R744 (CO2) Refrigerant Cooling Systems and Their Performances

İ. Ekmekci
Department of Industrial Engineering, İstanbul Commerce University, İstanbul, Turkey

Abstract

Natural refrigerants are the most significant alternatives in refrigeration systems nowadays. The CO_2 presents an effective solution regarding with environmental effects and CO_2 has been widely used in the developing stages of the cooling industry. However, it has been replaced by halocarbon refrigerants due to the drop in coefficient of performance that emerge due to heat transfer around and above the critical point, as well as high operating pressures. The harmful effects of halocarbon refrigerants on the environment have in turn led to a return to CO2 as an alternative, natural refrigerant. The current machine and exchanger technology, and system control elements have enabled CO2 to reach competitive levels in terms of efficiency particularly in northern countries through the transcritical cycle, and in the southern countries through the subcritical cascade cycle. Due to its low critical temperature and high critical pressure, R744 (CO2) has some additional technical requirements to other conventional refrigerants. In this study, thermophysical properties, required cycles, benefits and disadvantages of CO_2 have been discussed.

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1. Introduction

Natural refrigerants that do not have an effect on global warming and do not harm the ozone layer are without a doubt the most significant alternatives in refrigeration. The CO2 gas presents itself as an effective solution at this point. CO2 has been widely used in the developing stages of the cooling industry. However, it has been replaced by halocarbon refrigerants due to the drop in coefficient of performance that emerge due to heat transfer around and above the critical point, as well as high operating pressures [1]. The harmful effects of halocarbon refrigerants on the environment have in turn led to a return to CO2 as an alternative, natural refrigerant. The current machine and exchanger technology, and system control elements have enabled CO2 to reach competitive levels in terms of efficiency particularly in northern countries through the transcritical cycle, and in the southern countries through the subcritical cascade cycle. Due to its low critical temperature of 31.06°C and high critical pressure of 73.8 bars, R744 (CO2) has some additional technical requirements to other conventional refrigerants.

2. R744 (CO2) As Refrigerant

The use of R744 (CO2) as refrigerant was first suggested in 1850 by the Alexander Twining of Britain. Yet the first CO2 refrigerated system was built toward the end of the 1860's by the American Thaddeus S.C. Lowe. It was widely used in ships and industry until the 1920's due to its clean and reliable nature. With the advent of CFC's in 1928, CO2 was gradually pushed out of the market, and was no longer used in the 1950's. The increasing restrictions on CFC's toward the end of the 20th century have led to new pursuits, causing old natural refrigerants such as CO2 and NH3 to be revisited. Proffesor Gustav Lorentzen's patenting of the transcritical CO2 cycle in 1990 was a milestone in this subject [2].

2.1. Environmental Properties of CO2

There are two basic concepts regarding the environmental properties of refrigerants.

1. ODP (the Ozone Depletion Potential): Denotes the damage that a gas can have on the ozone layer. It is expressed as a relative figure [3].

2. GWP (the Global Warming Potential): It is a measure of the impact of a greenhouse gas on the environment over a specific time interval in relation to CO2 , taking the GWP of CO2 as 1 [3].

Table.1: Enviromental Properties of Various Widely Known Refrigerants [6]			
Refrigerant	**Refrigerant Classification**	**ODP**	**GWP**
R 11	CFC	1	4600
R 12	CFC	0,82	10600
R 22	HCFC	0,034	1700
R 134a	HFC	0	1300
R 410a	HFC	0	1980
R 404a	HFC	0	3780
R 407c	HFC	0	1650
R 507a	HFC	0	3850
R744 (CO_2)	***Naturel Refrigerant***	***0***	***1***
R 717 (NH_3)	*Naturel Refrigerant*	0	<1
ODP: (R11=1 admitted) GWP: (CO_2=1 admitted)			

CO_2 has an ozone depletion potential of zero (ODP=0) and has very low direct impact on global warming (GWP=1). Table 1 shows the environmental properties of common refrigerants.
Another concept exists in the literature in addition to ODP and GWP: the Total Equivalent Warming Impact (TEWI). The Total Equivalent Warming Impact (TEWI) denotes the direct or indirect global warming impact of the refrigerant and the system of which it is part. The impact that the refrigerant has on the environment is the direct impact. The CO_2 emission that occurs during the supply of energy to the cooling system of which it is a part is the indirect impact. The sum of the two impacts is defined as the Total Equivalent Warming Impact (TEWI). CO_2 as a refrigerant is effective in reducing total equivalent warming impact in cooling systems [4].

2.2. CO2 Safety

Refrigerants are collected in 2 groups with respect to toxicity. Class A rating indicates no evidence of toxicity below 400 ppm. Class B rating indicates evidence of toxicity below 400 ppm. CO_2 is included in Class A, which indicates no toxicity at concentrations below 400 ppm [5]. Refrigerants are divided in 3 classes in terms of flammability. Class 1 indicates a refrigerant which will not burn in the flammability test under conditions of 21°C and 101 kPa pressure. Class 2 indicates refrigerants that is mildly flammable and produces a combustion heat of less than 19 kJ/kg under conditions of 21°C and 101 kPa pressure. Class 3 indicates refrigerants that is highly flammable and produces a combustion heat of more than 19 kJ/kg under conditions of 21°C and 101 kPa pressure. CO_2 is rated as Class 1, as inflammable [5]. Although CO_2 has been described as non-toxic, it has some physical effects on people depending on its concentration in the air. When the volume concentration of CO_2 in the air is between 2 and 3%, rapid breathing and mild headache may be experienced. The Immediately Dangerous to Life or Health (IDLH) concentration has been fixed at 4% and the lethal concentration has been declared as 10%. In practice the %5 limit for CO_2 volume in the air is a quite reasonable figure [9]. Consequently designs should be based on these limits, and the damage on living things in case of an accident or leak should be minimised. Table 2 shows the safety classification of common refrigerants.

2.3. Thermophysical Properties of CO_2

The properties of the refrigerant are very important in designing a refrigeration system. CO_2 is known to have different properties than other conventional refrigerants. In comparison, the most

Table.2: Safety Classification of Various Widely Known Refrigerants [8]										
Refrigerant	R 11	R 12	R 22	R 134a	R 410a	R 404a	R 407c	R 507a	***R744 (CO_2)***	R 717 (NH_3)
Toxicity	A	A	A	A	A	A	A	A	***A***	B
Flammable	1	1	1	1	1	1	1	1	***1***	2

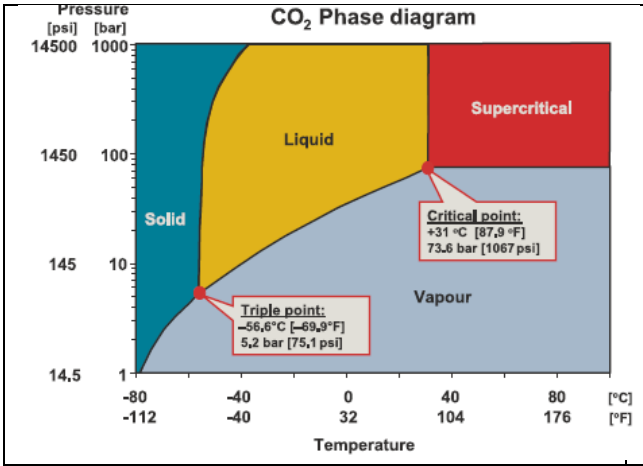


Figure.1: CO_2 Phase Diagram [7]

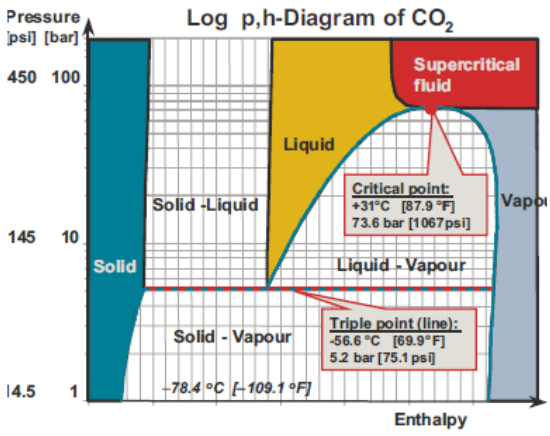


Figure.2: CO_2 lnP – h Diagram [7]

remarkable property of CO_2 is its low critical temperature (31.06°C) and high critical temperature (73.8 bar). Another limiting factor in the application of CO_2 is its high triple point that occurs at -56.6°C and 5.1 bar pressure. Also in comparison with conventional refrigerants (CFC, HCFC, HFC, HC), it has a fairly high steam pressure and volumetric heat transfer capacity (22545 kJ/m^3 at 0°C') [6]. As can be seen from the CO_2 phase diagram, there are three conditions where two phases are in equilibrium: Solid-Gas, Solid-Liquid, and Liquid-Gas equilibrium states. CO_2 can only exist as a solid or gas under atmospheric pressure. The liquid phase is not possible at this pressure. Above this temperature, CO_2 sublimates, transitioning to the gaseous phase. 5.2 bar and -56.6°C are the conditions where all states of CO_2 are in equilibrium. The three states of the substance are in equilibrium under these conditions. CO_2 reaches the critical point at 31.1°C. At this point, the densities of the liquid and gas phases are equal and the difference between the two phases disappears. A new phase emerges as a result. This phase of matter is called the supercritical phase. Figure 1 shows the CO_2 Phase Diagram, while Figure 2 shows the CO_2 In P-h Diagram.

As shown in Table.3, CO_2 has desirable thermophysical properties and lower viscosity, higher volumetric capacity, higher thermal conductivity, and higher steam density than similar halocarbon refrigerants.

2.4. Cost of the CO_2 Refrigerant

Table 4 shows a comparison of the prices of common refrigerants. It is seen that CO_2 as a natural refrigerant has a much lower cost than conventional refrigerants.

3. BASIC CO_2 REFRIGERATION CYCLES

CO_2 refrigeration systems have two types of basic cycles: Subcritical and Transcritical. In the cycle

Table 3. Thermophysical Properties of Various Widely Used Refrigerants [8]

Refrigerant	T_{crit} (°C)	P_{crit} (bar)	Liquid Phase Density ρ_f, (kg/m3) [a]	Gas Phase Density (kg/m3) [b]	Specific Heat Capacity cp, (kJ/kg) [a]	Volumetric Capacity (kJ/m3) [a]	Thermal Conductivity k (W/m.K) [a]	Dynamic Viscosity μ, (mPa.s) [a]
R 11	198	44,1	1536,9	2,36	0,85	450,76	0,09	0,5
R 12	112	42,2	1400,1	17,185	0,93	2636,52	0,62	0,25
R 22	96,2	49,9	1285,7	20,41	1,16	4205,28	0,09	0,22
R 134a	101,1	40,6	1298,9	13,9	1,3	2773,75	0,09	0,27
R 410a	72,13	49,3	1175	28,82	1,5	6566,35	0,1	0,16
R 404a	72	37,3	1154,8	29,91	1,3	4953,99	0,07	0,18
R 407c	86,74	46,2	1240,8	18,86	1,4	3973,24	0,01	0,21
R 507a	70,6	37,05	1161,1	30,98	1,37	5055,32	0,072	0,18
R744 (CO_2)	***31***	***73,7***	***934,26***	***94,148***	***2,5***	***22089,00***	***0,11***	***0,101***
R 717 (NH_3)	132,3	113,3	640,28	3,31	4,41	4192,51	0,56	0,172

[**a**] For saturated liquid at -1,1°C**;** [**b**] For saturated vapor at -1,1°C

Table 4. Cost Comparison of Widely Known Refrigerants [9]

R134a	R404a	R407c	R410a	R507	***R744 (CO_2)***	R717 (NH_3)
9,38 €/kg	8,85 €/kg	10,68 €/kg	9,58 €/kg	19,53 €/kg	0,52 €/kg	1,3 €/kg

known as Subcritical, the pressure is below the critical point throughout the cycle. In the Transcritical cycle, heat transfer to the environment occurs above the critical point.

3.1. Subcritical Cycle

3.1.1. Direct Expansion CO_2 Subcritical Cycle

The subcritical cycle is the most commonly used system in the refrigeration industry. All temperatures and pressures are below the critical point, and above the triple point. The single stage subcritical CO_2 cycle is a fairly simple system. However, it has some disadvantages such as a limited temperature range and high pressure. The low condensation temperature makes heat transfer to the environment more difficult. The operating pressure is around 60 bar [10].

3.1.2. CO_2 Subcritical Cascade Cycle

The CO_2 cascade system is a refrigeration cycle which consists of two separate refrigerants that do not intermingle. One of the two cycles is usually the compression cycle and the cycle where heat transfer to the outside occurs. In these systems, the most widely used refrigerant is R717 (NH_3, ammonia), which if followed by R404A and other suitable HFC refrigerant. The operating pressure in this type of system is about 40-45 bar. A different feature of cascade systems is that while CO_2 condenses in the heat exchanger known

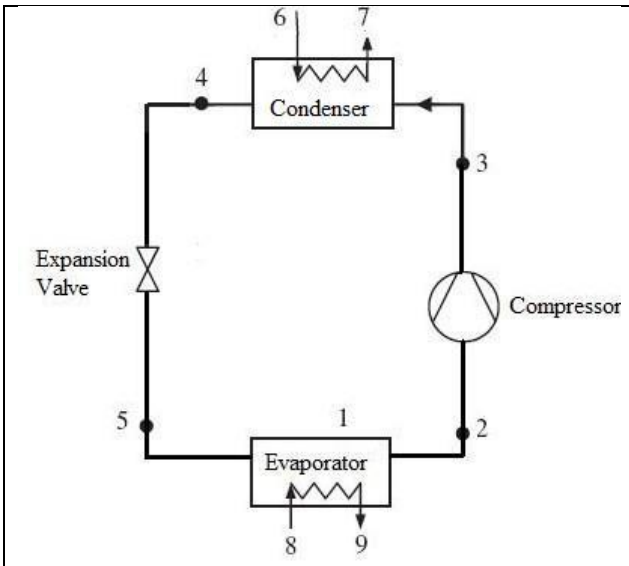


Figure 3. Direct Expansion CO_2 Subcritical Cycle [11]

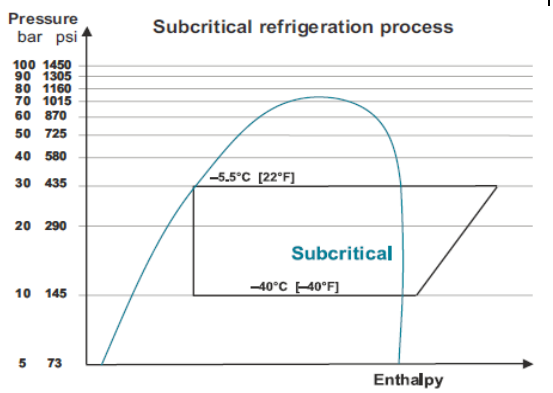


Figure 4. Direct Expansion CO_2 Subcritical Cycle ln P – h Diagram [7]

as the cascade condenser, the refrigerant on the high temperature side evaporates. This type of heat exchanger can be plate type or shell and tube type [13].

3.2. CO_2 Transcritical Cycle

3.2.1. CO_2 Transcritical Cycle

CO_2 has a low critical temperature of 31.06 °C and a high critical temperature of 73.8 bar. As is the case in conventional steam compression cycles, it is not possible for the refrigerant to reject heat to the atmosphere by condensing in the condenser. Heat transfer to the environment in the supercritical area, as the temperature of gaseous CO_2 drops without condensation. Cycles that occur in this way are called "transcritical CO_2 cycles" [3]. Hence, the gas cooler replaces the condenser in the system. In the Transcritical CO_2 cycle, the compressed CO_2 in the compressor rejects its heat to the atmosphere in the gas cooler.

3.2.1.1. Simple One Stage Transcritical Cycle with Internal Heat Exchanger

An internal heat exchanger is used to increase efficiency in transcritical systems. To increase the EER of the exchanger system, this lowers the gas cooler outlet temperature while serving as an accumulator to prevent liquid leaking to the compressor, ensuring that there is gas at the evaporator outlet.

3.2.1.2. Simple Gas Bypass Transcritical Cycle with Internal Heat Exchanger

Gas bypasses are also included in designs to increase the efficiency of transcritical systems. Unlike conventional systems, a second expansion valve is added to the system. While the first expansion occurs from the gas cooler to the liquid tank, the liquid and gas states occur here. Afterwards, the liquid is once again brought to the desired evaporation temperature. In these systems, the dryness at the evaporator inlet is decreased due to the second expansion, thus increasing the EER of the system, while the connection of the system with the outside environment is reduced since a liquid tank is used in the intermediate pressure stage. The system also includes a balancing valve. Since this valve regulates the pressure level in the liquid tank, the temperature before the expansion valve, and therefore the inlet enthalpy of the evaporator are regulated.

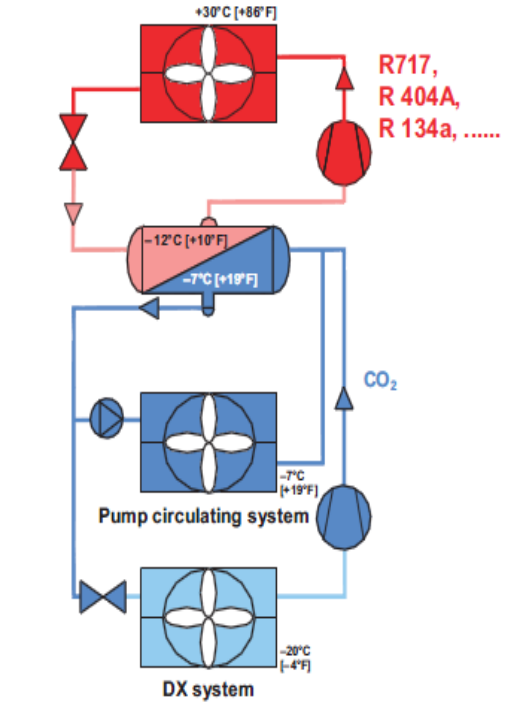
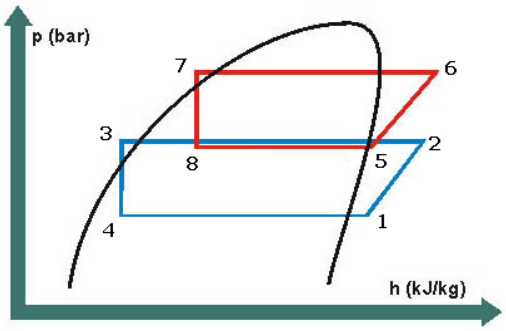


Figure 5. Subcritical CO_2-717/R404A/R134A Cascade Cycle Diagram [12]



1-2 Isentropic compression in the CO_2 compressor
2-3 Isobaric condensation of CO_2 in the Cascade Condenser (shell and tube)
3-4 Expansion of liquid CO_2 in the Expansion Valve
4-1 Isobaric evaporation in the Subcritical Evaporator
5-6 Isentropic compression in the R717/R404A/R134A etc. Compressor
6-7 Isobaric condensation in the R717/R404A/R134A etc. Condenser
7-8 Isenthalpic expansion in the R717/R404A/R134A etc. Expansion Valve
8-5 Isobaric evaporation of NH3 in the Cascade Condenser (shell and tube)

Figure 6. Subcritical CO_2 - 717/R404A/R134A Cascade Cycle In P - h Diagram [14]

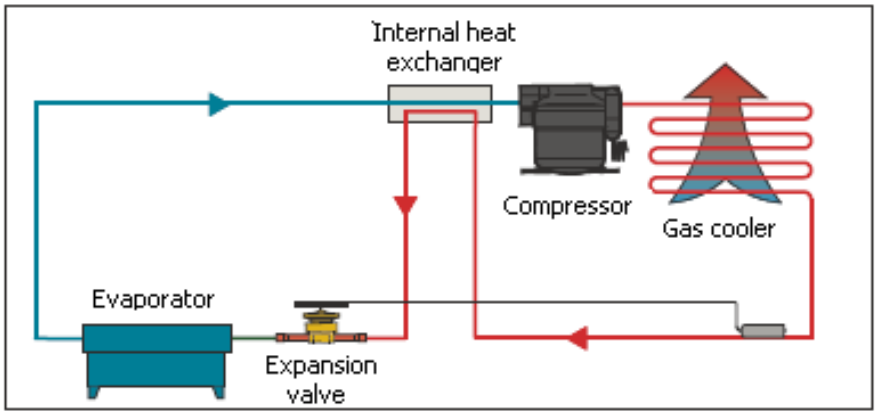
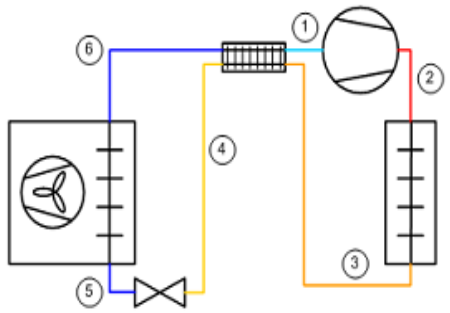


Figure 9. One Stage Transcritical Cycle with Internal Heat Exchanger

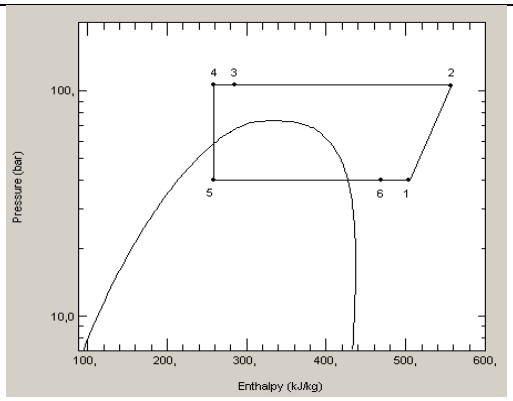
4. Comparision of CO_2 Refrigerant Systems

Studies conducted in recent years on CO_2 Transcritical Refrigeration systems indicate that this cycle is more profitable particularly in temperate and cold climates. The reason that stresses this opinion is the fact that the system EER is higher in regions with lower outdoor ambient temperatures. The TESCO supermarket chain in the UK and the FAKTA supermarket chain in



1-2 Isentropic compression compressor
2-3 Isobaric heat transfer in the Gas Cooler
3-4 Refrigeration in the Internal Heat Exchanger
4-5 Isenthalpic expansion in the Expansion Valve
5-6 Isobaric evaporation in the Transcritical Evaporator
6-1 Superheating in the Internal Heat Exchanger

Figure 10. One Stage Transcritical Cycle with Internal Heat Exchanger



Figure,11: CO_2 Transcritical Cycle with Internal with Heat Exchanger ln P – h Diagram

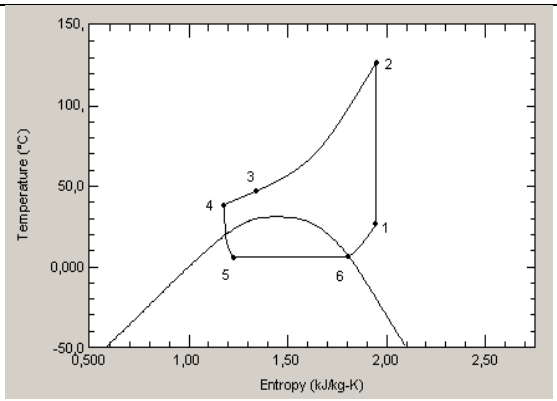
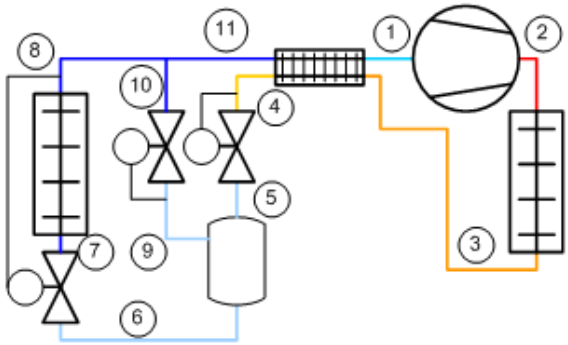


Figure.12: CO_2 Transcritical Cycle with Internal Heat Exchanger T-S Diagram

Denmark are leaders in Europe in terms of CO_2 Transcritical Refrigeration applications. Even in periods where summers are warm, the energy expended in CO_2. Transcritical refrigeration systems in these countries have been observed to be close to conventional systems. The energy saving comparisons of the R404A single stage system and the CO_2 Transcritical system in major European cities based on average annual temperatures are shown below on the geographic map of Europe. R744 refrigeration systems have been shown to be more efficient in temperate and cold climates with medium and low temperatures. The use of cascade systems is recommended in regions with very warm climates. Efforts to achieve higher efficiency coefficients and increases in efficiency in supermarket systems that combine deep-freezing with normal refrigeration are in progress. Furthermore, it is predicted that efforts to increase efficiencies through evaporative condenser systems in warm climates will intensify in the years to come.

5. Conclusion

For along time, CFC and HCFC refrigerants have been widely used in refrigerant systems that are an absolute necessity in all areas of life, from the past to the future. Since these chemical gases cause a greenhouse effect, they exacerbate the problem of global warming. For this reason, a search has begun for new alternatives in refrigerants. Among natural refrigerants that are in the limelight, CO_2 applications are becoming more widespread. The ozone depletion factor of the R744 gas is zero, and its global warming potential is one. Aside from being very cheap, it is also easy to procure. Its most significant properties are its high volumetric cooling capacity and its thermal properties. This facilitates a reduction in the intake and discharge lines of the tubing to other conventional refrigerants due to its low critical temperature of 31.06°C and high critical



1-2 Isentropic compression compressor
2-3 Isobaric heat transfer to the environment in the Gas Cooler
3-4 Refrigeration in the Internal Heat Exchanger
4-5 Isenthalpic expansion in the Expansion Valve
5- Separation of the liquid and gaseous phases in the Receiver
6-7 Isenthalpic expansion of liquid in the Expansion Valve
7-8 Isobaric evaporation in the Transcritical Evaporator
9-10 Isenthalpic expansion in the Expansion Valve
11-1 Superheating in the Internal Heat Exchanger

Figure 13. CO_2 Gas Bypass CO_2 Transcritical Cycle with Internal Heat Exchanger [17]

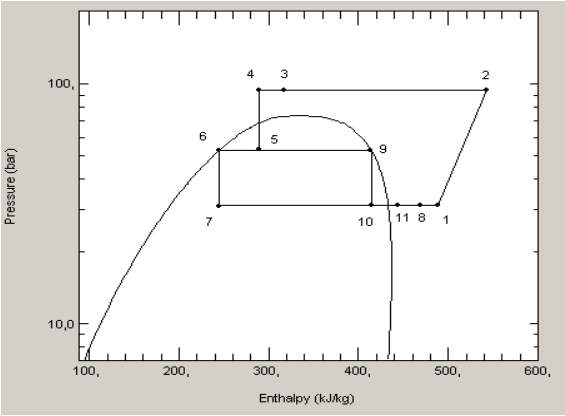


Figure.14: Gas Bypass CO_2 Transcritical Cycle with Internal Heat Exchanger ln P – h Diagram

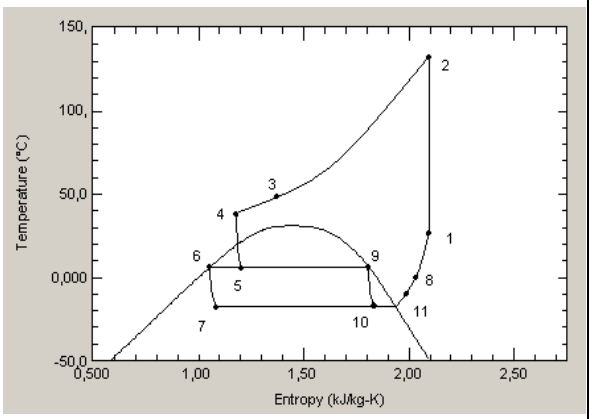


Figure.15: Gas Bypass CO_2 Transcritical Cycle with Internal Heat Exchanger T-S Diagram

pressure of 73.8 bars. To make sure that the very high critical pressure as compared to other gases does not create problems particularly in terms of safety, the mechanical strength of the system equipment used should be increased. The low critical temperature makes operation of the system's discharge line difficult particularly in countries with temperate and warm climates. This is eliminated by cascade system applications and optimization of gas cooler applications above the critical temperature. As can be seen from the studies above, the selection of the system that is compatible with design conditions becomes important. Particularly in more temperate and colder climates, subcritical and transcritical systems operate with higher efficiency. In warm climates on the other hand, CO_2 cascade applications are more efficient. Software development efforts required for the design of evaporators and gas coolers –among the most important components of the system- were conducted.

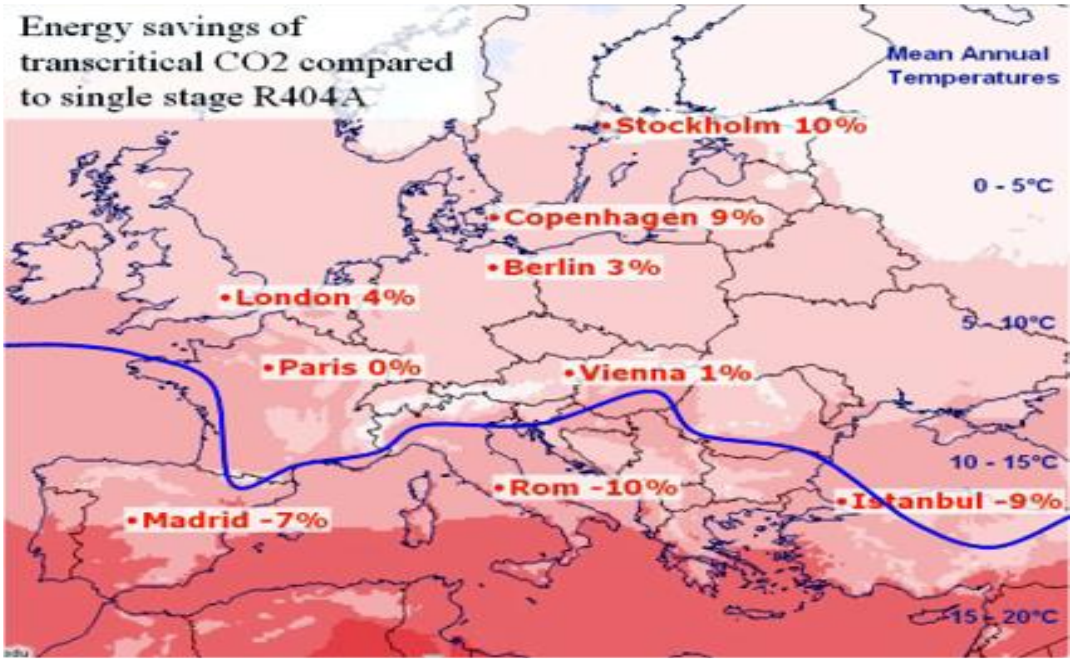


Figure 16. Comparison of the R744 (CO_2) Transcritical Refrigeration System Efficiency with the R404A gas in the European region [19].

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