COOLING SYSTEMS WORKING WITH NATURAL REFRIGERANTS

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Abstract

The use of natural refrigerants has attracted considerable interest in the past decade because of environmental concerns attached with CFC, HCFC and HFCs. This paper discusses potential cooling systems working with natural refrigerants. Single, two stage and cascade systems operating at different temperature levels were studied for both direct and indirect expansion. It was concluded that a single stage ammonia system offers the best COP for evaporating temperatures up -10°C. For evaporating temperatures up to -35°C a two stage ammonia system offers the best performance. A propylene two stage system is also applicable. For evaporating temperatures up to -45°C, propylene offers the best COP. Also in this temperature range an ammonia-CO_2 cascade system is a promising candidate. CO_2 operating as a secondly refrigerant can have significant cost advantages over glycol/brine systems. For evaporating temperatures below -70°C an ammonia-ethane cascade system is proposed. Various glycols and brines were analyzed for the indirect systems. It was concluded that natural refrigerants offer interesting refrigerant alternatives for energy efficient and environmentally friendly refrigerating equipments. However, safety precautions due to flammability must seriously be taken into account.

1. Introduction

Over the past years, there has been a growing interest in the use of natural refrigerants. This interest is mainly due to the phase-out of the ozone depleting substances as decided in the Montreal Protocol and the reduction in emission of green house gases as required by the Kyoto-Protocol in order to minimise global warming. Global warming is due to two effects, namely the direct and the indirect effect. The direct effect is caused by leakage of refrigerants from the refrigeration systems while the indirect effect is caused by CO_2 emissions from power plants that generate the energy used to run the refrigeration or heat pump systems.

Natural refrigerants reduce both effects and therefore contribute to the conservation of the environment. Natural refrigerants have global warming potentials (GWP) of less than 10 as compared to HFCs, which are currently used in many applications and have high GWPs.

This paper discusses potential cooling systems working with natural refrigerants. Single, two stage and cascade systems operating at different temperature levels are discussed for both direct and indirect expansion systems. Calculations show that a single stage ammonia system offers the best COP for evaporating temperatures up -10°C, while for evaporating temperatures up to -35°C a two stage ammonia system offers the best performance. For evaporating temperatures up to -45°C propylene offers the best COP. Also in this range an ammonia-CO_2 cascade system is a promising candidate while CO_2 operating as a secondly refrigerant can have significant cost advantages over other indirect expansion systems. For evaporating temperatures below -70°C an ammonia-ethane cascade system is proposed. Various glycols and brines were analyzed for the indirect systems.

For industrial applications, CO_2 is particularly interesting in cascade systems, in low temperature applications where it is used in the lower stage, and as a secondary refrigerant.

The very good transport and heat transfer properties of CO_2 combined with low compression ratios offer high overall efficiencies in heat pump, refrigeration or air-conditioning applications.

Use of CO_2 in industrial applications may lead to a reduction of ammonia use in such plants, thereby reducing burdens associated with approval procedures that large ammonia plants are subjected to in most countries.

CO_2 is abundantly available, cheap and the toxicity expressed as TLV of 5000 ppm compared to ammonia with a TLV of 50 ppm is low.

The good transport and heat transfer properties may result in smaller heat exchangers, compressors and pipings thereby reducing investment costs to some extent.

To further investigate the possibilities of a cascade system working with ammonia in the high stage and CO_2 in the lower stage, a plant was constructed and tests are being carried out.

2. Theoretical Investigation

Table 1. shows the operating temperature ranges of the natural refrigerants investigated.
The table includes boiling points, flammability limits, ASHRAE safety grouping and GWPs of the natural refrigerants. While natural refrigerants have very low GWPs, it can be seen that most of them are flammable and would be best applied in indirect expansion systems. Theoretical calculations in this section were performed for both direct and indirect expansions conditions. Table 2. shows the calculating conditions while the secondary refrigerants considered in this study are shown in table 3.

Table 1. Operating Temp. ranges and suitable Natural Refrigerants.

Room Temp. (Eva. Temp.) Application			Natural Refrigerant						Alternative Refrigerant (HFC)		
			R717 NH_3	R744 CO_2	R290 C_3H_8	R1270 C_3H_6	R170 C_2H_6	R729 Air	R404A	R410A	R23 CHF_3
0 ℃	(-10℃)	Refrigerator	◎	◎	◎	◎	×	×	◎	◎	×
-25 ℃	(-35℃)	Refrigerator	◎	◎	◎	◎	×	×	◎	△	×
-35 ℃	(-45℃)	Freezer	◎	◎	◎	◎	×	×	◎	×	×
-45 ℃	(-55℃)	Freeze-Dry	△	△	△	△	△	△	△	×	△
-70 ℃	(-80℃)	Tuna	×	×	×	×	◎	◎	×	×	◎
Boiling point			- 33℃	-56℃ (Trip pt)	-42℃	-47℃	-88℃	-194.3 ℃	-47℃	-52.7 ℃	-82℃
Lower Flammability Limit (% vol in air)			16-25 %	non	2.4-10.3 %	2.3-9.5 %	3.3-12.5 %	non	non	non	non
ASHRAE Standard 34 Safety group			B2	A1	A3	A3	A3	A1	A1/A1	A1/A1	A1
GWP(100yrs)			<1	1	3			0	3,850	1,370	12,000

◎ Applicable, △ Applicable limit, × Not Applicable

Table 1 shows that ammonia, Carbon dioxide, Propane and Propylene are applicable to evaporating temperatures of -40℃ and the applicable is -55℃. Below this evaporation temperature cascade systems with ethane or R23 in the lower stage are applicable. The high GWP of R23 makes ethane the lead candidate. Air is also interesting refrigerant in this temperature range.

Table 2 calculating conditions

Item	Two stage Cycle		Cascade cycle	
	Direct Exp.	Indirect Exp.	Direct	Indirect
Room Temp.	-25, -35, -50, -70 ℃			
Cond. Temp.	40 ℃			
Sub cool	5 ℃			
Temp. diff.	Inter mid. = 5 ℃		Cascade = 5 ℃	
Super heat	0 ℃			
Eva Temp.	room temp.-10	Room temp.-12	room temp.-10	room temp.-12

Table 3. Secondary Refrigerants considered in this study.

Secondary Refrigerant / Type Room Temp.		Propylene glycol	Calcium Chloride	Ethylene glycol	Ethyl alcohol	Potassium Formate	CO_2	Hydro fluoro ether	Silicon oil	Propane
			$CaCl_2$					HFE 7000		C_3H_6
Refrigerator	-25 ℃	△	◎	△	◎	◎	△	×	×	△
Freezer	-35 ℃	×	△	△	◎	◎	◎	×	×	△
FreezeDry	-45 ℃	×	×	×	◎	×	△	×	◎	◎
Tuna	-70 ℃	×	×	×	×	×	×	◎	◎	◎
Freezing Point ℃		<-50	-55	-50	-65	-55	-56 (Trp pt)	-130	-86	-42 (Bpt)
Applicable with foodstuff		Yes	×	×	Yes	×	Non Toxic	Toxic	×	Non Toxic
Closed System		—	—	—	Need	—	Need	Need	Need	Need

◎Applicable, △ Applicable Limit, ×Not Applicable

Table 3 shows that calcium chloride can be applied in applications with room temperatures up to –25℃, ethyl alcohol up to -45℃ and potassium based brines and carbon dioxide up to –35℃. The triple point of carbon dioxide is -56℃, therefore, the applicable room temperature limit in indirect expansion systems is -45℃ while for direct expansion it is –48℃. For room temperatures below -70℃, Hydro fluoro ether, silicon oil and propane are the applicable cooling mediums.

The table also shows secondary refrigerants applicable with food stuffs and those which need to be operated in closed systems only.

Table 4 and figures 1(a), (b), (c), (d) show a summary of the results of the cooling systems investigated. For evaporation temperatures up to -10℃ a single stage ammonia system is the best alternative. For evaporation temperatures up to -45℃ an ammonia compound system is the best alternative. A propylene compound or an ammonia/CO_2 cascade system are the best alternatives for evaporating temperatures of -55℃. In the ammonia/CO_2 cascade system, the good transport and heat transfer properties of CO_2 will result in smaller heat exchangers and pipings thereby reducing investment costs. For evaporation temperatures lower than -70℃ an ammonia/ethane cascade system is the best alternative.

Table 4 Summary of investigation results.

Type	Room Temp.	Eva. Temp	Cooling System			Remarks
			System	Direct Exp.	Indirect Exp.	
Refrigerator	0℃	-10℃	NH_3 Single stage	Dry	——	Ammonia flows through the freezer
				——	Propylene glycol Potassium Formate	
Refrigerator	-25℃	-35℃	NH_3 Compound	Dry	——	Ammonia flows through the freezer
				——	CO_2 Potassium Formate	CO_2 leakage : anoxia
Freezer	-35℃	-45℃	NH_3 Compound	Dry	——	Ammonia flows through the freezer
				——	CO_2 Ethanol	Not directly applicable with food stuff
Freeze-Dry FD	-45℃	-55℃	NH_3/CO_2 Cascade	Dry Liquid Pump	——	CO_2 leakage : anoxia
			Propylene Compound	——	CO_2	CO_2 leakage : anoxia
Tuna (SF Class)	-70℃	-80℃	NH_3/Ethane Cascade	——	Hydrofluoro ether Silicon oil	Silicon Oil : PRTR

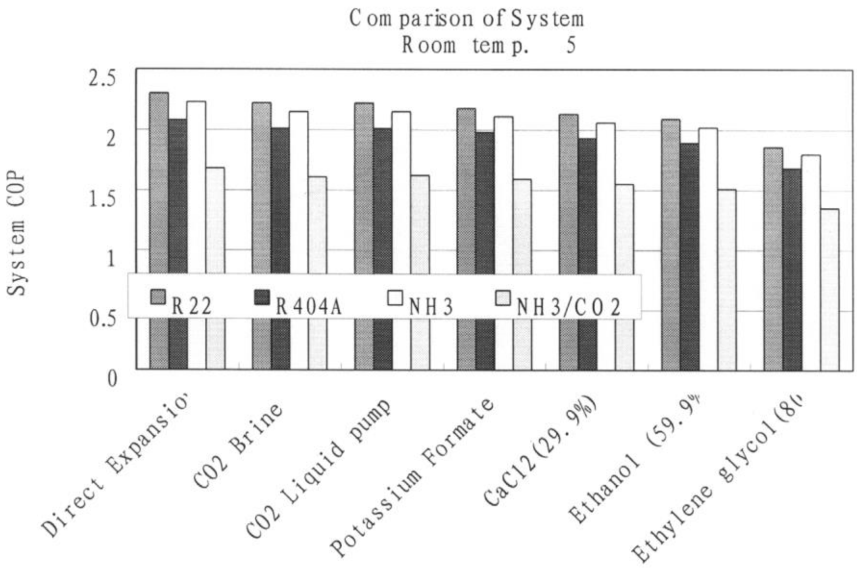

Fig.1(a) Comparison of system COP for room temp.-25℃

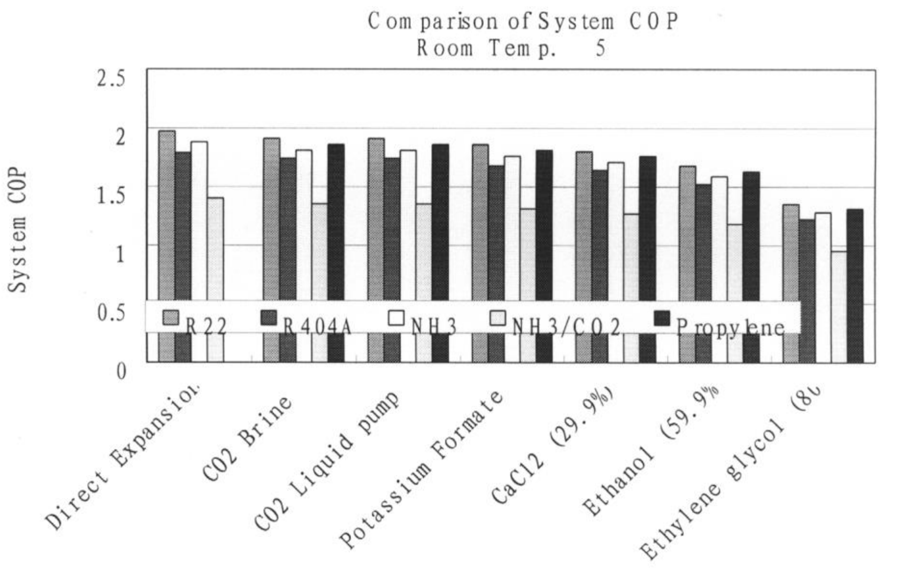

Fig.1(b) Comparison of system COP for room temp.-35℃

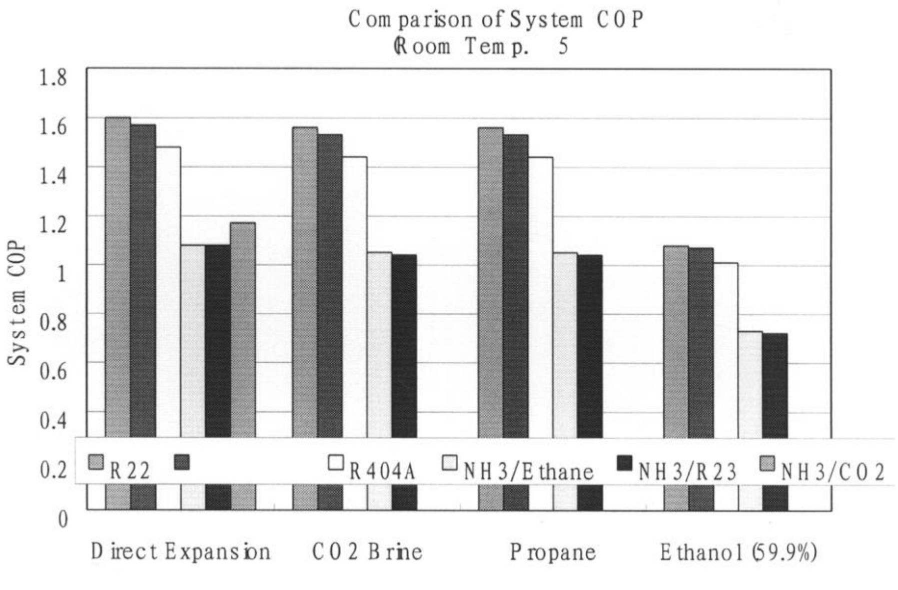

Fig.1(c) Comparison of system COP for room temp.-45℃

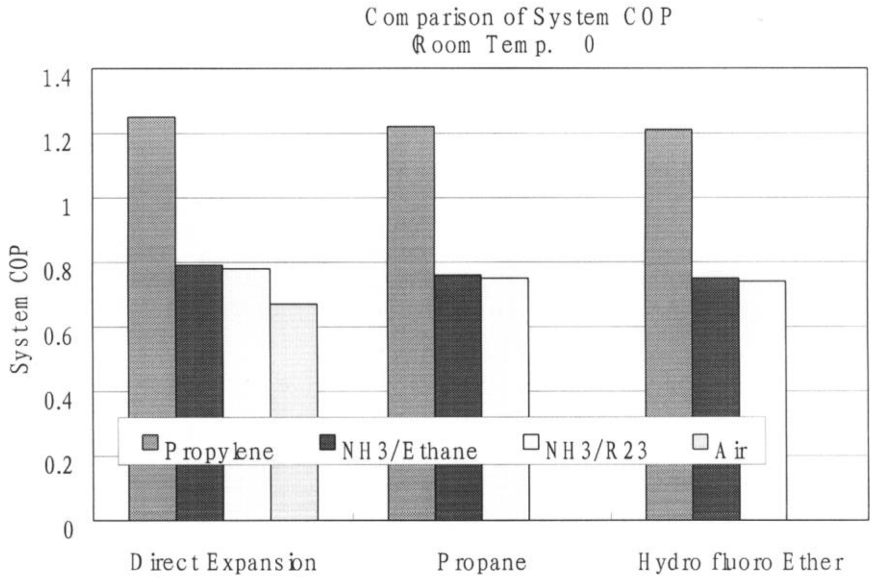

Fig.1(d) Comparison of system COP for room temp.-70℃

3. Cascade Plant

The good transport and heat transfer characteristics of CO_2 show potential possibilities of investment cost reductions in cascade plants working with ammonia in the high stage and CO_2 in the lower stage. As shown in fig.1(c) the system COP of an ammonia/ CO_2 cascade direct expansion system when fully investigated can compete well with an ammonia or propylene compound system.

A cascade system working with ammonia in the high stage and CO_2 in the lower stage was constructed and tests are being carried out. Specifications of the system are shown in table 5.

Table 5 Specifications of the Ammonia/ CO_2 Cascade system.

High Stage Compressor	Ammonia Screw Model: N125LUD-M Cond. Temp. : 35℃ (1.35MPa) Eva.Temp. : -19.8℃ (0.192Mpa)
Low Stage Compressor	CO_2 Screw Model: C125SUD-L Cond.Temp. : -14.8℃ (2.30Mpa) Eva. Temp. : -54℃ (0.578Mpa)
Cooling Capacity	81.2 kW
Power	80 kW
COP	1.01
Type of Cooling	High stage : Direct Exp.(Dry) Low stage : Liquid Pump

The system is mainly composed of oil injection screw compressors both in the low and high stages, a high stage shell and tube condenser, a shell and tube cascade condenser, low stage receiver, oil separators, an evaporator, and a CO_2 liquid pump. The flow of the system is shown in figure2.

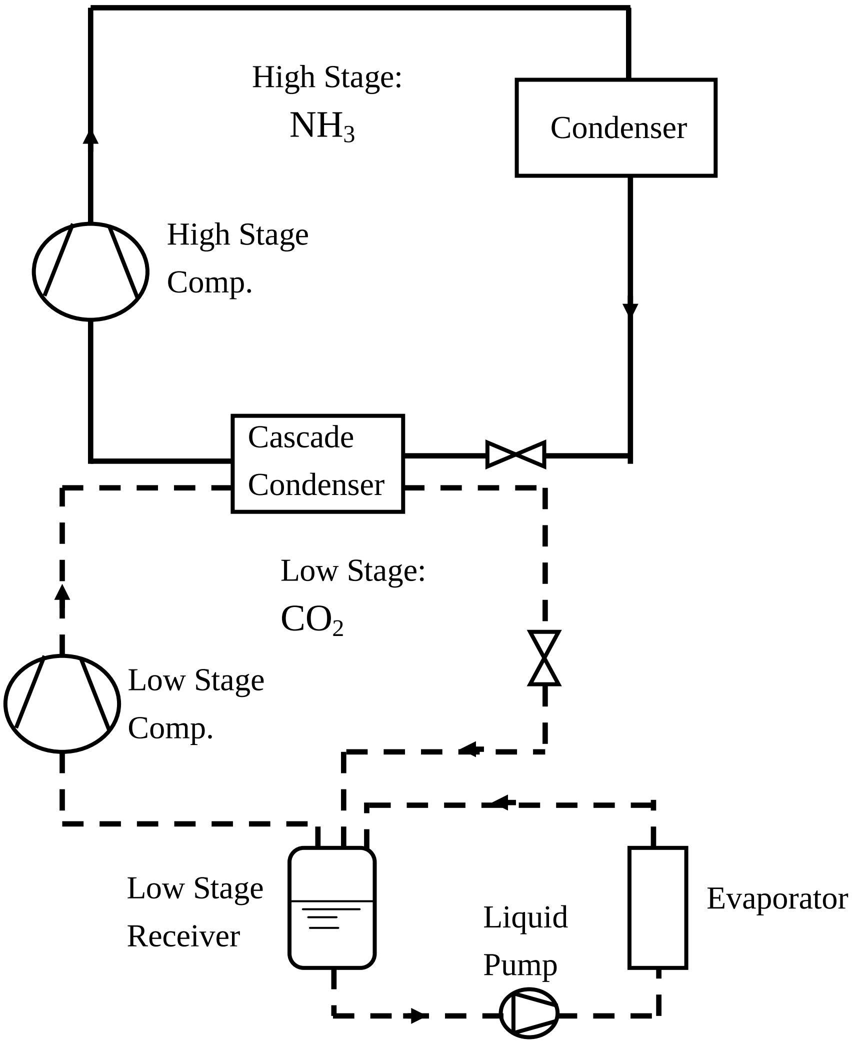

Fig. 2. Flow of the Ammonia/ CO_2 Cascade system.

Saturated CO_2 vapor from the low stage receiver is compressed to the low stage condensation pressure by the low stage compressor. The discharged gas from the low stage compressor is liquefied in the cascade heat exchanger, where heat is exchanged with ammonia in the high stage. Liquid CO_2 from the cascade heat exchanger is expanded to low temperature and pressure through the expansion valve and released into the low stage receiver. From the low stage receiver, liquid CO_2 is pumped to the evaporator where it is evaporated and returned to the receiver.

In the high stage, ammonia vapor leaving the cascade heat exchanger flows into the high stage compressor where it is compressed to high temperature and pressure. The discharged gas from the high stage compressor flows through the condenser where it is condensed, to the expansion valve where it is expanded to low temperature and pressure and into the cascade heat exchanger where it is evaporated, thus competing the cycle.

4. Conclusions

Theoretical and experimental investigations have been carried out on cooling systems working with natural refrigerants. The following conclusions were reached.

1) Single stage ammonia system offers the best COP for evaporating temperatures up -10°C.
2) For evaporating temperatures up to -35°C a two stage ammonia system offers the best performance.
3) For evaporating temperatures up to -45°C propylene offers the best COP. Also in this range an ammonia-CO_2 cascade system is a promising candidate while CO_2 operating as a secondly refrigerant can have significant cost advantages over glycol/brine systems.
4) For evaporating temperatures below -70°C an ammonia-ethane cascade system is proposed.
5) Natural refrigerants offer interesting refrigerant alternatives for energy efficient and environmentally friendly refrigerating equipments. However, safety precautions due to flammability must seriously be taken into account.
6) A cascade plant working with ammonia in the high stage and CO_2 in the lower stage was constructed and tests are being carried out.

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