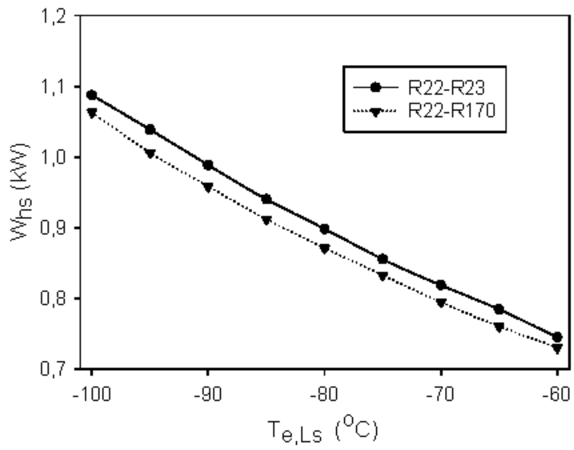

Fig. 7 High stage compression powers versus low stage evaporation temperature

5. CONCLUSION

In the future, the environmental issue is become most important consideration for selecting refrigerant. Some refrigerant we know today will be capped, thus the environmental friendly refrigerant must be studied to replace it. R170 or ethane is expected to be good refrigerant to replace halocarbon refrigerant, it has no environmental impact to the nature. It also has lower normal boiling point (-88.9 ℃) compare to halocarbon refrigerant (R23 and R13). Therefore, lower temperature can be achieve by utilize ethane. This paper discusses the performance of ethane for the low temperature cascade-refrigeration system application, and the result is compared to R23.

The results of this study affirm that in the two-stage cascade vapor-compression system, with R22 in the high cycle. For every variation of evaporation temperature and evaporation pressure, R170 gives better performance over R-23.

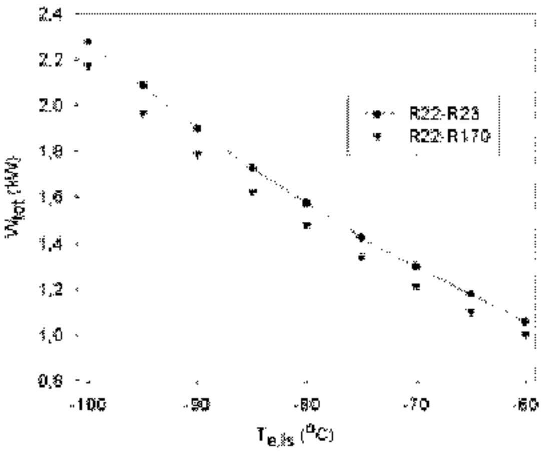

Fig. 8 Total compression powers versus low stage evaporation temperature

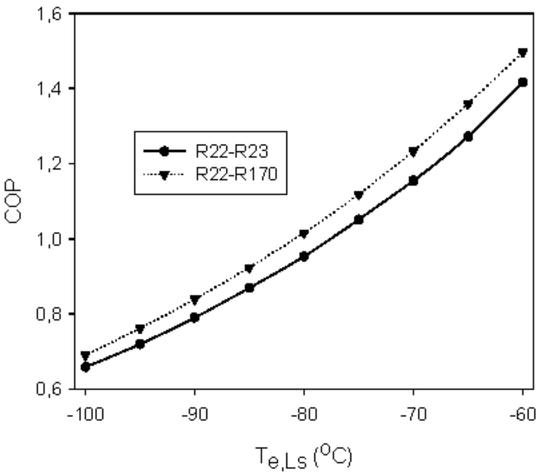

Fig. 9 Coefficient of performance of two stage cascade refrigeration system versus low stage evaporation temperature

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