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# POSSIBLE CONFIGURATIONS OF MULTIEJECTOR DRIVEN CO2 SYSTEMS FOR INDIAN SUPERMARKETS

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## ABSTRACT

An Integrated $CO_2$ Refrigeration Facility is designed for hot climate conditions to improve the basic knowledge of the $CO_2$ refrigeration in India, especially in the supermarket sector. The operational modes can be adapted to simulate different applications. The gas cooler outlet temperature can be regulated to simulate various ambient conditions. For Southern India, a parallel compression configuration with ejectors for expansion work recovery is the most efficient mode. It can deliver and perform freezing, refrigeration and air conditioning loads, and has a heat reclaim option. The different operation configurations help to understand the behavior of $CO_2$ refrigeration for a wide range of applications as well as reveal the respective influences between components. The most interesting is, the possibility to demonstrate the feasibility of R744 transcritical systems as a non-HFC based alternative to HCFC-22 in retail applications in countries with high ambient temperature. The $CO_2$ refrigeration test facility is a preparation and demonstration site for a full-scale replacement of existing commercial refrigeration installations in India.

Keywords: Refrigeration System, R744, Carbon Dioxide, Transcritical Cycle, Multi-Ejector

## 1. INTRODUCTION

Worldwide it is committed to eliminate the usage of ozone depleting HCFC and HFCs due to their high global warming potential (GWP). Therefore, the development of energy efficient and integrated refrigeration and air-conditioning (A/C) systems based on natural working fluids, adapted to the climatic conditions in India, is necessary. A supermarket multifunctional test facility using $CO_2$ as the only working fluid is designed to improve the basic knowledge of $CO_2$ refrigeration and its applications, especially for the supermarket sector. The operational mode can be changed simulating different applications as well as the gas cooler outlet temperature to simulate various ambient conditions. For high ambient temperature regions like Southern India, a parallel compression configuration with ejectors for expansion work recovery is the most efficient mode. It can deliver and perform freezing, refrigeration and air conditioning loads, and has a heat reclaim option. Higher ambient temperature conditions can be simulated by reducing the rotational speed of the gas cooler fans. For each ambient temperature the receiver pressure can be manually controlled maintaining the A/C evaporating temperature. By changing the glycol inlet temperature of the evaporators the particular evaporating temperatures can be adjusted. All those different configurations resulting in the possibility to understand the behavior of $CO_2$ refrigeration for a wide range of applications as well as the respective influences between components. The most interesting is the

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possibility to demonstrate the feasibility of R744 transcritical systems as a non-HFC based alternative to HCFC-22 in retail applications in countries with high ambient temperature. The newly commissioned $CO_2$ refrigeration test facility at IIT Madras, Chennai, India, is a preparation and demonstration site for a full-scale replacement of existing commercial refrigeration installations in India.

In this paper, the advantage of R744 as a refrigerant, the purpose of the test facility as well as the different modes and their possible applications are described. Especially the mode for South Indian conditions is amplified here. The results of first experiments run at the CO2 test facility at IIT Madras are listed and evaluated in paper Blust et al, 2018.

## 2. COMPARISON OF R744 WITH OTHER REFRIGERANTS

Carbon dioxide, R744, is a natural refrigerant with no ozone depletion potential (ODP) and negligible global warming potential (GWP). It is neither toxic nor flammable resulting in an ASHRAE safety classification of A1, i.e the only low GWP and nonflammable A1 fluid registered. Based on these facts R744 is a favorable refrigerant compared to R717 being toxic and flammable, R1234yf being flammable, as well as R22 and R404a having a high GWP (Table 1). R744 transcritical units can be adapted for high ambient temperature conditions, however, $CO_2$ systems fit especially for fast freezing and De-icing applications, domestic hot water production and as a secondary fluid or even in cascade systems using carbon dioxide is an efficient and effective refrigerant mainly on the low and medium temperature part.

**Table 1** Comparison of the natural refrigerant R744 and R717 with HCFC, HFCs properties [Emerson, 2015; ASHRAE, 2017; BOC]

| Classification | Natural | Natural | HCFC | HFC | Unsaturated HFC |
|---|---|---|---|---|---|
| Refrigerant | R744 | R717 | R22 | R404A | R1234yf |
| Name | Carbon dioxide | Ammonia | Chlorodifluoromethane | | Opteon YF |
| ODP | 0 | 0 | 0.055 | 0 | 0 |
| GWP | 1 | 0 | **1810** | **3920** | 4 |
| Classification | A1 | **B2** | A1 | A1 | **A2L** |
| Flammability | NO | **YES (low)** | NO | NO | **YES** |
| Toxicity | NO | **YES** | NO | NO | NO |
| Critical Point [bar]; [°C ] | 73.8; 31.1 | 112,8; 132.4 | 49.36; 96.2 | 34.7; 72 | 33.8; 94.7 |
| Application | Fast freezing and De-icing; Cascade; Secondary loop; Domestic hot water heating (high temp lift) | Low / medium / high temperature region; Transport / industrial refrigeration | Low / medium / high temperature region; Commercial / industrial refrigeration Total ban by 2020 (developed countries), 2040 (developing countries)[2] | Low / medium temperature region; Commercial / industrial refrigeration | Domestic refrigeration; Mobile air conditioning |

## 3. CO2 / R744 PROPERTIES

Considering the theoretical $CO_2$ properties only, such as low critical temperature, high critical and high operational pressure, it is not a favorable refrigerant. However, practically these properties are advantage for many applications. In Table 2 a comparison of the theoretical and practical properties is shown.

[2] ~0.5% of base level consumption until 2030 to service existing equipment [Ozone Cell, 2009]

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| **Table 2** Comparison theoretical and practical CO2 properties. [Emerson, 2015] | |
|---|---|
| Theoretically | Practical |
| Low Critical Temperature (T=31.1°C) | Heat Rejection at Transcritical Pressures ($CO_2$ rejects heat at gliding temperatures -> favorable for high temperature lifts of the cooling fluid);<br>No condensation above 28 °C;<br>Fluid exit temperature up to 90 °C;<br>High pressure lift => high temperature lift (10- 90 °C);<br>Heat transfer coefficient changes with temperature<br>->Gas cooler divided in 3 parts; (water- and space heating) |
| Low COP During Subcritical Operation:<br>Large throttling losses<br>If GC outlet temperature is high;<br>If condensation temperature close to critical point | High COP in Transcritical Region:<br>Low pressure ratio ($p_{GC}/ p_e$)<br>->Compressor work at high efficiencies;<br>Low temperature loss ($\Delta T/\Delta p$)<br>->Heat exchanger design for large $\Delta p$, enhanced heat transfer, low temperature approach and temperature difference |
| High operational pressure (5-10 times higher than for HFC)<br>Large volumetric expansion coefficient for liquid CO2<br>->Liquid/vapor mixture expand with 25% while heating from -10 to 20 °C | High vapor density<br>-> Lower compressor ratio<br>-> Small compressor volume needed;<br>-> Efficiency increase<br>Low temperature loss ($\Delta T/\Delta p$) due to pressure loss<br>->Heat exchanger dimensioned for high velocities<br>Large volumetric heat capacity for liquid $CO_2$<br>->Partly compressible liquid close to critical point<br>Peak of heat capacity at critical point;<br>Low viscosity<br>->Compact system; small dimension for pipelines and valves; 20-40% lower weight despite higher wall thickness; compact |
| High critical pressure (p=73.8 bar); Triple point above atm (p=5.18 bar);<br>Possibility of dry ice formation ($T_s$= -78.5°C in atmospheric conditions);<br>Evaporation temperature limited to triple point ($T_t$=-56°C) | Especially high performance for industrial freezing applications, where lower evaporation temperatures can be achieved compared to Ammonia systems. Compact units for e.g. fishing vessels. |
| | High conductivity;<br>High heat transfer coefficient at supercritical conditions |
| | Cost efficient<br>->$CO_2$ as a byproduct from several processes |

## 4. R744 SAFETY ASPECTS

R744 has an ASHARE safety classification of A1, but systems are operating in high pressure ranges and its critical temperature is very low (31°C). Below the triple point (p ~5 bar) dry ice formation takes place. These properties have to be taken in account when applying and handling this natural working fluid (Table 3).

| **Table 3** HSE perspectives of R744 [Emerson, 2015]. | |
|---|---|
| High operational pressure (p< 130 bar);<br>High stand still pressure | Special components, equipment;<br>Pressure relief valve; auxiliary cooling system while stand still;<br>Slow charging necessary |
| Low critical point;<br>Dry ice formation at pressure below 5.2 bar; | Blocking valves and pipes;<br>Causing brittle fractures and frostbites |

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| | |
|---|---|
| Dry ice at p< 1bar is very cold (~-78°C) | ->Avoiding low pressure region |
| Purges must handle ΔT=100K (not designed for): $T_{amb}$=40°C; $T_{5\ bar}$=-78°C | ->Avoiding blowout |
| ASHARE Safety Classification A1 (Nonflammable, Nontoxic): $CO_2$ concentration > 10 %: lethal; $CO_2$ concentration = 2-3% Bodily reaction (headache, increased pulse,..) | Odorless, heavier than air, asphyxiate<br>-> Permanent leak detection necessary |
| Large volumetric expansion coefficient for liquid $CO_2$ | Pressure relief protection for trapped liquid between closed valves;<br>Charging at highest possible $T_{amb}$=50°C and then split the mass in receiver and accumulator |

## 5. R744 TECHNOLOGIES

The Coefficient of Performance (COP) of R744 for a simple booster system can be increased by 17% using a parallel compression system. At high heat rejection temperatures COP can be improved by 22% by utilizing expansion work recovery, e.g. via ejectors instead of expansion devices. A comparison of the various R744 technologies is listed in Table 4.

**Table 4** Comparison of R744 technologies. [Emerson, 2015; Sarkar, 2010]

| Technologies | Booster | Parallel Compression | Ejector |
|---|---|---|---|
| Main Components | 2 temperature levels;<br>2-stage (MT / LT) compressor;<br>Throttling valves;<br>Gas Cooler;<br>Evaporator;<br>Receiver | Compressors in parallel mode;<br>Gas Cooler;<br>Expansion device;<br>Evaporator;<br>Receiver | Compressor;<br>Gas Cooler;<br>Ejector;<br>Evaporator |
| COP | | + 16% | + 22% |
| PRO | Small investment costs;<br>One refrigerant<br>Standard components;<br>Robust;<br>Well developed;<br>Leading in large systems | Direct compression of flash gas from MPR | No power needed other than motive gas;<br>No moving parts;<br>Easy to install/operate/maintain;<br>Recycling waste steam;<br>Expansion work recovery;<br>Flooded systems;<br>No superheat (1bar=1K);<br>Very pressure lift achievement |
| CONTRA | Gas cooler outlet temperature in the range of 25-35°C | Higher complexity; Slightly higher investment costs | High investment costs;<br>High load can only be lifted low;<br>High complexity |

## 6. INDEE $CO_2$ TEST FACILITY

The INDEE multifunctional test facility, as shown in Figure 1, uses $CO_2$ as working fluid and consists of three evaporators for freezing (16), cooling (17) and air conditioning (18). A parallel compression system configuration with ejectors for expansion work recovery as well as a heat reclaim option (5) was applied. Low (LT) and medium temperature (MT) compressors (1,3) suck the saturated and precooled (14,15), for better efficiency, gas of the LT and MT evaporators (16,17) respectively and compress it to a high-pressure level. Before entering the evaporators, the pre-heated working fluid gets expanded to the required pressure level by passing a throttling valve (h-j). LT and MT compressors are series-connected with an intermediate gas cooler, de-superheater (2), reducing the MT suction temperature. Typically, for $CO_2$, a decreasing evaporating temperature with 1 K decrease the compressor

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power demand by about 0,5% and reduce the cooling capacity by 3%. The small amount of oil in the subcritical gas gets removed by the oil separator (20) before entering the gas cooling process. The evaporated gas of the air conditioning (A/C) evaporator (18) gets compressed by ejectors utilizing this high-pressure gas coming from the gas cooling process. There is a possibility to operate with only one ejector, the low (low ER EJ, 9) and high pressure ratio (high ER EJ, 11) ejector block, or with both ejector blocks in series or parallel-connected. $CO_2$ EJ can achieve very high pressure lift due to large work recovery. Another feature of this rack is the usage of liquid ejector (liq EJ, 10) allowing the evaporators to stay flooded all year. The gas-fluid mixture is stored in the receiver maintaining the volume of liquid $CO_2$ in the pipelines.

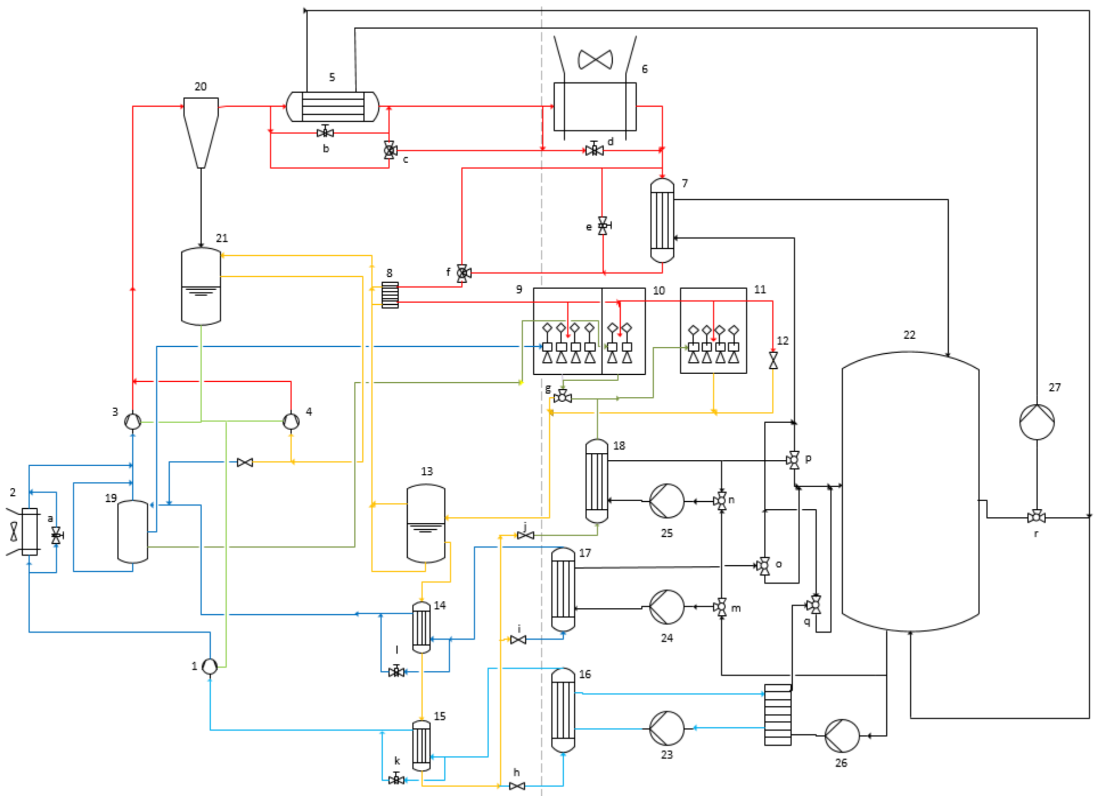

**Figure 1** Flow diagram of INDEE container (simplified).

**Table 5** Key of INDEE Main Components.

| | | | |
|---|---|---|---|
| 1 | Low Temperature Compressor | 15 | Heat Exchanger Low Temperature |
| 2 | De-superheater, Fan | 16 | Low Temperature Evaporator |
| 3 | Medium Temperature Compressor | 17 | Medium Temperature Evaporator |
| 4 | Auxiliary Compressor (AUX) | 18 | Air Conditioning Evaporator |
| 5 | Pre-cooler | 19 | Liquid Suction Accumulator (ACC) |
| 6 | Gas Cooler, Fan | 20 | Oil Separator |
| 7 | Sub-cooler | 21 | Oil Receiver |
| 8 | Heat Exchanger | 22 | Glycol Tank |
| 9 | Low Pressure Ratio Ejector (low ER EJ) | 23 | LT Pump |
| 10 | Liquid Ejector (liq EJ) | 24 | MT Pump |
| 11 | High Pressure Ratio Ejector (high ER EJ) | 25 | A/C Pump |
| 12 | High-pressure Expansion Valve | 26 | Secondary Pump |
| 13 | Middle Pressure Receiver (MPR) | 27 | Heat Reclaim Pump |
| 14 | Heat Exchanger Medium Temperature | a, b, d, e, k, l | Gate Valves, Manually Operated |
| c, g, m-r | 3-Way Valves, Electronically Operated | h-j | Throttling Valves, Electronically Operated |

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The gas gets entrained by the auxiliary (AUX, 4) or/and MT compressors, passing the oil receiver (21), for cooling down the oil stored there, and suction liquid accumulator (ACC, 19). MPR is installed at the lowest temperature and pressure point to keep the costs low. It adjusts the high-pressure level by removing gas when the ambient temperature increases and is a liquid storage in case of leakage. Furthermore, on the gas pipeline directly after MPR there is an installed pressure valve to keep the pressure level constant. Parallel compression of MT and AUX compressors resulting in direct compression of flash gas from MPR instead of flashing vapor to the main compressors suction group. The high pressure gas gets then cooled down by the pre-cooler (5), gas cooler (6) and sub-cooler. While cooling the gas cooler (GC) follows the constant pressure line at gliding temperatures. The specific heat capacity of the refrigerant is not constant during this process but changes significantly with temperature. Based on this property the GC are designed. Therefore, the three different applications such as preheating, heating of hot tap water as well as space heating can be integrated. The temperature approach ($T_a$) is limited by the pinch point and is typically located on the outlet of the GC, to get the minimum of $T_a$ = 2-4K, means on low pressure side. Therefore, GC inlet pressure should be high resulting in high cooling capacity, low throttling losses and thus, high COP. The higher the GC outlet temperature the higher the pressure, at $T_{GC}$ =46°C the optimum p~105bar for the highest COP. Sub-cooling is an application for preheating the tap water as well as improving the COP. Before entering the ejector another improvement is the installation of a heat exchanger. The passing glycol (G) takes the heat and transfers it to the individual evaporator. Two G loop circuits are arranged, one for MT, A/C load and another one for LT load with different G concentrations (42% and 56% respectively). The temperature of the G inlet temperature of each heat exchanger, regardless of the gas cooler, can be maintained by changing the opening degree of the 3-way valves (m-r). G is stored in the G tank (22). By changing the opening degree of the gate valves (a, b, d, e, k, l) manually or the 3-way-valves (c, g) electronically the CO2 mass flow of each heat exchanger can be maintained, for e.g. testing the efficiency of those heat exchangers and their different applications. A simplified flow diagram of the multifunctional test facility is shown in Figure 1 and a list of the components are listed in Table 5.

## 6.1 DIFFERENT MODES OF THE SUPERMARKET TEST FACILITY

The supermarket test facility is designed to improve the basic knowledge of $CO_2$ refrigeration (mode 0, Figure 2) and its applications, especially for the supermarket sector. The operational mode can be changed simulating different applications (mode 1-6) as well as the gas cooler outlet temperature to simulate various ambient conditions ($T_{amb}$ =34-46°C). For Southern India, a parallel compression configuration with ejectors for expansion work recovery is the most efficient mode (mode 4; Figure 4). It can deliver freezing, refrigeration and air conditioning loads, and has a heat reclaim option. Mode 1 (Figure 2) is a 2-stage compression system suitable for colder climate zones. The parallel compression configuration in mode 2 (Figure 3) and 6 (Figure 5) is suitable for European and North Indian temperature since the A/C is switched off. Mode 2 operates with low ER EJ and mode 6 with high ER EJ. Mode 3 (Figure 3) only includes an A/C operation. The most advanced configuration is mode 5 (Figure 4) running with all evaporators and compressors as well as ejectors connected in series. In Table 6 the different modes are listed. Higher ambient temperature conditions can be simulated by reducing the rotational speed of the gas cooler fans. For each ambient temperature the receiver pressure can be manually controlled maintaining the A/C evaporating temperature. By changing the glycol inlet temperature of the evaporators, the evaporating temperatures can be adjusted. All those different configurations resulting in the possibility to understand the behavior of CO2 refrigeration for a wide range of applications as well as the respective influences between components. The most interesting is the possibility to demonstrate the feasibility of R744 transcritical systems as a non-HFC based alternative to HCFC-22 in retail applications in countries with high ambient temperature.

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**Table 6** Different modes of INDEE container

| Modes | Mode 0 | Mode 1 | Mode 2 | Mode 3 | Mode 4 | Mode 5 | Mode 6 |
|---|---|---|---|---|---|---|---|
| LT | | | | | | | |
| MT | | | | | | | |
| A/C | | | | | | | |
| AUX | | | | | | | |
| Low ER EJ. | | | | | | | |
| High ER EJ. | | | | | | | |
| Components | Basic Booster | 2 Stage Compression | Parallel compression & ejectors | Basic Booster | Parallel compression & ejectors | Parallel compression & ejectors in serious | Parallel compression & ejectors |
| Application | Study Purposes | Cooler climate zones | European / North Indian Conditions | AC only | Indian Conditions | Indian Conditions | European / North Indian Conditions |

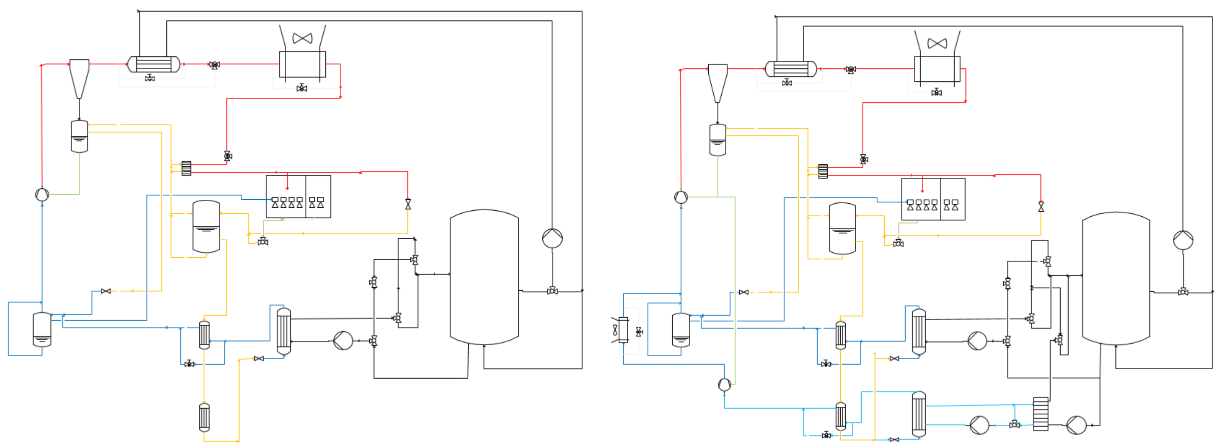

**Figure 2** Simplified flow Diagram of Mode 0 and 1 (from left to right).

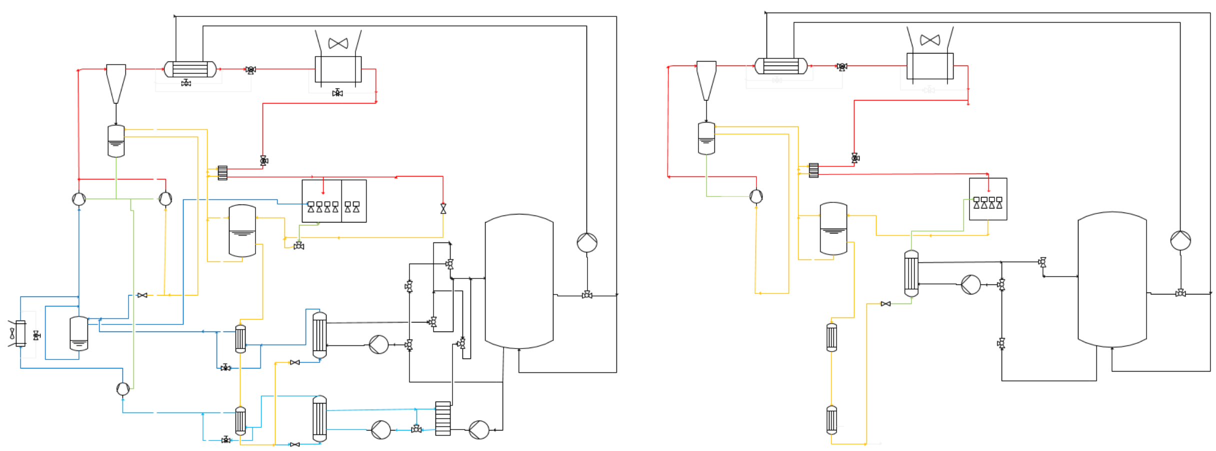

**Figure 3** Simplified flow Diagram of Mode 2 and 3 (from left to right).

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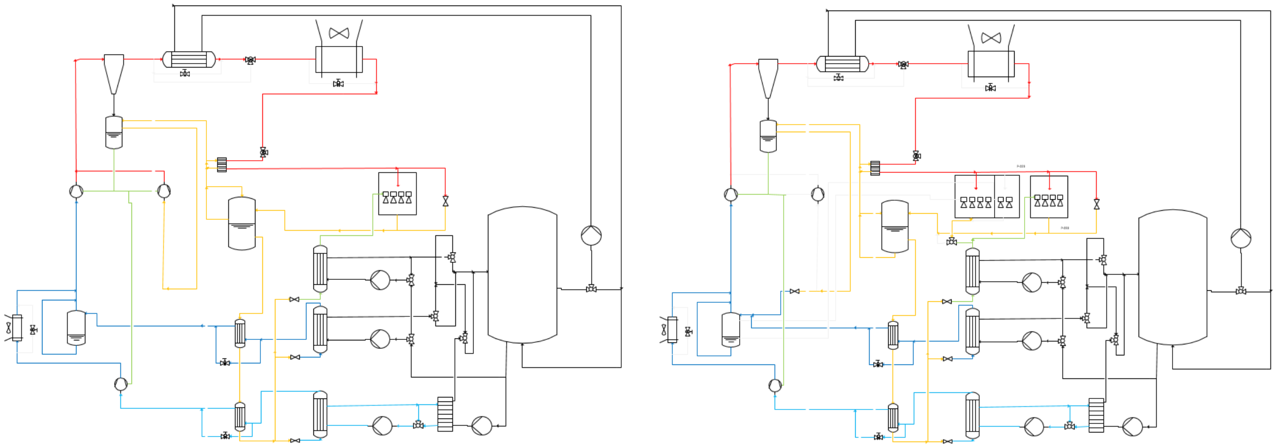

**Figure 4** Simplified flow Diagram of Mode 4 and 5 (from left to right).

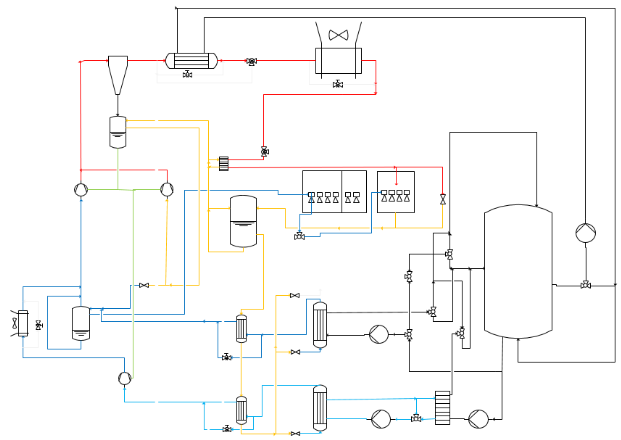

**Figure 5** Simplified flow Diagram of Mode 6

## 7. CONCLUSION AND FUTURE WORK

Based on R744 practical properties, it is a particularly suited working fluid for high ambient temperature countries. A refrigeration system with parallel compression configuration with ejectors for expansion work recovery (mode 4) is theoretically the most efficient mode for its application.

The next step is doing experiments on the test facility (mode 4) for different ambient temperatures (T=36-46°C) to get the efficiency of CO2 in high ambient temperature regions and to prove its feasibility. Simultaneous, first efficiency tests on Indians supermarket refrigeration and air conditioning installations need to be done to get tangible results. Then, those results get compared and evaluated. The last step is a full-scale replacement of existing commercial refrigeration installations with multifunctional CO2 refrigeration systems in India.

## NOMENCLATURE

| | | | |
|---|---|---|---|
| HCFC | Hydrochlorofluorocarbons | ASHRAE | American Society of Heating, Refrigerating and Air-Conditioning Engineers |
| HFCs | Hydrofluorocarbons | INDEE | Energy-efficient and environmentally friendly refrigeration and air conditioning for supermarkets in India |
| CFCs | Chlorofluorocarbons | T | Temperature, °C |
| ODP | Ozone Depletion Potential | $p_{GC}$ | Gas Cooler Pressure, bar |

| | | | |
|---|---|---|---|
| GWP | Global Warming Potential | $p_e$ | Evaporation Pressure, bar |
| A/C | Air Conditioning | $T_{amb}$ | Ambient Temperature, °C |
| $CO_2$ | Carbon dioxide | $T_a$ | Temperature approach, °C |
| COP | Coefficient of Performance | PRO | To be for it |
| MPR | Middle Pressure Receiver | CONTRA | To be against it |
| ACC | Liquid Suction Accumulator | G | Glycol |
| AUX | Auxiliary Compressor | liq | liquid |
| LT | Low Temperature | PIR | Power Input Ratio |
| MT | Medium Temperature | | |
| ER | Pressure Ratio | | |
| EJ | Ejector | | |

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