

CO₂ Based Secondary Loops for Cold Storage Applications

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Abstract

From safety point of view, use of suitable secondary fluids is desirable when environment friendly but toxic and/or flammable refrigerants such as ammonia or hydrocarbons are used in cold storages and other low temperature refrigeration systems. Studies show that use of carbon dioxide as secondary fluid offers several benefits, particularly at low temperatures. In this article, issues related to secondary fluids and benefits of using CO₂ as secondary fluid are discussed. Using simple thermodynamic models it is shown how use of CO₂ as volatile secondary fluid can give rise to performance that is equal to or better than other systems. The superiority of CO₂ over other secondary fluids is established through figure of merit comparison.

Keywords

Cold storages, secondary fluids, carbon dioxide, figure of merit

Introduction

The concept of preservation of perishable food products through refrigeration is very well known for centuries. However, due to various reasons, the first large scale artificial refrigeration system could be built only in the second half of 19th century. However, since then the development of refrigeration systems for food preservation has increased rapidly. Food preservation is certain to become critical with ever increasing population and reducing agricultural land.

Proper food preservation requires the maintenance of a cold chain beginning from the place of harvest and ending at the place of consumption. A typical cold chain consists of facilities for pre-treatment at the place of harvest, refrigeration/freezing at food processing plant, refrigeration during transit, storage in refrigerated warehouses (cold storages), refrigerated displays at the market, and finally storage in the domestic freezer/refrigerator. It is very important that suitable conditions must be provided for the perishable products throughout the chain. Since, for most of the time, the food products will be stored in the cold storages, it is essential to design and build cold storages where the food products can be stored with minimum loss of quality for as long a time as possible.

Preservation of perishable products using cold storages equalizes the prices and makes the products available round the year. Without this, the prices would be very low at the time of harvest and very high during the off-season. With storage facilities, it would also be possible to make the products available in areas where they are not grown.

In India, the need for proper cold storage facilities grew rapidly with the green revolution and subsequent increase in yield per acreage. As a result, at present there is a great mismatch between the demand-and-supply as far as the cold storage facilities are concerned. Even though India is the second largest producer of food in the world, the facilities available for food preservation in terms of cold storages, etc. are grossly inadequate. With the existing cold storage facilities, only a fraction of the total output of fruits and vegetables can be preserved. It is estimated that the post-harvest loss due to inadequate cold storage facilities is high as 30 percent of the total output. The quality of remaining 70 percent is also affected by inadequate cold chain facilities. Realizing the importance of food preservation, the Indian government is promoting development of proper food processing and cold storage facilities by offering subsidies and concessions and by lifting restrictions on import of cold storage equipment. Since construction and operation of cold storages involve considerable cost, it is very essential to design and build economically viable, environmentally safe and energy efficient cold storage facilities. Selection of suitable refrigeration system is a critical step in the design of cold storage systems, as the refrigeration system is a major cost component of any cold storage.

Refrigeration Systems for Cold Storages

The selection of refrigeration system for a cold storage must be done in the early stages of planning. The selection can be relatively simple if the cold storage is a single purpose, low

temperature storage facility. However, if the cold storage is to cater to mixed products requiring different storage temperatures, a system must be selected that may require the use of several isolated rooms and conditions.

Refrigeration systems for cold storages can be classified in several ways:

- a) Depending upon the working principle
 - i) Vapour compression refrigeration systems
 - ii) Vapour absorption refrigeration systems
 - iii) Vapour jet refrigeration systems
 - iv) Air cycle refrigeration systems

Of the above, the refrigeration systems based on vapour compression are most widely used. These systems require mechanical energy as input for driving the compressor. Vapour absorption and vapour jet refrigeration systems are thermal energy driven systems and are suitable when waste heat or solar energy is available in required quantities at required temperatures. Air cycle refrigeration systems are less commonly used, even though there is a growing interest in these systems due to the possibility of using the refrigerant (air) directly for cooling the product without any heat exchanger.

- b) Depending upon size/application
 - i) Factory-built package units
 - ii) Central systems

Factory-built package systems are ideal for small cold storages and/or for multi-room cold storage units with requirements of mixed storage. Central systems are used for large cold storage systems. While, in general, the initial cost is less and operating cost is more for package units, it is vice-versa for central systems.

- c) Depending upon type of cooling
 - i) Direct type
 - ii) Indirect type

In direct type, the storage space is cooled directly by the primary refrigerant; this means that the evaporators cool the air that is circulated through the storage space directly. *Figure 1* shows the schematic of a basic direct type vapour compression refrigeration system with ammonia as refrigerant.

In indirect type, the refrigeration system is confined to the plant room, while a secondary fluid transfers heat from the cold storage to the refrigeration system using additional heat

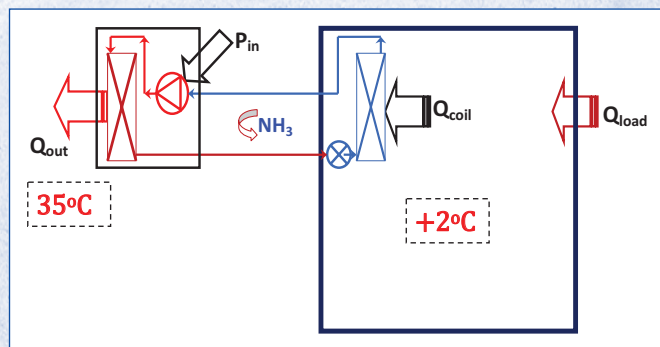


Figure 1: A typical, direct type refrigeration system for cold storage with ammonia (P_{in} : Power input to compressor)

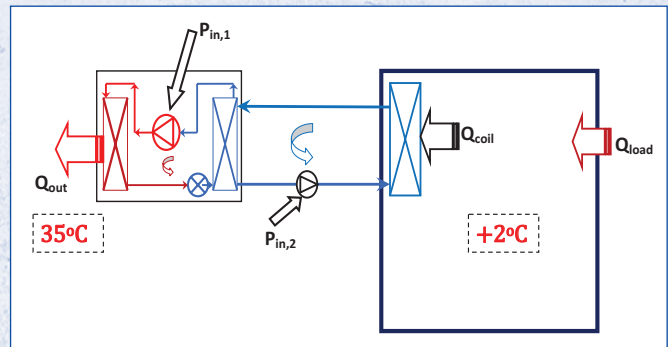


Figure 2: An indirect type system with NH_3 as primary refrigerant and CO_2 as secondary refrigerant ($P_{in,1}$: Power input to compressor, $P_{in,2}$: Power input to pump)

exchangers located in the cold storage. *Figure 2* shows the schematic of an indirect type refrigeration system that uses ammonia (NH_3) as primary refrigerant and carbon di-oxide (CO_2) as secondary refrigerant.

Direct type systems are well suited for small systems and where the plant room is kept close to the cold storage. They are generally more efficient compared to the indirect type and also cost less, initially. However, the cost can go up and performance degrade if the amount of refrigerant required is large and long pipelines have to be used. Direct type systems are not recommended for large refrigerant inventory systems working with toxic and hazardous refrigerants such as ammonia or hydrocarbons. Indirect type systems are well-suited in applications involving large distances and/or large refrigerant inventory and in particular with toxic/flammable refrigerants. In such cases, the hazardous refrigerant can be confined to the plant room and a safer secondary fluid can be used for transporting heat from the plant room to the cold storage. This ensures safety to the products as well as people in the cold storage. Normally, water, brines, glycols or aqueous alcohols are used as secondary fluids. These secondary fluids do not undergo any phase change and the heat transfer is sensible. This may require a large mass flow rate of secondary fluid leading to large pipe sizes and pumping power. It is also possible to have secondary fluid that undergoes phase change as it flows through the cooling coil. Such a fluid is called as a volatile secondary fluid. Since, in this case, the heat transfer is accompanied by phase change, and as the latent heat of vaporization is much larger than the specific heat, for a given refrigeration capacity, the required mass flow rate of secondary fluid is much less if it is volatile. This reduces the required pumping power significantly.

Refrigerants for Cold Storage Applications

Prior to the realization of environmental issues of ozone layer depletion and global warming, the most widely used refrigerants in cold storages were: R-12 (Chloro-Fluoro-Carbon-12 or CFC-12); R-22 (Hydro-Chloro-Fluoro-Carbon-22 or HCFC-22); R-502, which is an azeotropic blend of CFC-115 (48.8 percent by mass) and HCFC-22 (51.2 percent by mass) and ammonia (NH_3 or R-717). Of

these, R-12 was used primarily in small capacity cold storages, while the other refrigerants were used in large cold storages. Among the refrigerants used, except ammonia, all the other refrigerants are synthetic refrigerants and are non-toxic and non-flammable. Though ammonia is toxic, it has been very widely used due to its excellent thermodynamic and thermophysical properties, easy availability and low cost. The scenario changed completely after the discovery of ozone layer depletion in 1974. The depletion of stratospheric ozone layer was attributed to chemicals containing chlorine and bromine such as Halons, CFCs, HCFCs etc. Since ozone layer depletion could lead to catastrophe on a global level, it has been agreed by the global community to discontinue the use of ozone depleting substances (ODS) completely in a phased manner. As a result, except ammonia, all the other refrigerants used in cold storages had to be phased-out and a search for suitable replacements began in earnest. At the same time, it was also observed that, in addition to ozone layer depletion, most of the conventional synthetic refrigerants also cause significant global warming. In view of the environmental problems caused by the synthetic refrigerants, opinions differed on replacements for conventional refrigerants. The alternate refrigerants can be classified into two broad groups:

- i) Non-ozone depleting, synthetic refrigerants based on Hydro-Fluoro-Carbons (HFCs) or Hydro-Fluoro-Olefins (HFOs) and their blends
- ii) Natural refrigerants including ammonia, carbon dioxide, hydrocarbons and their blends

It should be noted that the use of natural refrigerants such as carbon dioxide and hydrocarbons is not a new phenomena, but is a revival of the once-used-and-discarded technologies in a much better form. Since natural refrigerants are essentially making a comeback, one advantage of using them is that they are familiar in terms of their strengths and weaknesses. Another important advantage is that they are completely environment friendly, unlike the HFC based refrigerants, most of which have considerable global warming potential. The alternate synthetic refrigerants are normally non-toxic and non-flammable. It is also possible to use blends of various HFCs to obtain new refrigerant mixtures with required properties to suit specific applications. However, most of these blends are non-azeotropic in nature; as a result there could be significant temperature glides during evaporation and condensation. It is also important to take precautions to prevent leakage, as this will change the composition of the mixture.

Use of Ammonia as Refrigerant in Cold Storage Applications

Ammonia is the only natural refrigerant that survived the onslaught of synthetic refrigerants without any break for the last 150 years or so. The resilience of ammonia can be attributed to a) its favorable thermophysical and transport properties resulting in excellent system performance, b) low cost, and c) easy availability. In addition, ammonia is also environmentally

safe with zero ODP and zero GWP. The pungent smell of ammonia also forewarns the users of leaks (though it may also create unnecessary panic!). In view of these advantages, ammonia is generally the most preferred refrigerant for applications that require large amounts of refrigerant, such as cold storages. However, due to the safety concerns related to its toxicity and flammability, ammonia is facing some safety regulations and restrictions.

The potential hazards of ammonia can be reduced greatly by confining ammonia to the plant room away from the conditioned space. This will automatically reduce the amount of refrigerant that is used per unit capacity, thereby enhancing not only the safety but also the overall performance of the system. Ammonia can be confined to the plant room by using either a cascade system or by using a secondary fluid. Both these strategies are in vogue. With these measures, it is expected that the use of ammonia will grow to a much a greater level in the near future. However, either in cascade mode or with a secondary fluid, a suitable low temperature refrigerant and/or secondary fluid that can match ammonia needs to be identified. Carbon dioxide is expected to meet these requirements and NH₃/CO₂ systems are supposed to offer the most efficient and cost effective solution to refrigeration requirements in supermarkets, cold storages etc.

Use of Carbon Dioxide in Cold Storage Applications

One of the most significant developments in the aftermath of ozone layer depletion and global warming problems is a renewed interest in carbon dioxide. The comeback of carbon dioxide is indeed dramatic, as it is one of the oldest and most well-known refrigerants, has been used widely (before the invention of CFCs and HCFCs) and was discarded completely due to its supposedly bad properties of low critical temperature (31.2°C) and high operating pressures. The renewal of carbon dioxide is largely due to the pioneering efforts of Prof. Gustav Lorentzen of Norway. He has shown that the unique properties of carbon dioxide such as low critical temperature and high pressures can be turned into advantages by modifying the thermodynamic cycle. One of the outcomes of this is the development of transcritical cycles, in which part of the cycle is subcritical and part of it is supercritical. In these cycles, the heat rejection to the heat sink is non-isothermal with a large temperature glide (in a gas cooler), unlike conventional condensers, which are essentially isothermal.

The operation in transcritical region offers several benefits such as the possibility of devising simultaneous cooling and heating systems, easier capacity control, etc. It was realized that even though the operating pressures are typically one order of magnitude higher than the conventional refrigerant based systems, carbon dioxide compressors can operate very efficiently due to small pressure ratios. Also, the heat transfer in evaporator and gas cooler can be very efficient due to the excellent transport properties of carbon dioxide. Since the

continued from page 20

pressure difference between heat rejection and heat extraction is very large, it is possible to replace the throttling device by an expansion engine or an ejector, thereby recovering a part of the work of expansion.

For cold storage applications, carbon dioxide can be used as:

- i) Primary refrigerant in single stage systems
- ii) Primary refrigerant in cascade systems
- iii) Volatile secondary refrigerant in indirect systems

Due to its many excellent properties and environment friendly nature, carbon dioxide is gaining popularity as a primary as well as a secondary fluid in various refrigeration and air conditioning applications [1-6]. Systems that use CO₂ as primary refrigerant are already in market in the form of heat pump water heaters, and refrigeration systems for supermarkets, vending machines etc. Cascade systems that use ammonia as the high temperature refrigerant and CO₂ as the low temperature refrigerant are also gaining popularity due to their excellent overall performance.

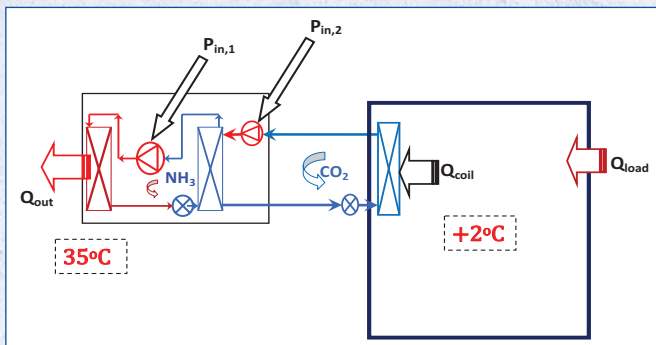


Figure 3: A typical, cascade system with NH₃ as high temperature refrigerant and CO₂ as low temperature refrigerant ($P_{in,1}$: Power input to NH₃ compressor, $P_{in,2}$: Power input to CO₂ compressor)

Figure 3 shows a typical NH₃-CO₂ cascade system for cold storage applications. Several companies such as Mayekawa and Danfoss are offering NH₃-CO₂ cascade systems for supermarkets, cold storages, etc.

Studies show that CO₂ can also be an excellent secondary fluid with several beneficial features. One of the potential applications of CO₂ as secondary fluid is in cold storages and supermarkets that use natural but flammable and/or toxic refrigerants such as hydrocarbons or ammonia. Studies clearly show that use of CO₂ as secondary fluid can give rise to very compact loops with performance that is much superior to traditional secondary fluids such as water or brines. Use of a secondary fluid in these applications not only enhances safety aspects, but also can improve the performance of the refrigeration system due to greatly reduced refrigerant charge.

The secondary fluid systems can be of different types, e.g., forced circulation or natural circulation, loops with or without phase change, etc. Forced circulation loops without phase change are widely used in refrigeration and air conditioning with water being the most popular fluid for temperatures above 0°C and various types of brines, glycols, etc. for sub-zero temperatures. Of late, systems have been developed that use CO₂

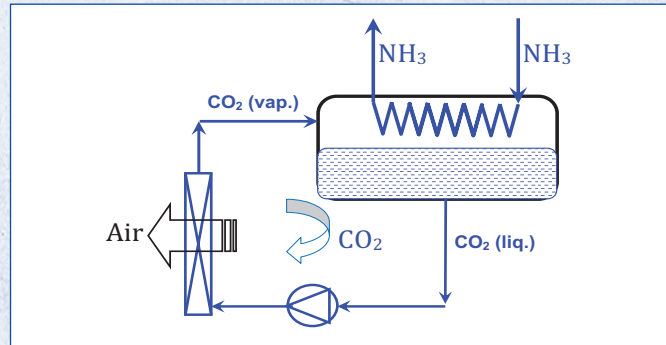


Figure 4: A typical, forced circulation type, volatile secondary fluid system with NH₃ and CO₂

as secondary fluid in forced circulation loops with suitable pumps and heat exchangers. Figure 4 shows a typical forced circulation type secondary loop with volatile CO₂ as secondary fluid and NH₃ as primary refrigerant. In recent times, such systems are being offered by companies such as Mayekawa.

Figure 5 shows Mayekawa's NH₃/CO₂ system with CO₂ acting as volatile secondary fluid [7]. The company presented the data on the above system and stated that use of volatile CO₂ led to smaller pumping power, smaller pipe size and lower installation costs. The ideal temperatures suggested for this system are -40°C to 0°C. It is stated that the company has installed more than 900 such systems all over the world in applications such as cold storages, supermarkets, food and beverage processors, etc. [7].

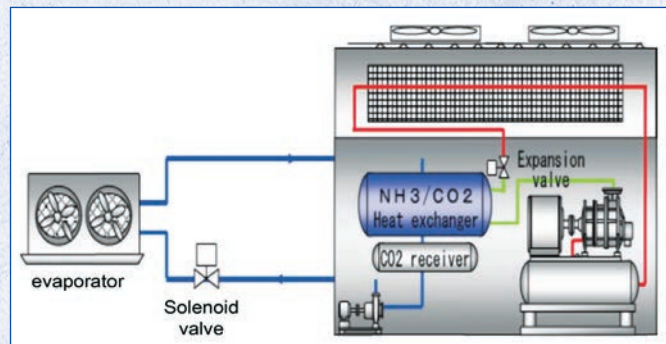


Figure 5: A forced circulation type NH₃/CO₂ PVB chiller offered by Mayekawa [7]

In smaller capacity refrigeration and air conditioning systems, use of buoyancy-driven, natural circulation secondary loops may be more appropriate compared to pump-driven forced circulation loops from the considerations of cost, reliability and simplicity. Figure 6 shows a typical natural circulation type secondary loop with volatile CO₂ as secondary fluid and NH₃ as primary refrigerant. In the absence of pump, as seen in the figure, the circulation is maintained by placing the condensing liquid at a higher level compared to the coil where boiling of CO₂ takes place. Proper orientation is, thus, one of the limitations of natural circulation type loops compared to the forced circulation loops.

Modification of a basic refrigeration system by the addition of a secondary loop may increase the initial cost and may also affect the overall system performance, if not designed

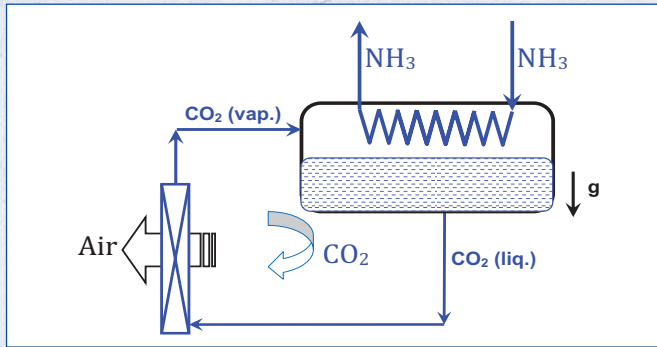


Figure 6: A typical, natural circulation type, volatile secondary fluid system with NH_3 and CO_2

properly. Though some increase in the initial cost is inevitable, it is essential to design the system such that increase in initial cost and reduction in performance, if any, are minimal. This requires thorough understanding of the system characteristics so that the system can be modeled properly leading to an optimized design.

It is well-known that modeling of a natural circulation loop based system is more complex compared to a forced circulation loop due to the inherent coupling between the momentum and energy transfer. Very few studies are available in open literature on refrigeration and air conditioning systems that use natural circulation type secondary loops. Yanagisawa et al. [5] have successfully carried out design and experimental studies on an ammonia based refrigeration system whose evaporator is coupled to a CO_2 based natural circulation loop. Figure 7 shows the experimental loop employed by Yanagisawa et al. [5] for their studies.

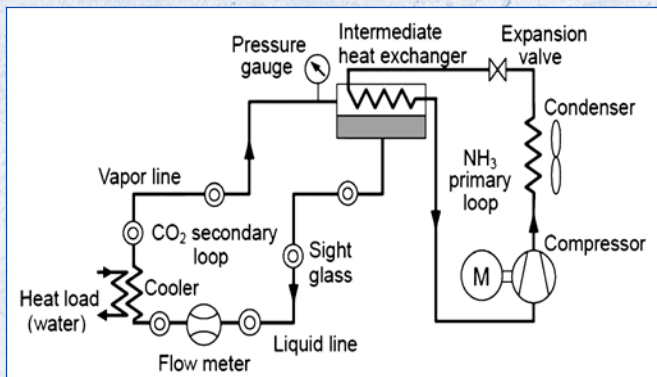


Figure 7: Experimental test rig on natural circulation loop with NH_3 and CO_2 employed by Yanagisawa et al. [5]

This system yielded a capacity of approximately 3.5 kW at around 5°C with a driving head of 0.9 m. Forbes Pearson of Star Refrigeration, UK has patented volatile CO_2 based secondary refrigeration systems and discussed a volatile, natural circulation type NH_3/CO_2 system with pumped recirculation [3]. Figure 8 shows the system presented by Pearson [3]. It may be observed from the figure that flow of CO_2 between the NH_3/CO_2 cascade heat exchanger and HP receiver is by natural circulation, while liquid CO_2 is pumped through the cooling coil using a circulating pump.

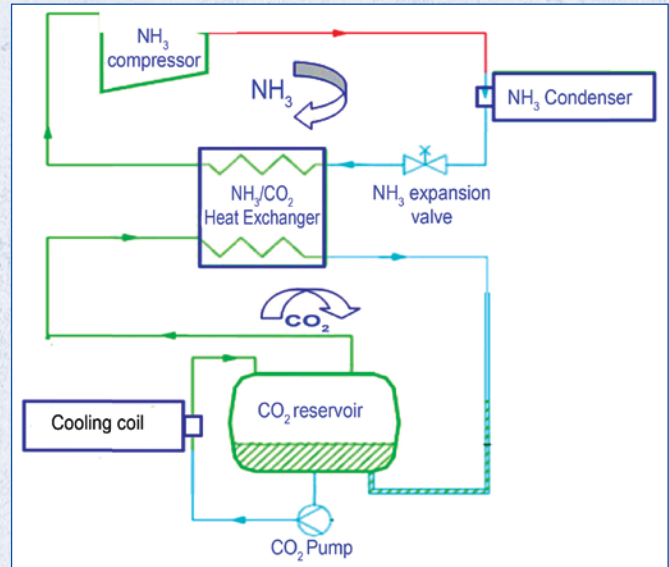


Figure 8: A natural circulation loop secondary fluid system with NH_3 and CO_2 proposed by Pearson et al. [3]

Kaga et al. [6] have developed a small R600a based refrigeration system (capacity 170 W to 230 W) that uses a CO_2 based natural circulation loop for transferring heat from the refrigerated space to the evaporator kept outside. Figure 9 shows the system developed by Kaga et al. [8]. It is stated that the energy consumption of this system is 5% less than the baseline R134a system [8]. Kiran Kumar and Ramgopal have carried out studies on CO_2 based natural circulation loops and their application in refrigeration and air conditioning [9-12]. Commercially, companies like Mayekawa, Danfoss and Shecco are offering refrigeration systems for supermarket and other applications that use CO_2 as secondary fluid operating in forced circulation mode. However, no commercial development as yet has taken place on systems that use natural circulation.

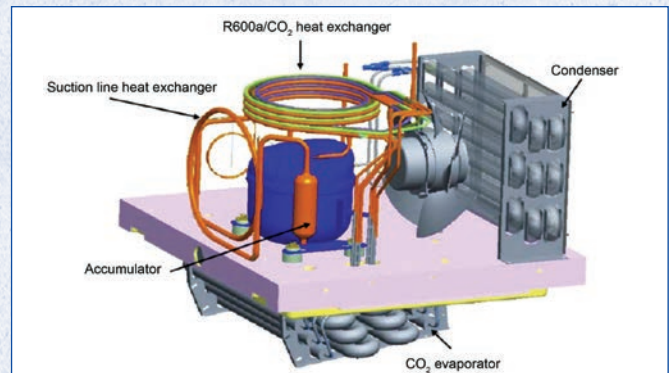


Figure 9: A small, variable capacity refrigeration system with CO_2 as naturally circulating secondary fluid, Kaga et al. [8]

Current State of the Research

Most of the research work on CO_2 based refrigeration systems is primarily focused on its use as primary refrigerant suitable for various refrigeration, air conditioning and heat pump

applications. Several European, Japanese and Chinese companies are offering these systems of varying capacities suitable for small to medium capacity applications. A few companies such as Danfoss, Emerson and Shecco are offering NH₃/CO₂ cascade refrigeration systems and NH₃/CO₂ systems with CO₂ as forced circulation, secondary loop [13-15].

A large amount of research is being carried out all over the world to improve the performance of CO₂ based refrigeration systems. In India, research is being carried out on use of CO₂ as primary refrigerant at IIT Kharagpur, IIT Madras, IIT-BHU Benares, BITS Pilani, etc. Several experimental and theoretical studies on natural circulation loops based on CO₂ are carried out at BARC, Mumbai and IIT Kharagpur, Kharagpur. Though few studies [5, 6, 12] are carried out on coupling of CO₂ based natural circulation loops with refrigeration systems, detailed analyses of such systems suitable for cold storages or supermarkets are very scarce in literature. Hence, there is a greater need for more studies on these systems in Indian context.

Performance Comparison of Various Systems

Based on simple thermodynamic analyses of the basic as well as modified cycles, comparison is made between several options for typical cold storage applications. Calculations are carried out for the input data presented in Table 1.

Table 1: Input values used for cycle comparison

Parameter	Value
Cooling capacity	30 TR (105.5 kW)
Refrigerated (cold storage) space temperature	2°C
Ambient temperature	35°C
Isentropic efficiency of pumps and compressors	65%
Temperature difference for heat transfer	
a) Between refrigerant and air	7 K
b) Between secondary fluid (CO ₂) and air	7 K
c) Between refrigerants (in cascade)	2 K
Pressure drop on secondary fluid (CO ₂) side	300 kPa

Calculations are carried out considering a single stage saturated cycle. Table 2 shows comparison between base cycle, cascade cycle and a cycle with CO₂ as secondary fluid (single phase as well as volatile). Power consumption of indoor and outdoor fans are not considered as it is assumed that they are common for all the cycles. For base case, comparison is made between refrigerants R22, R134a, R290 and R717. For cascade cycle, NH₃ (R717) is the high temperature and CO₂ (R744) is the low temperature refrigerant. The cascade condensing temperature for the cascade cycle is optimized by minimizing total power consumption. Similarly, for secondary fluid system with CO₂ in single phase and forced circulation, the temperature rise across the cooling coil is optimized by minimizing total power consumption.

From Table 2 it can be seen that among the base cycles, R717 offers the best performance. Among the modified cycles, the performance of the cascade cycle is best, even though the difference between this and the volatile secondary fluid systems

Table 2: Performance comparison between base and modified cycles

Cycle	P _{Compressor} (kW)	P _{Pump} (kW)	P _{Total} (kW)
Base cycle (R22)	36.23	-	36.23
Base cycle (R134a)	36.79	-	36.79
Base cycle (R290)	37.52	-	37.52
Base cycle (R717)	34.55	-	34.55
Cascade (R717/R744)	30.82 + 5.23	-	36.05
Secondary fluid, forced circulation, single phase	41.3	4.96	46.26
Secondary fluid, forced circulation, volatile	36.6	0.21	36.81
Secondary fluid, natural circulation, volatile	36.6	-	36.6

(P_{compressor}: Compressor power, P_{Pump}: Pump power, P_{Total}: Total power)

is marginal. It may be seen that even though the cascade and volatile secondary fluid systems consume about 6% higher power compared to the base R717 system, they are on par with or slightly better than the other base cycles that use R22, R134a and R290. Figure 10 shows the performance comparison between the base cycle using refrigerants NH₃, R1234yf and system with NH₃ as primary refrigerant and CO₂ as secondary volatile fluid (forced circulation) over a large refrigerated space temperature. It can be seen that even though the total power consumption of the secondary fluid system is higher than the base cycle that uses NH₃, it is much smaller than the base cycle that uses R1234yf as the refrigerant. It can also be seen that the difference between R1234yf cycle and NH₃/CO₂ cycle is higher at lower temperatures, indicating that the CO₂ based secondary fluid cycles offer superior performance at lower cold storage temperatures.

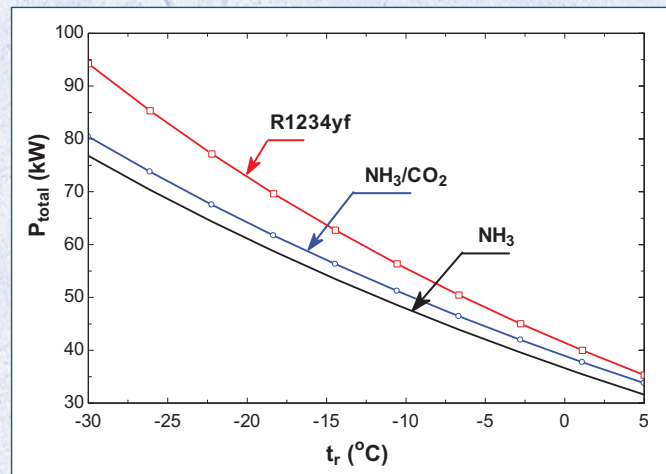


Figure 10: Performance comparison between base cycles with R1234yf, NH₃ and volatile secondary fluid cycle with NH₃/CO₂ (P_{Total}: Total power consumption for 30 TR capacity)

It may be noted that the simple thermodynamic comparison does not completely reflect the benefits of using volatile secondary fluid (CO₂) along with ammonia. As mentioned before, in addition to greatly increased safety aspects, use of CO₂ also leads to much smaller pipelines and insulation,

and reduced space requirement. The combined effect can be lower installation costs as mentioned in literature. Use of natural circulation in place of forced circulation eliminates the need for CO₂ pump, further reducing the installation cost. In addition, lower refrigerant charge also improves the pull-down performance of the refrigeration system. Thus, to obtain true benefits of the secondary fluid system a detailed techno-economic analysis is needed followed by experimental studies for model validation, etc.

Comparison between Different Secondary Fluids

Several fluids (aqueous as well as non-aqueous) are being used as secondary fluids in a variety of refrigeration and air conditioning applications. However, very few fluids can be considered as candidates for volatile, secondary fluid systems. Though, in principle, all refrigerants can be used as volatile secondary fluid, the choice becomes very narrow once one considers the aspects of toxicity, flammability, ozone depletion potential, global warming potential, operating pressures, etc. None of the well known natural refrigerants, except CO₂ can be considered as volatile secondary fluids due to the constraints mentioned. Among the environment friendly synthetic refrigerants, only R1234yf or R1234ze meet the requirement of zero ODP and negligible GWP. Even though these synthetic refrigerants that belong to the general family of Hydro-Fluoro-Olefins (HFOs) are non-toxic, studies show that they are mildly flammable. However, among the newer refrigerants, the HFOs appear to be the most prominent. Hence, a simple comparison is made between CO₂ and R1234yf for volatile secondary fluid based system.

Though comparison can be made in terms of individual fluid properties that influence heat transfer and pressure drop, it would be desirable if the relevant properties can be grouped suitably. Though several researchers have suggested different performance parameters such as Figure of Merit (FOM) for comparing non-volatile secondary fluids in forced circulation, no suitable performance comparison that takes into account all the relevant properties in a group is available for volatile fluids. Hence, in this article, comparison between R1234yf and CO₂ is made considering both saturated liquid and saturated vapour phases.

The Figure of Merit is defined in different ways by different researchers. Murakami and Mikic [16], in their studies on VLSI chip cooling, have derived an expression for FOM by optimization. Their expression, which may be defined as ratio of heat transfer to pumping power under certain assumptions, is given by the equation [17]:

$$FOM = \frac{\rho^2 c_p^{1.6} k^{1.8}}{\mu^{1.4}}$$

In the above expression, ρ , c_p , k and μ stand for secondary fluid density, specific heat, thermal conductivity and viscosity,

respectively. Taking CO₂ as reference fluid, the FOM ratio (FOM_r) is defined in terms of FOM of R1234yf (FOM_f) and FOM of CO₂ (FOM_{CO₂}), i.e.,

$$FOM_r = \frac{FOM_f}{FOM_{CO_2}}$$

Since the size of the pipelines carrying the secondary fluid and the fluid mass flow rate are also important, expressions for the ratio of pipe diameter and mass flow rates for different fluids can be derived by making suitable assumptions. Assuming equal heat transfer, equal pressure drop and temperature difference, Yadav et al. have obtained expression for ratio of diameter of any secondary fluid to that of CO₂. It is given by:

$$D_r = \frac{d_f}{d_{CO_2}} = \left(\frac{c_{p,f}}{c_{p,CO_2}}\right)^{\left(\frac{-3}{8}\right)} \left(\frac{\rho_f}{\rho_{CO_2}}\right)^{\left(\frac{-5}{24}\right)} \left(\frac{\mu_f}{\mu_{CO_2}}\right)^{\left(\frac{1}{24}\right)}$$

For equal heat transfer rate for any secondary fluid and CO₂, the mass flow rate ratio (m_r), assuming change of phase from saturated liquid to saturated vapour in the coil, is simply given by:

$$m_r = \frac{\dot{m}_f}{\dot{m}_{CO_2}} = \frac{h_{fg,CO_2}}{h_{fg,f}}$$

In the above equation, h_{fg, CO₂} and h_{fg,f} stand for the latent heats of vaporization of CO₂ and any fluid f, respectively.

Figure 11 and 12 show the variation of Diameter ratio (D_r) and FOM ratio (FOM_r) of R1234yf over a temperature range for saturated liquid and saturated vapour phases.

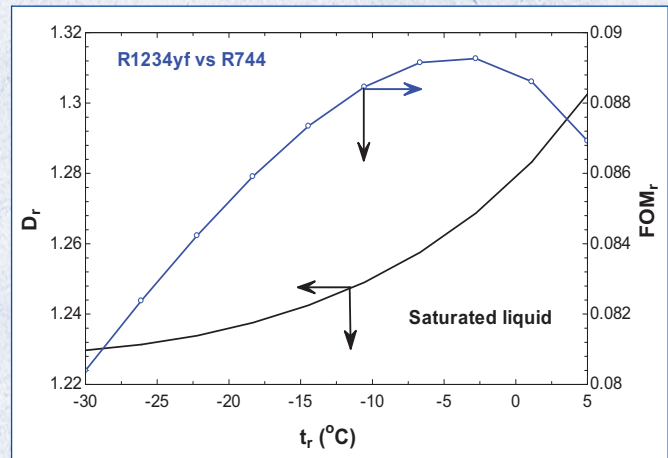


Figure 11: Variation of Diameter ratio (D_r) and FOM ratio (FOM_r) for saturated liquid R1234yf

It can be seen from the figures that for the same pressure drop and heat transfer rate, the Diameter ratio is more than 1.0 for both saturated liquid and vapour phases, implying that CO₂ pipelines will be smaller than R1234yf. Similarly, the FOM ratio is at least an order of magnitude smaller than 1.0, implying that the pumping power for CO₂ will be very small in comparison with that of R1234yf. Figure 13 shows the variation of pump

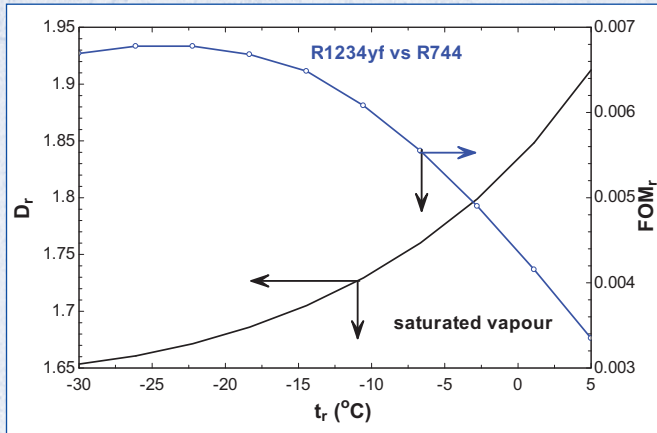


Figure 12: Variation of Diameter ratio (D_r) and FOM ratio (FOM_r) for saturated vapour R1234yf

power for R1234yf and CO₂ for conditions mentioned in Table 1. It can be seen that as predicted from FOM variation, the required pumping power of CO₂ is much smaller than that of R1234yf.

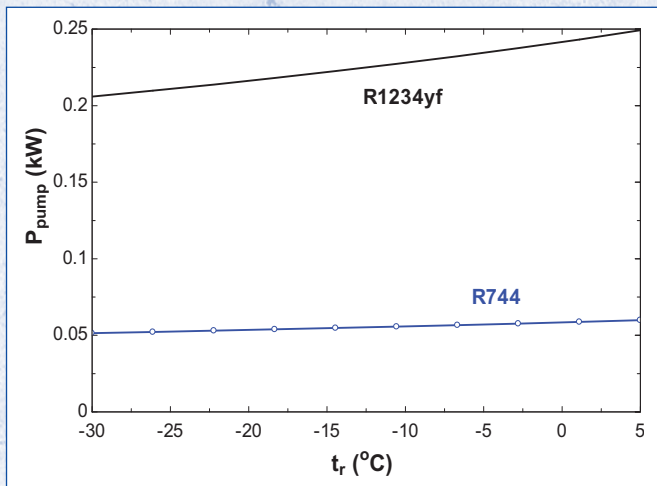


Figure 13: Variation of pumping power of volatile secondary fluids R1234yf and R744 (CO₂) for 30 TR capacity

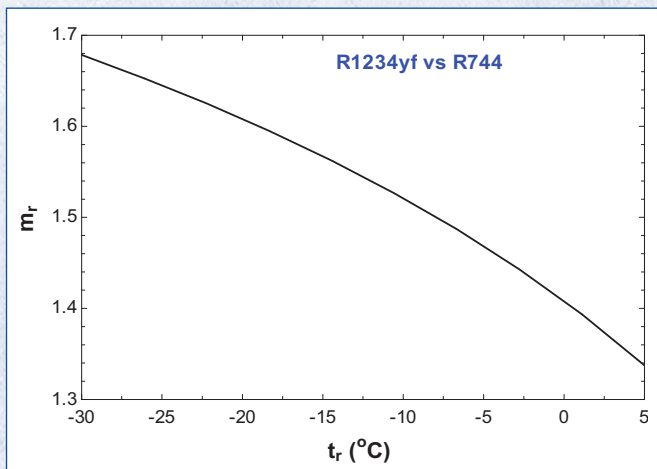


Figure 14: Variation of mass flow rate ratio of R1234yf

Figure 14 shows the ratio of mass flow rates of R1234yf to CO₂ for same heat transfer rate. It can be seen that due to higher latent heat, the mass flow rate of CO₂ is much smaller than that of R1234yf.

Finally, for the sake of completion, comparison is also made between compressed CO₂ ($p=60$ bar) and some commonly used aqueous secondary fluids, e.g., CaCl₂ (25% by weight), Propylene Glycol (45% by weight) and Ethyl Alcohol (45% by weight). Figure 15 and 16 show the comparison between compressed CO₂ and other conventional fluids over a large temperature range in terms of diameter ratio and FOM ratio, respectively. It can be seen that as non-volatile secondary fluid also, CO₂ performs much better than other secondary fluids in terms of required pipe sizes and pumping power. The performance of CO₂ systems becomes more and more superior as the space temperature decreases for both volatile as well as non-volatile fluids as shown by the figures presented.

Studies carried out by Kiran Kumar and Ramgopal [19] show that CO₂ outperforms most of the conventional secondary fluids in natural circulation mode also.

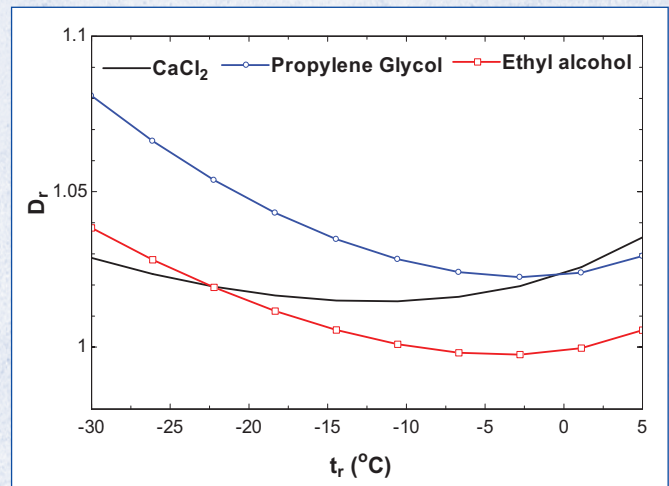


Figure 15: Variation of diameter ratio for different non-volatile secondary fluids

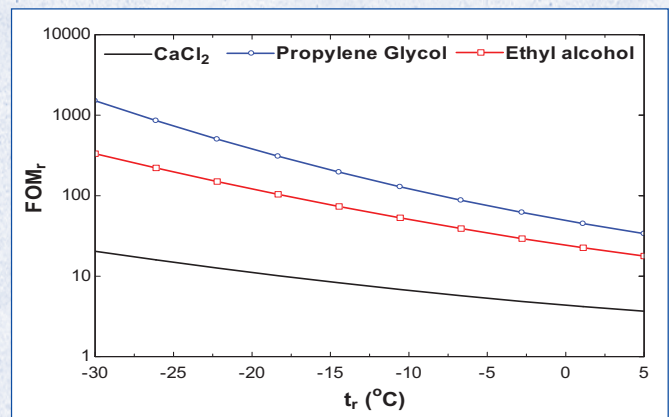


Figure 16: Variation of diameter ratio for different non-volatile secondary fluids

From the simple analyses and results presented above, it is clear that for low temperature refrigeration applications, CO₂ appears to be an ideal secondary fluid. Water is and should be the preferred fluid for higher temperature (above 5°C) refrigeration and air conditioning applications. However, for higher temperatures also it can be shown that CO₂ based volatile secondary fluid systems perform better than water based systems as the latent heat of CO₂ is much larger than the specific heat of water.

It may be mentioned here that the operating pressures of CO₂ are high compared to conventional fluids, hence component design must take care of this. A higher operating pressure does not necessarily mean higher risk, as the volume of CO₂ used will be considerably low due to smaller pipe sizes. However, proper training and adherence to best practices are needed to ensure safe operation. Unlike many conventional fluids such as brines, CO₂ does not suffer from problems related to corrosion and/or material compatibility. Besides, it is inexpensive and is readily available. Large scale use of captured CO₂ in closed systems may also be viewed favorably from the global warming point of view. Thus, considering all the issues in a holistic manner, it is apparent that CO₂ is an excellent secondary fluid.

Conclusions

Numerous theoretical and experimental studies clearly show the superiority of CO₂ as a secondary fluid for low temperature refrigeration and cold storage applications. Field experience by various researchers and industries confirms this fact. Use of CO₂ as volatile secondary fluid with other natural but toxic/flammable fluids as primary refrigerants provides a permanent solution to the environmental problems, in addition to providing safety. Systems that are based on forced circulation of CO₂ appear to be maturing with several companies already offering them on large scale. However, more development is needed on natural circulation based loops. There is also a need to indigenously develop components such as pumps, heat exchangers, valves, etc. for CO₂ based systems.

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