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A Review on Technologies for the Use of CO_2 as a Working Fluid in Refrigeration and Power Cycles

Orelien T. Boupda[1], Hyacinthe D. Tessemo[1], Isidore B. Nkounda Fongang[2], Francklin G. Nyami[1], Frederic Lontsi[1*], Thomas Djiako[3]

[1]Laboratory of Energy, Higher National Polytechnic School of Douala, University of Douala, Douala, Cameroon
[2]Institut Ucac-Icam, Douala, Cameroon
[3]Department of Energy and Mechanical Engineering, ISTA-IUG, University of Ngaoundere, Ngaoundere, Cameroon
Email: *lontsi@yahoo.fr

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Abstract

The use of carbon dioxide as a working fluid has been the subject of extensive studies in recent years, particularly in the field of refrigeration where it is at the heart of research to replace CFC and HCFC. Its thermodynamic properties make it a fluid of choice in the efficient use of energy at low and medium temperatures in engine cycles. However, the performance of transcritical CO_2 cycles weakens under high temperature and pressure conditions, especially in refrigeration systems; On the other hand, this disadvantage becomes rather interesting in engine cycles where CO_2 can be used as an alternative to the organic working fluid in small and medium-sized electrical systems for low quality or waste heat sources. In order to improve the performance of systems operating with CO_2 in the field of refrigeration and electricity production, research has made it possible to develop several concepts, of which this article deals with a review of the state of the art, followed by analyzes in-depth and critical of the various developments to the most recent modifications in these fields. Detailed discussions on the performance and technical characteristics of the different evolutions are also highlighted as well as the factors affecting the overall performance of the systems studied. Finally, perspectives on the future development of the use of CO_2 in these different cycles are presented.

Keywords

Refrigeration Cycle, Power Cycle, System Performance, Transcritical CO_2 Cycles, Working Fluid

1. Introduction

Carbon dioxide (CO_2), as a working fluid with surprisingly favorable properties in the field of refrigeration, heating and power generation, is attracting more and more attention to solve the problems caused by conventional CFC and HFC fluids, in particular the degradation of the ozone layer. The use of CO_2 converted into a working fluid mitigates the greenhouse effect to the extent that it is captured and sequestered [1]; therefore contributes to the preservation of the environment. In addition, these conventional fluids must be phased out in accordance with the Montreal [2] and Kyoto protocols, which consider HFC to be the second major source of global warming after the combustion of fossil fuels [3]. Among the many strategies for mitigating global warming, the design of more efficient and sustainable CO_2 energy systems is part of it in order to limit the growth of global energy consumption, which in 2017 amounted to 2.2% [4]. CO_2 as a natural working fluid, non-flammable, inexpensive and available with a GWP of 1 [5] has been considered an ideal alternative to synthetic refrigerants in refrigeration, heating and power cycle transcritical technology. However, these performances as a refrigerant in this technology are lower than those of HFC, which constitutes a challenge for research, of which several technological improvements have been developed by researchers. The first technology working with CO_2 as a refrigerant was built by Lowe for the production of artificial ice [6]. Lorentzen and Pettersen published the experimental results of the first prototype CO_2 system in 1993 [7] then its results were improved by Pettersen whose performances were similar to those of R12 [8]. Kim *et al.* [9] presented a review of transcritical CO_2 cycle technology in various refrigeration, air conditioning and heat pump applications presenting fundamental process and system design issues. After his work, enormous research has been carried out in this area over the past two decades. As a result, the use of CO_2 as a working fluid in power cycles for the recovery and efficient use of energy at low and medium temperatures often associated with low capacity and intermittent availability, particularly waste heat, solar heat or geothermal heat are proving to be quite effective in dealing with the energy shortage faced by humanity. One of the most mature technologies for converting this low-quality heat into electricity is the organic Rankine cycle (ORC) whose operating principle is analogous to that of the classic water/steam cycle. However, the working fluid used in this technology is an alternative fluid like CO_2 having beneficial thermophysical properties to cope with heat at low temperatures, since many problems are encountered when using water as a working fluid for this cycle [10] [11]. The first supercritical electric cycle using CO_2 as working fluid was proposed at the end of the 1940s, the theoretical foundations and possible configurations of which were raised by Angelino and Feher [12] [13]. In power cycle development, the first SCO_2 cycle was proposed by Sulzer [14] with a partially condensing Brayton cycle. However, further work resumed in 1990 as the technology for manufacturing turbines and compact heat exchangers in SCO_2 power systems had limitations in practical applications. Nevertheless, most studies have focused on the cycle with nuclear reactor as the heat source and therefore such cycles for low quality heat is relatively new.

In view of the above discussion, periodic review of the state of alternative technologies to conventional fluid is useful to examine whether these technologies have been developed to the point where they can compete with or replace existing systems. Although the open literature has provided in-depth reviews of CO_2-powered systems, there is no review that simultaneously presents systematic and detailed explanations of new technologies for improving refrigeration and engine cycles, both using CO_2 as a working fluid; which causes a disadvantage in the search whose option could be to couple these two technologies. Based on this point, the present study aims to present a complete analysis of the state of the art on an update of improved technologies of refrigeration, heating and CO_2 supply cycle as working fluid. This review begins with a brief description of the properties of CO_2, the basic principles of the transcritical refrigeration and heating cycle before delving into the nuances associated with each modification in order to inform improvement approaches and discuss the development of these technological advances. With respect to the CO_2 engine cycle, the system configurations, operating characteristics, applications and advantages in the use of low-grade energy are briefly reviewed. The transcritical CO_2 refrigeration system as an alternative to conventional working fluid refrigeration systems was examined, along with the various constraints related to the development of CO_2 technology in the refrigeration and motor cycle for power generation and associated solutions were proposed. The state of the art of technical advances of SCO_2 Brayton cycles and TCO_2 Rankine cycles are also discussed. Finally, the future prospects and challenges of CO_2 technologies as a working fluid are presented.

2. CO_2 as Working Fluid

Carbon dioxide reaches the pressure and the critical temperature at the point (Pc = 7.3773 MPa and Tc = 304.12 K). As shown in **Figure 1**, the phase state of supercritical CO_2 has density close to liquid, viscosity and diffusion close to gas. Thus, supercritical CO_2 exhibits gaseous properties with liquid density during the expansion process. It has abundant stock and reasonable price of 1/10 cost of helium and 1/70 of R134a organic working fluid [15]. As shown in **Figure 2**, its physical properties vary with temperature near the critical point. The specific heat ratio of CO_2 changes when the pressure is close to the critical point, and the temperature corresponding to the specific heat peak increases with increasing pressure. In addition, CO_2 exhibits excellent thermophysical properties, although it poses some challenges due to its low critical temperature value and high operating pressures. It has a much higher volumetric capacity than conventional refrigerants. **Table 1** compares the characteristics and properties of CO_2 with other refrigerants [16] [17]. This fluid is characterized by high thermal conductivity and high density in the gas phase, which results in good heat transfer; its high pressure vapor density being relatively high, results in a high volumetric heating capacity and therefore makes it possible to recycle a small volume of CO_2 to achieve a large heating demand requiring smaller components and a more compact system [9] [18]. The work of Vesovic *et al.* [19] presents the transport properties of CO_2 (viscosity and thermal conductivity) while improved viscosity data has been published by Fenghour *et al.* [20], the database of CO_2REF properties has been developed by Rieberer [16] which covers both subcritical and supercritical regions. Liley and Desai [21] for their part presented the thermophysical properties (specific heat, thermal conductivity, viscosity, speed of sound and surface tension) of CO_2. The comparison between theoretical calculation and application shows that the organic Rankine cycle using CO_2 has generalized application potential [22] and a comparison between CO_2 and water as the working fluid for a geothermal system states that CO_2 is more efficient with a heat extraction rate of 58% compared to water [23].

Table 1. Characteristics of some refrigerants [17].

	R-12	R-22	R-134a	R-407C	R-410A	R-717	R-290	R-744
ODP/GWP	1/8500	0.05/1700	0/1300	0/1600	0/1900	0/0	0/3	0/1
Flammability/toxicity	N/N	N/N	N/N	N/N	N/N	Y/Y	Y/N	N/N
Molecular mass (kg/kmol)	120.9	86.5	102.0	86.2	72.6	17.0	44.1	44.0
Normal boiling point (˚C)	−29.8	−40.8	−26.2	−43.8	−52.6	−33.3	−42.1	−78.4
Critical pressure (MPa)	4.11	4.97	4.07	4.64	4.79	11.42	4.25	7.38
Critical temperature (˚C)	112.0	96.0	101.1	86.1	70.2	133.0	96.7	31.1
Reduced pressure	0.07	0.10	0.07	0.11	0.16	0.04	0.11	0.47
Reduced temperature	0.71	0.74	0.73	0.76	0.79	0.67	0.74	0.90
Refrigeration capacity (kJ/m^3)	2734	4356	2868	4029	6763	4382	3907	225.45
First commercial use as a refrigerant	1931	1936	1990	1998	1998	1859		1869

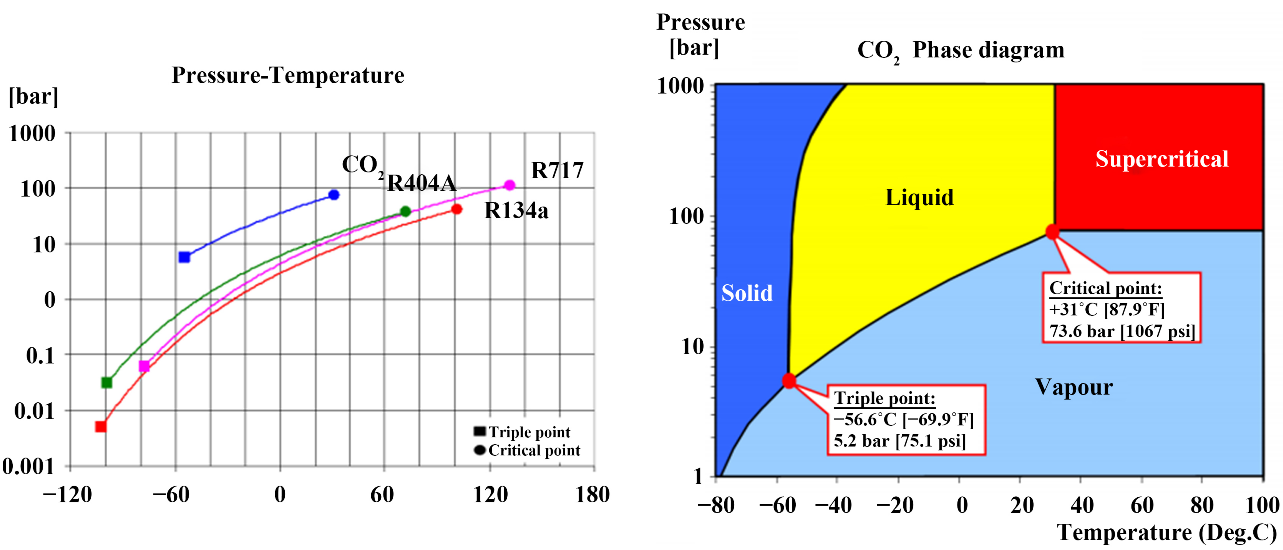


Figure 1. Pressure temperature phase diagram of carbon dioxide [24].

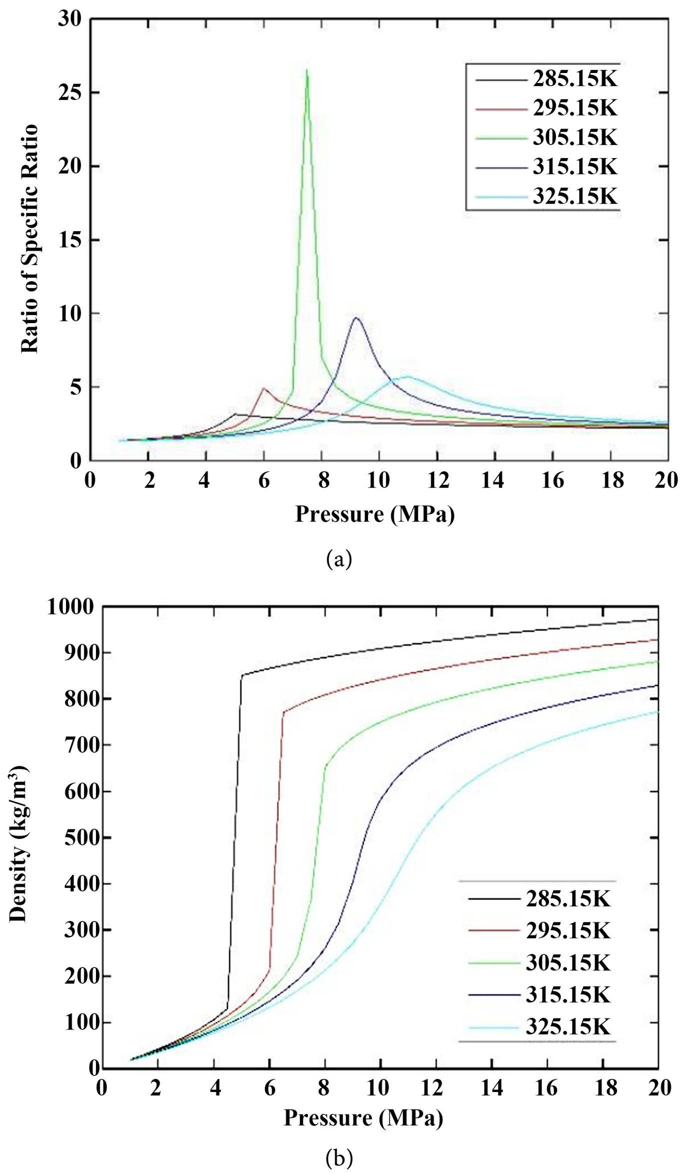


Figure 2. Variation of specific heat ratio and density of CO_2 near the critical point [25].

3. Technologies Using CO_2 as a Working Fluid

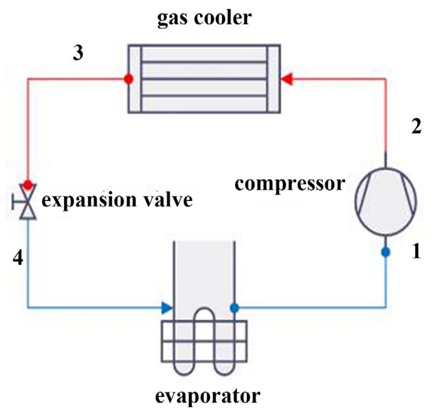
3.1. Transcritical CO_2 Technologies in Refrigeration and Heating Systems

Refrigeration and heat pump systems are closely linked, using the same working fluid developed for refrigeration, a study by Chanson *et al.* presents a review of this technology [26]. Carbon dioxide was among the first refrigerants used in vapor compression refrigeration systems, the detailed history of the role of CO_2 in the development of refrigeration has been compiled by Pearson [27]. The CO_2 transcritical cycle technology, unlike the conventional refrigeration cycle, works with a compressor discharge pressure higher than the critical pressure, which prevents any condensation of the CO_2 which is used as refrigerant. In this zone, there is no longer any relationship between pressure and temperature, so no condensation. The condenser used in the conventional vapor compression cycle is replaced by a gas cooler called a "gas cooler". However, cold occurs by heat absorption and evaporation after expansion of low pressure refrigerant such as similar in conventional subcritical cycle [28]. **Figure 3** presents the basic transcritical CO_2 cycle as well as its lg p-h diagram which was established on the basis of the assumptions presented in **Table 2.** Theoretically compared to a classic vapor compression cycle, the transcritical CO_2 cycle is less efficient under the same conditions. Its basic characteristics define a significantly higher operating pressure than conventional refrigerant systems; The absence of phase change during the transfer of sensible heat from the high pressure side prevents a continuous drop in temperature of the CO_2 fluid and therefore can be heated to a very high temperature continuously. Due to the better flow and heat transfer properties of CO_2 [29], the volume and size of CO_2 heat exchangers can be reduced compared to other refrigeration systems. Even taking into account these advantages, the transcritical cycle presents less efficient performance at high outdoor ambient temperatures as presented by a drop in COP of 10% on a study carried out on the CO_2 air conditioning system [30] [31].

CO_2 used as working fluid in transcritical cycle technology to compete with conventional cycle is a major challenge. Efficiency remains the disadvantage of the transcritical system as the vapor produced at the outlet of the gas cooler must be compressed, not to mention the high compression ratio to be achieved. This phenomenon is all the more important as the outside temperature is high. The implementation of more complex cycles by researchers on transcritical systems allowing an improvement in efficiency similar to that of conventional fluids is presented and analyzed in the following sections.

Table 2. Hypothesis allowing the layout of the basic transcritical refrigeration cycle to CO_2 [27].

Fluid	Cooling capacity (kW)	Mass flow (kg/s)	Isentropic efficiency	Gas cooler inlet pressure (Bar)	Gas cooler outlet temperature (˚C)	Evaporation temperature (˚C)
R744	5	0.03089	0.75	90	30	−5



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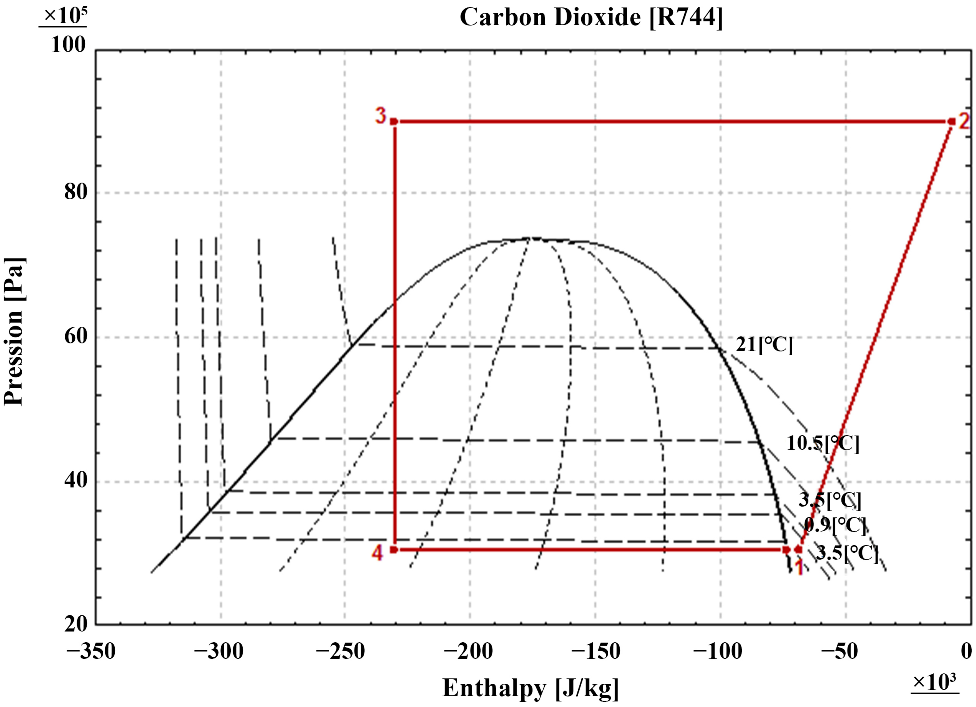


(b)

Figure 3. Basic transcritical CO_2 cycle (a) and lg p-h diagram (b) [27].

3.2. Transcritical CO_2 Cycle Technology Performance Improvements

In view of the results obtained in the comparison of the systems with conventional fluid and with CO_2 [32], it is noted that the efficiency of the basic system of the refrigeration cycle with transcritical CO_2 is lower. However, technological advances as illustrated in **Figure 4** promise to improve or even make this technology superior to conventional subcritical cycles.

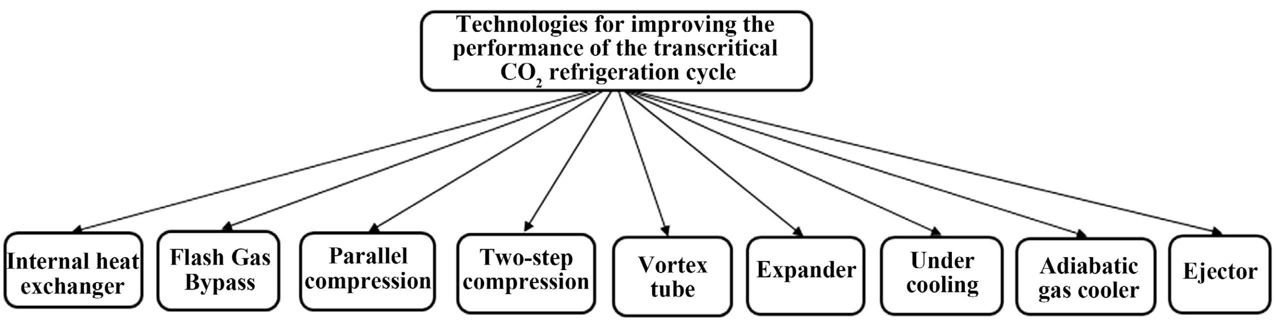


Figure 4. Transcritical CO_2 refrigeration cycle improvement technologies.

- **Cycle with internal heat exchanger**

To raise the level of performance of the transcritical refrigeration system, the internal heat exchanger (IHX) comes into play as shown in **Figure 5**, it is used to transfer heat between the base and high pressure circuits. It has been shown that it can both improve or decrease system performance due to the trade-off between increased capacity and discharge temperature depending on working fluids and operating conditions. [33] [34]. In improving the performance of the system, the IHX having a larger exchange surface is beneficial for the increase of the COP as well as the reduction of the optimal pressure to the value of the maximum COP by respecting the size limit to prevent the compressor discharge temperature to exceed its design limit [35] [36]. This COP value has undergone a 10% increase obtained in a transcritical CO_2 cycle for residential air conditioning [37]. In order to obtain the energy and exegetical performance of a transcritical CO_2 chiller with and without internal heat exchanger, Purohit *et al.* [38] carried out an experimental study in a hot climate situation (45˚C), the improvements obtained with the use of IHX were 5.71% and 5.05% in energy and exegetical efficiency respectively at an evaporation temperature of −5˚C.

Several other IHX configurations different from the one presented in **Figure 5** have been studied by Sanchez *et al.* [39] namely: cooler outlet, liquid reservoir outlet and in both positions at the same time. The best configuration was that of the coupling of the two positions from which an increase in the COP of 13% was obtained.

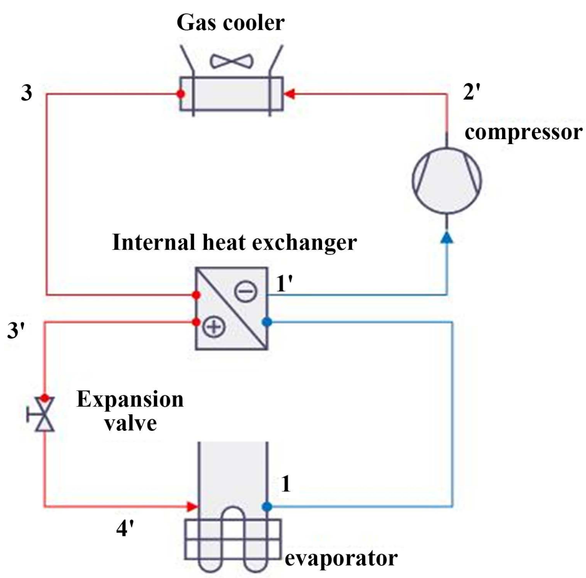


Figure 5. Transcritical CO_2 cycle with IHX [37].

A study carried out by Mohammed Tarawne on this cycle with a porous internal heat exchanger makes it possible to obtain an increase in the refrigerating capacity and the coefficient of performance of 49.7% and 93%, respectively and electrical consumption of the compressor per kW of refrigeration reduced by approximately 29.6% [40].

- **Flash Gas Bypass**

In the transcritical CO_2 refrigeration cycle, the proportion of fluid in the gaseous state coming from the gas cooler in the liquid receiver is greater compared to the conventional subcritical system where the condenser transforms the gaseous fluid partially or completely into liquid, and therefore the performance of the system is reduced when it ends up in the evaporator.

A possible approach to solve this problem is the implementation of a flash gas bypass (FGB), the purpose of this method is to have this vapor sucked directly by the compressor while avoiding its passage into the evaporator. Figure 6 shows the FGB configuration. Coming from the gas cooler, the fluid is throttled by the HP valve in a two-phase state and ends up in the liquid receiver where there is phase separation. Thus, the liquid found in the lower part of the tank is directed to the evaporator through the expansion device or expansion valve, while the vapor found in the upper part is led directly to the suction of the compressor through the MT valve. This valve plays an important role in controlling the evaporator outlet conditions in superheat regulation [41]. As part of the improvement of cycle performance by the FGB method, a parametric model of the CO_2 FGB system was established using an engineering equation solver, thus proving a COP improvement of 7% compared to the basic transcritical cycle [42], while an experimental comparison was carried out with a classic conventional system which presents an increase in the cooling capacity and the COP of 9 and 7% respectively thanks to the FGB [43].

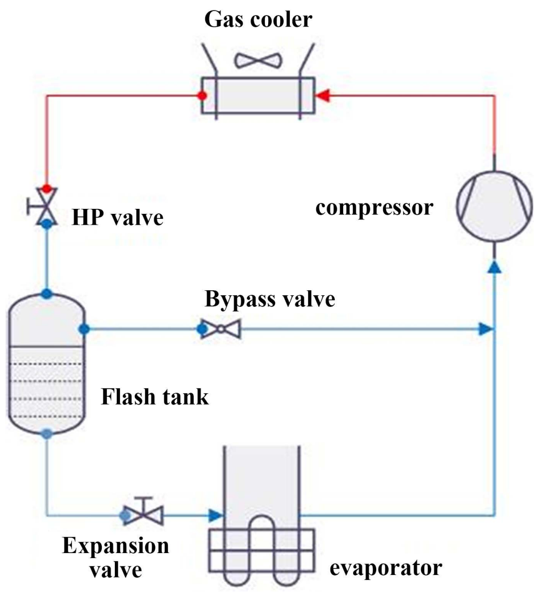


Figure 6. Transcritical CO_2 cycle with FGB [41].

- **Parallel compression**

The purpose of this technology is almost similar to that of the FGB discussed above, which is to avoid expanding the vapor coming out of the reservoir and then recompressing it. From the moment when the outside temperatures begin to increase (more than 15˚C), we will have inside the CO_2 tank a proportion of flash gas vapor which becomes very high and therefore this vapor must be eliminated not to disturb the operation of the MT compression stage. In addition to producing cold, this stage must also devote itself to eliminating gas flashes which increase with the increase in the outside temperature and therefore reduce the efficiency of the system. To compensate for these losses in efficiency, the setting up of a parallel compression stage which sucks from the reservoir is integrated into the transcritical cycle as illustrated in **Figure 7**, the concept being to reduce the losses of bottlenecks [44]. One method is to pass the flash gas through a vent in the main compressor compression chamber [45]. This design can also be made with a twin T-shaft compressor [46]. Another type uses a number of cylinders from the main compressor to do parallel compression [47]. The advantage of this technology is that there is less flash gas which disturbs the production of cold. Since this compression stage draws directly above the receiver, the required compression power is reduced and the system efficiency reaches at least or more the same level as refrigeration systems using FGB [48].

Some studies of the performance of this system have been carried out, including a theoretical and experimental study, which stipulates that an ideal cycle can achieve improvements in COP of more than 30% and cooling capacity of more than 65% compared to the basic CO_2 system [49]. Lui and coll [46] also compared parallel CO_2 compression to the base cycle and found up to 21% increase in COP and 5.3 bar reduction in discharge pressure at high outdoor ambient temperature although the improvement in COP is generally less than 10% under subcritical conditions. A study carried out by Tao *et al.* evaluates the thermodynamic performances of the CO_2 refrigeration cycle with ejector and parallel compression [50].

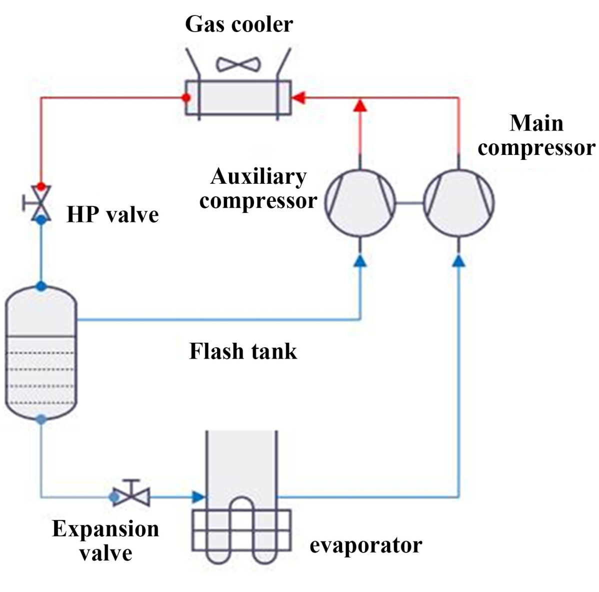


Figure 7. Cycle of the parallel compression system [44].

- **Two-step compression**

With respect to the fundamental system of the transcritical CO_2 refrigeration cycle, the two-stage compression as shown in **Figure 8**, is used for extremely low temperature cycles which cannot be produced economically through the use of a single-stage system. Indeed, the compression rate is too high to reach the temperatures necessary for the evaporation and condensation of the steam. Thus, the compression efficiency is reduced, the refrigerant vapor in the compressor increases in temperature and so does the energy consumption. Therefore, multi-stage compression with intercooling method can be used to improve system reliability. Various studies indicate that the heat rejection pressure alone is not enough to determine the optimal COP. In the case of the two-stage CO_2 refrigeration system, the other parameters such as the intermediate pressure and the intermediate temperature must be coupled and therefore require simultaneous optimization [9].

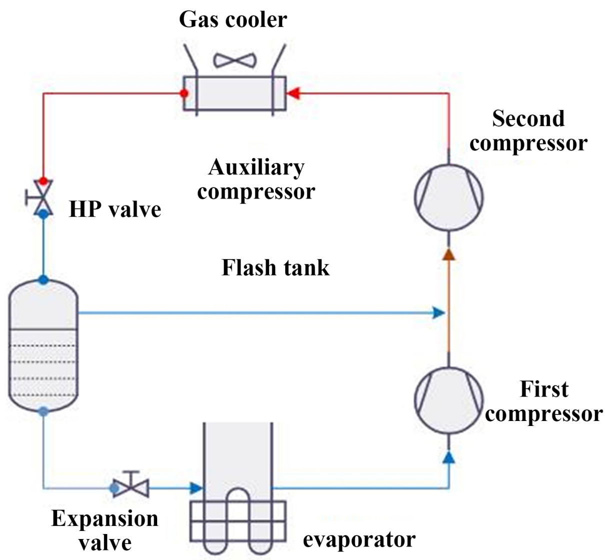


Figure 8. Cycle of CO_2 two-stage compression system with flash gas injection [51].

- **Vortex tube**

The vortex tube is an energy splitting device in which one airflow rises and the other descends, both rotating in the same direction with the same angular velocity. The speed of the internal vortex inside the vortex tube is conserved, which means that the torque of the internal vortex is lost. The lost energy manifests as heat in the outer vortex, which is why the outer vortex becomes hot and the inner one becomes cool as shown in **Figure 9**. The application of the vortex tube in the refrigeration system can reduce the loss of throttling process. CO_2 was used as the working fluid to simulate the energy splitting effect of the vortex tube [52]. In a study of the performance of two countercurrent vortex tubes, CO_2 provides greater thermal separation capacity than air [53]. Li *et al.* [54] studied a configuration of the transcrack CO_2 refrigeration system as shown in **Figure 10**. Assuming 100% gas-liquid separation efficiency, this system could provide up to 37% increase in cycle efficiency. A theoretical analysis of the transcritical CO_2 refrigeration cycle with vortex tube expansion was performed by Lui *et al.* [55].

The system with vortex tube was found to have a higher COP than the traditional system with expander.

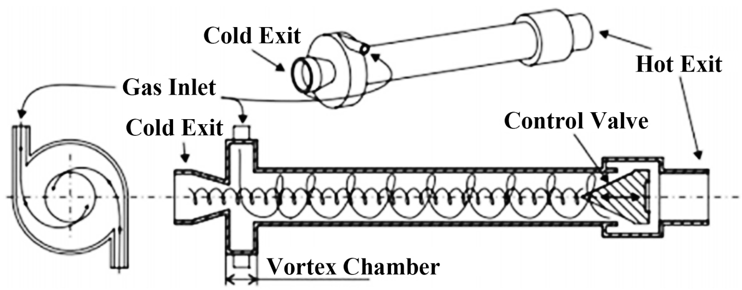


Figure 9. Vortex tube [56].

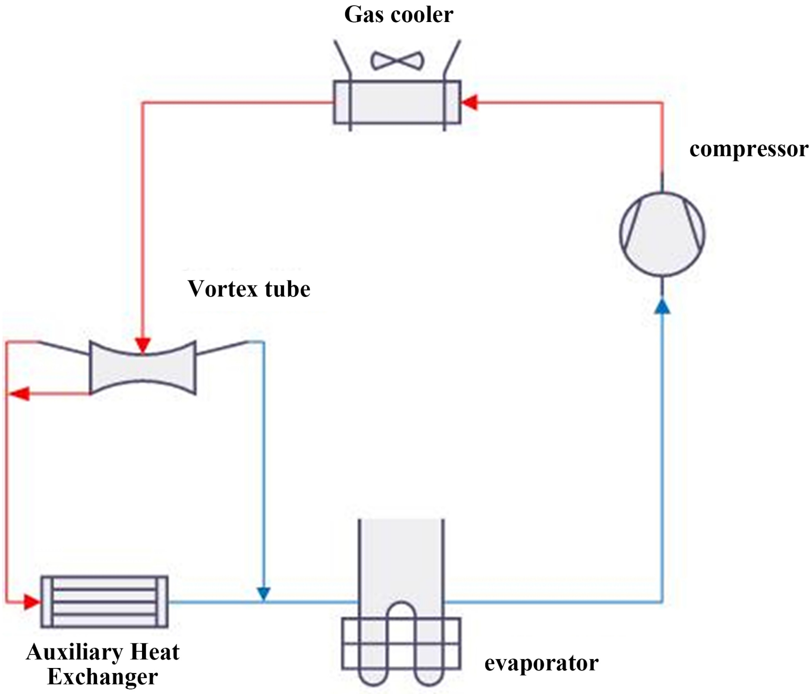


Figure 10. Vortex tube CO_2 refrigeration system [52].

- **Expander**

This technology allows expansion work recovery for the transcritical CO_2 cycle to reduce the throttling loss which is much higher due to the physical properties of CO_2. **Figure 11** shows the configuration of the expansion system in which the regulator is replaced by an expander. A few studies involving expanders in the CO_2 cycle have been elaborated among which Yang *et al.* [57] performed a thermodynamic analysis of the system and found that the efficiency of the transcritical CO_2 cycle with expander was more efficient, preventing a decrease of 50% exergy loss and a 30% improvement in overall system exergy efficiency. A recovery of about 37% of the compressor work can be observed with a marked improvement if the inlet temperature of the expander increases [58].

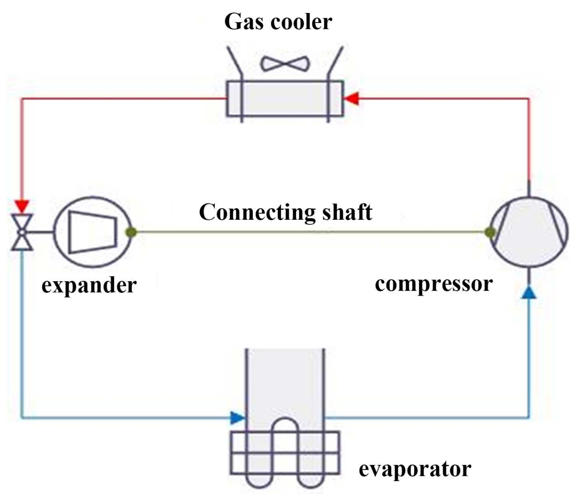


Figure 11. Expander CO_2 Refrigeration System [59].

- **Subcooling**

In the operation of the basic transcritical CO_2 cycle in a situation of high outside temperature, the temperature of the refrigerant at the outlet of the gas cooler is much higher than that of the ambient temperature, hence a high proportion of vapor which is unfavorable to the proper operation of the system. To overcome this restriction, the use of a subcooler as shown in **Figure 12** is one of the techniques to improve cycle performance to reach that of conventional systems at high ambient temperatures.

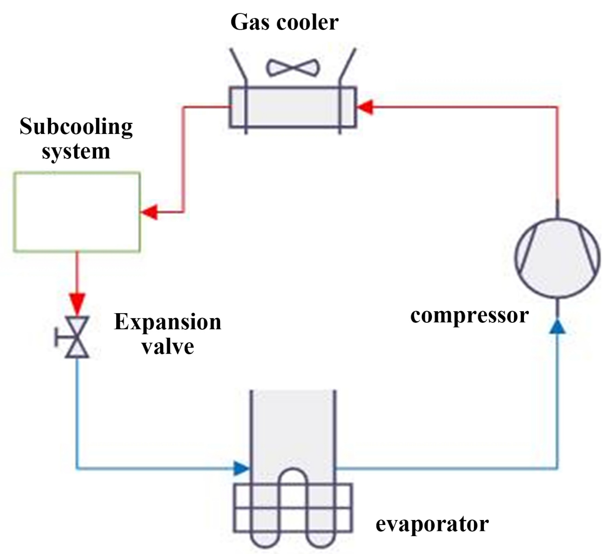


Figure 12. CO_2 refrigeration system with subcooling [60].

The objective is therefore to reduce the outlet temperature of the gas cooler to a value lower than that of the ambient temperature, thus producing a lower quantity of vapor in the expansion and consequently reducing the work of the parallel compressor. The researchers presented different subcooling technologies at the outlet of the gas cooler such as: the method of dedicated mechanical subcooling

(DMS) including a study of the performance compared to the parallel compression scheme and under cooling via gas cooler dedicated water was carried out by D'Agaro. For the thermoelectric subcooling (TES) method, a thermoelectric module based on the Peltier effect is used. This concept has been used in transcritical CO_2 refrigeration by Schoenfield *et al.* [60] who evaluated the effects of the input current on the overall cooling capacity of the system and the COP.

- **Adiabatic gas cooler**

As mentioned in the previous section, the efficiency of the basic transcritical CO_2 system weakens under high outdoor ambient operating conditions. The adiabatic gas cooler is an evaporative cooling method which consists of pre-cooling the air before it enters the gas cooler as shown in **Figure 13**. This method of spraying water to the condenser is also applied in refrigeration facing temperature peaks [61]. However, there is a trade-off between balancing water consumption and improving COP for practical application in CO_2 system. Girotto *et al.* [62] [63] analyzed both solutions and found an improvement in COP of 17% for a 30% precooling solution and a COP of 27% for a 100% precooling solution. However, the ideal choice should refer to the actual climate, the area where the equipment will be installed, and the availability of water.

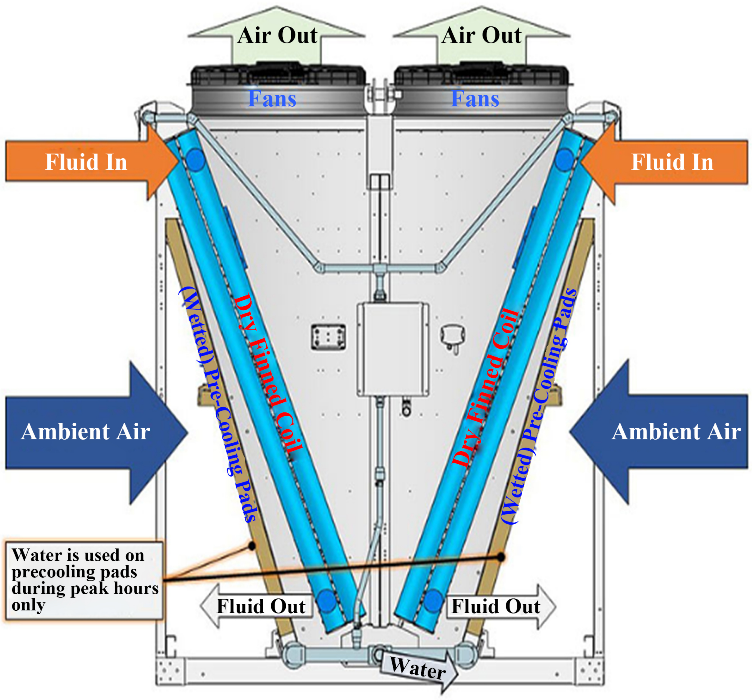
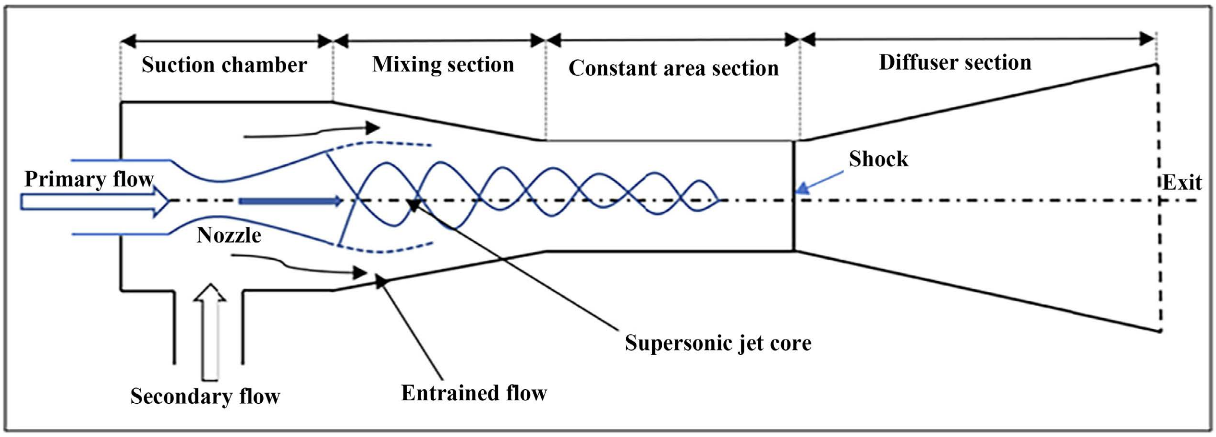


Figure 13. Adiabatic cooling process [64].

- **Ejector**

Specifically used as a vacuum pump in steam installations, the ejector is a device known since antiquity. Its technology has been widely studied over time of which a comprehensive review was presented by Besagni *et al.* in 2016 [65]. In transcritical CO_2 installations, it is used to increase the pressure of another refrigeration line completely free of charge by exploiting the expansion at the outlet of the gas cooler as shown in **Figure 14(a)**. Thereby, it can improve system efficiency and reduce exhaust pressure appropriately [66] as well as improve COP by up to 28% [67] [68]. The ejector is a simple, low-cost system with no moving parts, so it is widely used in the prospect of improving the efficiency of the transcritical CO_2 system. **Figure 14(b)** shows its integration into the modified cycle [69] which, thanks to its mechanism, makes it possible to exploit the depression created by the venturi effect and makes it possible, using first a pressurized fluid, to compress a second fluid by mixing them while transmitting energy to the fluids. This technology has undergone several studies in its process of improvement and optimization in the applications of mobile air conditioning [70], multi-ejector system in the refrigeration of supermarkets [71], dairy, sea water chiller [72], residential CO_2 air conditioning [73] and several other improvement studies as presented in **Table 3** [74]. Zheng *et al.* present a review of modeling, optimization and experimental studies of ejectors for CO_2 refrigeration [75].



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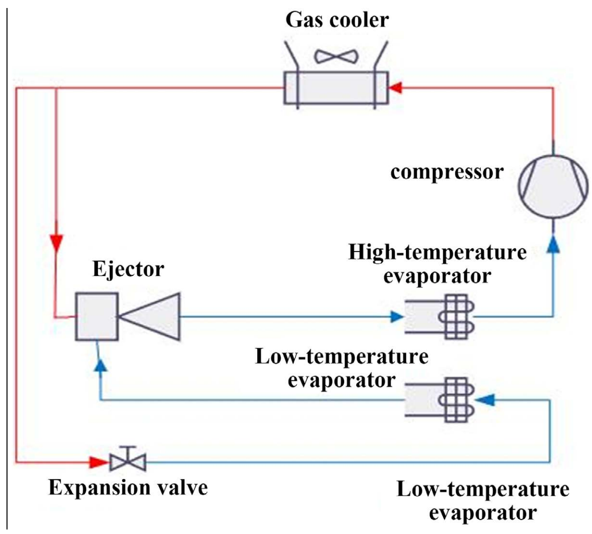

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Figure 14. (a). Diagram of the ejection [76]; (b). Integration ejector in the CO_2 refrigeration cycle [77].

Table 3. Hypothesis Latest advances in research on the ejector and its CO_2 refrigeration cycle system [83]

Reference	Date	System characteristic and cycle	Ejector types (primary stream)	Research method	Main conclusion
Belmanflores *et al.* [78]	2020	Transcritical CO_2 cycle with ejector	Supercritical CO_2 fluid	Advanced exergoeconomic analysis	The ejector system with the lowest environmental impact and the lowest cost of the exergy product
Lui Y *et al.* [79]	2020	Two-stage compression transcritical CO_2 refrigeration cycle with one ejector and dual evaporators	Supercritical CO_2 fluid	Theoretical analysis	Compared to the conventional system, the new system improved COP and exergy efficiency by 19.6% and 15.9% respectively and the HT compressor discharge temperature dropped by 10.5˚C
Kumar *et al.* [80]	2020	Hybrid transcritical CO_2 vapor compression and ejector refrigeration system	Two-phase R32 fluid	Theoretical analysis	At the temperature of 12.5˚C, the refrigeration capacity and the COP of the R32-CO_2 hybrid system increased by almost 50% and 45% respectively
Peris Perez *et al.* [81]	2021	Two-stage refrigeration cycle with CO_2 ejector and expansion	Supercritical CO_2 fluid	Thermo economic analysis	The system is more efficient and compact, while increasing the average annual COP
Elbarghthi *et al.* [82]	2021	Ejector boosted transcritical CO_2 refrigeration system	Supercritical CO_2 fluid	Exergy analysis and experimental study	Ejector can provide 20% exergy efficiency and lower exergy destruction at higher nozzle flow temperature
Liu X *et al.* [83]	2021	Transcritical CO_2 ejector refrigeration system equipped with thermoelectric subcooling	Supercritical CO_2 fluid	Exergy analysis	When compressor efficiency and ejector efficiency are increased from 0.5 to 0.9; 93.6% and 82.33% avoidable endogenous exergy destruction of the corresponding parts of the system can be avoided respectively
Lui J *et al.* [84]	2021	Transcritical CO_2 refrigeration cycle with double evaporators and double ejectors	Supercritical CO_2 fluid	Exergy and energy analysis	Under all given conditions, COP and exergy efficiency are increased by 15.9 to 27.1% and 15.5 to 27.5% respectively
Exposito-Carrilo *et al.* [85]	2021	Two-stage CO_2 refrigeration cycle with ejector	Supercritical CO_2 fluid	Thermodynamic analysis	COP increases up to 13% under typical ejector working conditions
Purjam *et al.* [86]	2021	The modified transcritical CO_2 cycle with ejector	Supercritical CO_2 fluid	Thermodynamic analysis	The ejector and the compressor have the greatest exergy destruction during operation but the ejector reduces the exergy destruction rate of the whole cycle. Meanwhile, the ejector is the main source of entropy production

3.3. Application of CO_2 Refrigeration and Heating Cycle Technology

- **Transcritical CO_2 technology in commercial refrigeration**

Refrigeration plays a central role in the process of preserving and transporting perishable goods. Applied in commercial supermarkets, it includes refrigerated display cases, refrigerators and cold stores. Traditional supermarket refrigeration equipment consumes a huge percentage of kilowatts compared to other commercial establishments [87] [88]. In addition, these traditional systems use conventional refrigerants as the working fluid, which represents a danger to the environment. The CO_2 used as a refrigerant in these systems is a much better solution in the field of food refrigeration [89].

In order to improve the CO_2 transcritical cycle technologies of supermarkets, researchers have developed the indirect CO_2 refrigeration system, the refrigeration system using CO_2 as a low temperature cascade configuration refrigerant and the refrigeration system using CO_2 as the main refrigerant [90]. Sun *et al.* [91] designed a partial cascade CO_2 two-stage commercial supermarket compression refrigeration system, then compared it to the traditional R134a system.

- **Transcritical CO_2 technology in winter sports fields**

The once natural ice and snow fields have gradually been replaced by artificial fields, which makes ice/snow sports one of the most popular activities. Artificial ice rinks generally use mechanical refrigeration systems to provide cooling. Early artificial ice rinks primarily used R22 as a refrigerant and brine as a secondary loop medium [92]. At the end of the 20th century, CO_2 began to be applied to the refrigeration systems of artificial ice rinks and the results obtained were remarkable [93]. For the first time in the field of winter sports, transcritical CO_2 technology has been used in the 2022 Winter Games in China, which not only meets the concept of "green Olympic science and technology", but also encourages the research and development of the application of transcritical CO_2 engineering technology in ice and snow sites [94].

- **Transcritical CO_2 technology in automotive air conditioning**

Conventional refrigerants such as R134a and R407c are often used for the air conditioning of passenger and commercial vehicles respectively. The use of transcritical CO_2 refrigeration system in automotive air conditioning has the advantages of high cooling capacity, low pressure ratio, high working efficiency and environmental protection [95].

Transcritical CO_2 technology in automotive air conditioning seems to be better suited but however exhibits very high operating pressures. A system configuration with indirect heating or cooling has been proposed as illustrated in **Figure 15** by Carrie *et al.* [96]. In order to meet the global cooling and heating demand of electric vehicles, Chen *et al.* [97] developed a CO_2 heat pump system with intercooling. Wang *et al.* [98] compared the performance characteristics of R134a and CO_2 heat pump systems in electric vehicles.

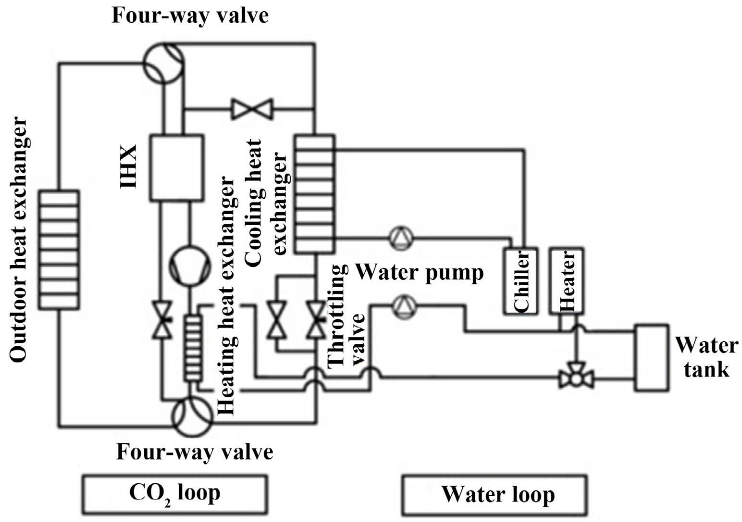

Figure 15. Diagram of the indirect AC-HP CO_2 system [96].

A bibliographic study carried out by Hongzeng *et al.* presents progress on transcritical CO_2 heat pumps and refrigeration cycles in the field of vehicles [99].

- **Transcritical CO_2 technology in heat pump systems**

Heat pump heating has become an increasingly popular technology due to its performance and ability to reduce energy costs [100]. The heat pump using CO_2 as the working fluid is an innovative and eco-responsible dual-use technology (heating and DHW) that offers superior performance to conventional systems [101]. The use of R744 in the heat pump cycle is accompanied by the high operating pressures in low and high pressure. In order to improve the efficiency of the system, a sub-cooler is used, but the expansion operated on the gas for this exchange also allows reinjection into the intermediate stage of the compressor. Thus, the overall pressure of the discharged gases decreases, and the power absorbed by the compressor is reduced. Ghazizade-Ahsaee *et al.* [102] introduced as presented in **Figure 16**, the thermoelectric subcooling and the ejector in the transcritical CO_2 direct expansion geothermal heat pump system, and found an increase in the COP and system stability. Feng *et al.* [103] built an experimental platform for a transcritical CO_2 heat pump water heater system. An experimental study on the performance of a compact, water-cooled CO_2 heat pump assisted by a subcooler presents a significantly increased cooling capacity and coefficient of performance of 40.7% and 37.7% respectively. Additionally, the optimum discharge pressure is lowered by 0.5 MPa [104].

- **Challenges and Prospects of Transcritical CO_2 Refrigeration Technology**

Carbon dioxide used as a working fluid in refrigeration systems has proven its potential in this field. However, it is clear that standard CO_2 systems were very well suited to cold (<8˚C) or even temperate (≤15˚C) climates. From the moment the external temperatures begin to increase, we find inside the CO_2 tank a proportion of flash gas vapor which becomes greater and disrupts the operation of the medium temperature compression stage; Which makes the standard base

CO_2 system less effective for hot climates. To compensate for these losses in efficiency, researchers integrated "a parallel compression stage". This technological advancement makes it possible to equip the standard system with one or more compressors which suck from the upper level of the CO_2 tank and therefore reduce the proportion of flash gas which disrupts the production of cold. Thus, the consumption of electrical energy is reduced compared to the compressor which sucks at the level of the evaporator.

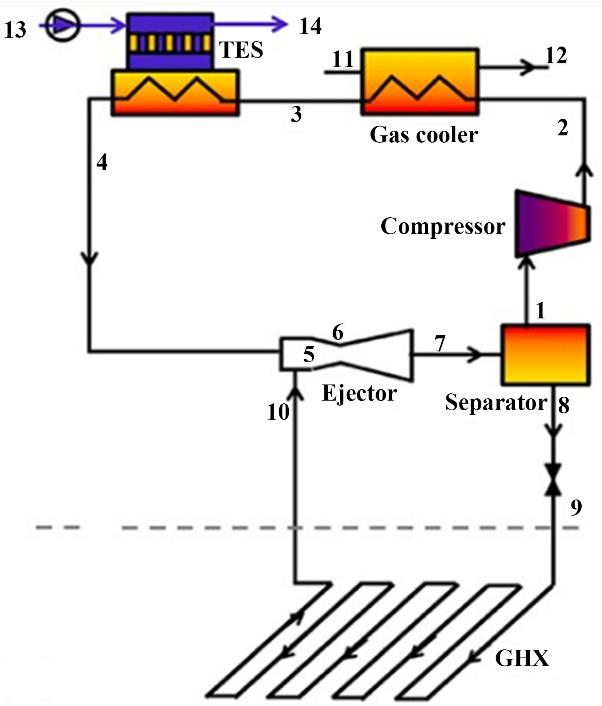

Figure 16. Schematic layout of a geothermal CO_2 heat pump with ejector and thermoelectric subcooling [102]

3.4. Engine Cycle and Power Technology Using CO_2 as the Working Fluid

After the text edit has been completed, the paper is ready for the template. Improving energy efficiency and reducing greenhouse gas emissions are key to the technological progress of electrical systems. Various engine cycles and CO_2 power have been proposed for various applications. However, their potentials for waste heat recovery are still largely unexplored. For low temperature heat applications, transcritical cycles, in particular the organic Rankine cycle (ORC) can compete with other existing technologies. While supercritical CO_2 cycles, in particular the supercritical Brayton cycle, are more attractive for medium and high temperature sources to replace Rankine vapor cycles. As a working fluid, the environmentally friendly fluid CO_2 has interesting thermophysical properties (density, isobaric specific heat capacity, thermal conductivity and viscosity), represented by the curves in **Figure 17**.

CO_2 can be used as an alternative to organic working fluids in small to medium sized electrical systems for low quality heat sources. It is considered a promising fluid for closed Brayton and Rankine cycles, but its unique property calls for new thinking in the design of cycle components.

Using low-grade heat as an energy source and recovering waste heat from various processes offers opportunities for sustainable energy in the future with fewer environmental issues. The fundamental technologies for converting this low quality heat into electricity using CO_2 as the working fluid, including transcritical organic Rankine cycle technology and supercritical Brayton cycle technology are elaborated in the following sections along with advances in engine cycle technology and CO_2 power.

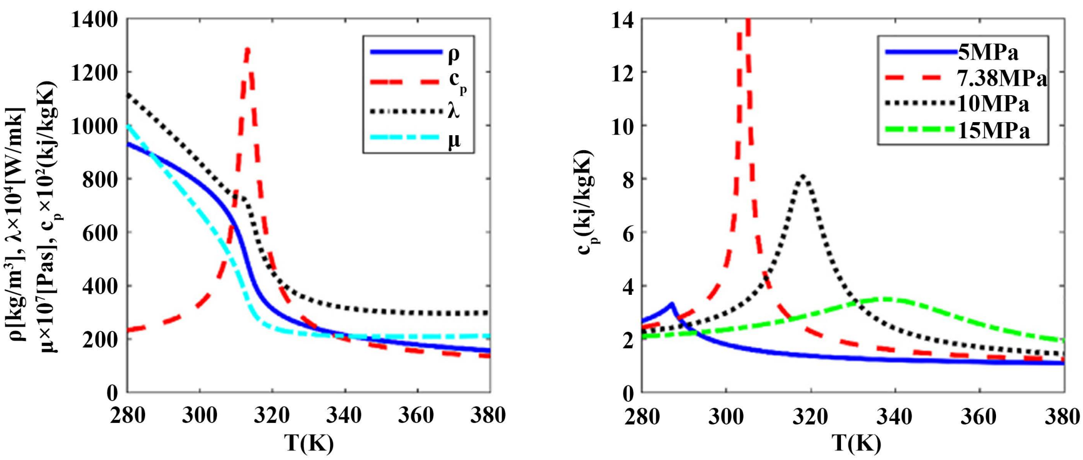

Figure 17. Thermophysical properties of CO_2: (a) the pressure is 9 MPa; (b) Isobaric specific heat capacity under different pressures [105].

3.4.1. Characteristic of Supercritical CO_2 Engine Cycle

Power conversion systems include organic Rankine cycle (ORC), steam Rankine cycle (steam turbine), air Brayton cycle (gas turbine), combined cycle gas turbine (CCGT) and the direct and indirect cycles SCO_2. The Brayton cycle SCO_2 is the power conversion system which combines the advantages of the steam Rankine cycle and the gas turbine system as schematically shown in **Figure 18**. Due to this, the fluid is compressed in the incompressible region and higher turbine inlet temperature can be operated with fewer material issues compared to steam Rankine cycle. System performance is affected by temperature and supercritical CO_2 pressure at the high pressure turbine inlet, as this temperature increases, system efficiency also increases, especially at low turbine inlet temperature pressure. For a simple CO_2 engine cycle, the efficiency of the system increases proportionally with the improvement in the efficiency of the turbine.

3.4.2. Application of the Supercritical CO_2 Engine Cycle

As indicated in the previous section, many potential advantages exist for the SCO_2 engine cycle. It can be applied to various heat sources such as: nuclear and coal-fired power plants, waste heat recovery, concentrating solar systems and geothermal energy devices. The following sections discuss recent progress of the various applications of supercritical CO_2 cycles.

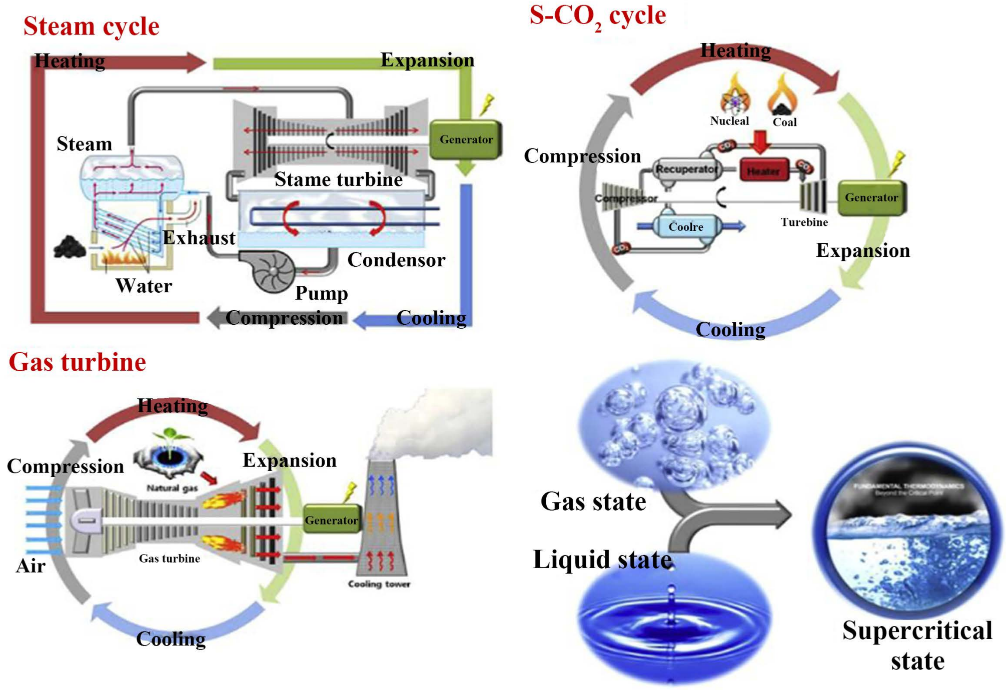

Figure 18. Principles of the power conversion system: steam engine cycle and supercritical CO_2 [106].

- **Nuclear reactor**

The SCO_2 power cycle is being researched for application to sodium-cooled fast reactors [107] [108]. This cycle is often used in high-temperature gas-cooled reactors, which have high thermal efficiency, relatively low turbine inlet temperature, compact size and simple layout [109]. However, the rate of heat transfer in the recuperator is limited by the pinch point [110]. To improve system performance, a recompression cycle as shown in **Figure 19** has been proposed, and the split-flow arrangement can effectively alleviate this problem. This SCO_2 recompression cycle can be applied to a fourth generation sodium-cooled fast reactor, it is also promising for fusion reactors whose estimated efficiency is 42.44% [111]. Although this cycle has a higher efficiency than other configurations, research indicates that it is difficult to improve it further [112].

- **Waste heat recovery**

SCO_2 power cycle can be used as lower cycle for waste or exhaust/waste heat recovery, which can be gas turbine or internal combustion engine with overall energy efficiency improvement. Hou *et al.* [113] designed a combined cycle consisting of a gas turbine, a SCO_2 recompression cycle, a steam Rankine cycle and an ORC with an azeotropic working fluid, they found a 2.33% efficiency increase compared to traditional gas-steam combined system.

In the marine application, a CO_2 power system was integrated with a compression refrigeration cycle using CO_2 as the working fluid; the exhaust heat from the gas turbine was used to drive the regenerative cycle of SCO_2, resulting in an 18% increase in system power output [114]. A mixture based on CO_2 in the combined cooling and power cycle for the recovery of residual heat from the engine was studied [115] [116] and an optimization was carried out by Ligeng *et al* [117]. Zhenchang *et al.* carried out a study on supercritical CO_2 power cycles for energy cascade use of natural gas engines, the thermal efficiency was increased from 42.4% to 48.94% [118]. Improving the performance of the combined CO_2 refrigeration and electricity cycle driven by engine exhaust gases is carried out by Elattar *et al.* [119].

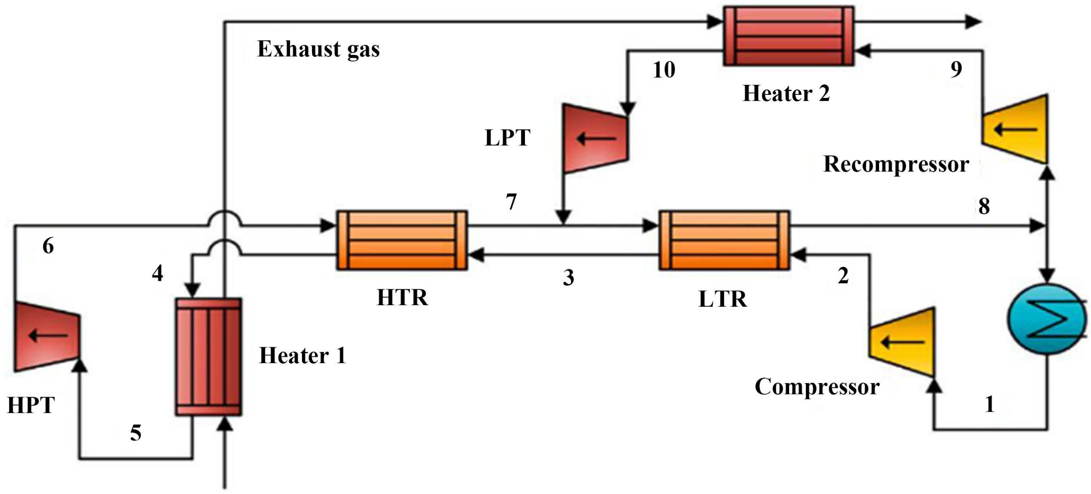

Figure 19. Modified SCO_2 recompression cycle for engine waste heat recovery [120]

Figure 19 shows the modified SCO_2 recompression cycle in which two heat exchangers have been installed to recover in series the waste heat which can be on an internal combustion engine, the heat of the coolant and that of the exhaust gases. Under the design conditions, the waste heat recovery efficiency was 17.86% higher than that of the recompression cycle for an efficiency of 74.83% [121]. In order to recover these two heat sources simultaneously, Song *et al.* [122] designed an SCO_2 cycle with two-stage regeneration and the maximum engine power output was increased by 6.9%. A modified SCO_2 Brayton recompression cycle which combines the advantages of the preheated Brayton SCO_2 cycle is being studied to recover waste heat from gas turbines [123]. An optimization study of the organic Rankine cycle powered by the residual heat of a multi-ejector CO_2 refrigeration cycle was carried out by Dimitrios *et al.* [124].

- **Concentrated solar power system**

The performances of the SCO_2 cycles were studied for high temperature solar thermal energy systems whose thermal efficiency was about 32% for a source of temperature 600˚C and a compressor inlet pressure of 85 bar [125]. Al Sulaiman *et al.* [126] evaluated five different SCO_2 cycle configurations for a solar power plant with a heliostat field, the best efficiency of 40% was obtained with the regenerative cycle whose performance Singh *et al.* [127] analyzed direct-fired regenerative CO_2 cycle dynamics for large-scale solar power generation. To cope with variations in solar radiation, a CSP system with heat storage has been studied [128]. When power output fluctuates frequently, turbine and compressor performance degrades significantly for every 1% reduction in turbine efficiency, system efficiency and relative power output could be reduced by 0.431 and 1.713% respectively [129]. Therefore, variations in turbine and compressor efficiencies should be assessed during the system design phase to improve the robustness of the SCO_2 cycle. A radial turbine can be used in an SCO_2 cycle thanks to its low expansion rate. El Samad *et al.* [130] designed a single-stage radial turbine for a 100 MW SCO_2 cycle. For solar power plants, a thermodynamic analysis of the CO_2 -SF6 mixture Brayton cycle is more effective than SCO_2 [131].

- **Geothermal energy production**

Rankine's transcritical CO_2 cycle is more suitable for this technology because it has much lower temperatures than nuclear reactors and coal-fired power plants. Few studies have assessed the feasibility of the SCO_2 cycle for the use of geothermal energy. Ruiz-Casanova *et al.* [132] compared four different configurations and reported that intercooling could reduce CO_2 mass flow as well as compressor work.

Compared with conventional Rankine steam cycle, SCO_2 cycle has low critical pressure, high density, high heat transfer rate, high specific power and small size which makes it suitable for various heat sources.

- **Improvements to the Rankine Cycle at transcritical CO_2**

Rankine's transcritical CO_2 cycle is suitable for low-grade energy use. Chen *et al.* [133] found that this cycle is suitable for energy recovery from low quality heat sources. In the transcritical Rankine cycle, the working fluid is heated directly from the liquid state to the supercritical state. CO_2 with a critical temperature (31.4˚C) and a relatively low pressure (7.38 MPa), can be compressed directly to its supercritical pressure and heated to its supercritical state before expansion in order to obtain a better thermal match with the heat source [134]. The temperature curves between the CO_2 and the heat source are approximately parallel due to the excellent temperature glide match, which can effectively avoid pinch point limitations as shown in **Figure 20** hence less loss of exergy [135].

Recent research has also shown that the SCO_2 power cycle has excellent performance in utilizing solar energy and geothermal heat which has low power generation cost [136], compact system size and superior thermal efficiency [137] [138]. Experimental studies on a transcritical solar CO_2 cycle using a solar collector field, a microturbine, a condenser, a feed pump and CO_2 as the working fluid have been carried out [139]-[142].

More importantly, the transcritical CO_2 Rankine cycle can efficiently utilize a lower temperature heat source than organic working fluids due to the low critical temperature of CO_2. In order to improve the performance of the CO_2 Rankine cycle for different heat sources and purposes, the following changes have been made: 1) an internal heat exchanger is introduced into the CO_2 Rankine cycle at high temperature of the heat source whose temperature range generates the optimum pressure is higher and the optimum pressure can be reduced by using an internal heat exchanger [143]. 2) Solar-based transcritical CO_2 Rankine cycle for heat and power cogeneration has two heat recovery systems whose efficiency Zhang *et al.* [139] [144] reported electrical, thermal and heat recovery efficiency of their Rankine transcritical CO_2 system could reach up to 20%, 36.2% and 68.0% respectively. 3) The transcritical CO_2 Rankine system with multiple heat sources should realize cascading use of energy. Farzaneh *et al.* [145] found that an additional heat source would increase the net power output and the thermal efficiency of the system. Rankine's CO_2 cycle with multiple heat sources reduces cooling water requirements. 4) Rankine transcritical CO_2 cycle with an ejector can improve maximum net power output by up to 10.2% but decrease thermal efficiency by 23.9% [146].

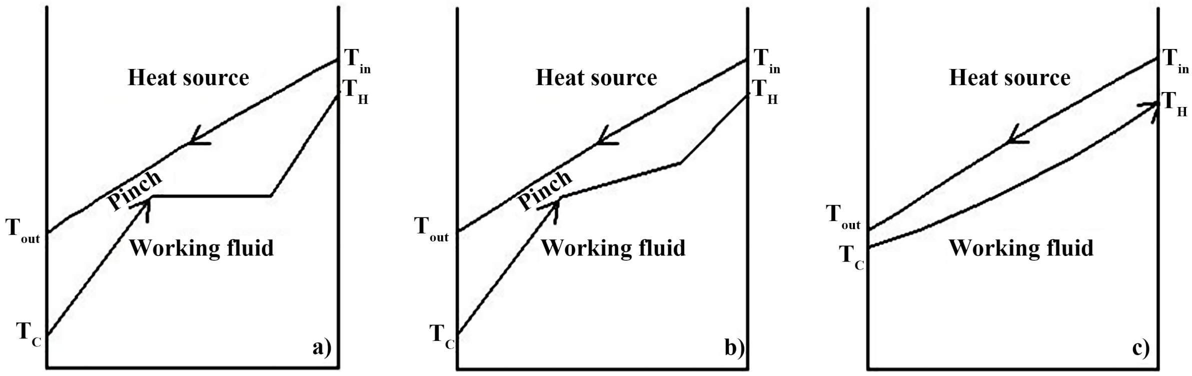

Figure 20. Heat source temperature profiles with (a) pure, (b) zeotropic, and (c) supercritical fluid [147].

- **Supercritical CO_2 Brayton cycle**

Principle **and advantage of the Brayton cycle**

The basic Brayton cycle consists of at least five main components namely: heater, turbine, pre-cooler, compressor and working fluid. The different basic processes are adiabatic compression, isobaric heating, adiabatic expansion and isobaric heat release. **Figure 21** presents the cycle and the T.S. diagram in which the actual process is represented by the red dotted line due to the loss of energy during the cyclic process.

1) Due to the low work of compression, the supercritical CO_2 Brayton system exhibits high thermal efficiency when applied at moderate temperatures. **Figure 22** presents the curves of variations of the thermal efficiency of the cycle with different forms of system varying with the temperature of the heat source under the typical operating conditions, including water-Rankine, helium Brayton (a turbine and a compressor), helium Brayton (three turbine, six compressors, intermediate heating and cooling).

2) Critical pressure is one-third that of water, allowing it to operate under relatively low pressure.

3) The high density of the supercritical CO_2 fluid allows smaller equipment such as: fairly compact turbomachines and more compact heat exchangers.

4) The pressure ratio decreases the number of stages in the turbine.

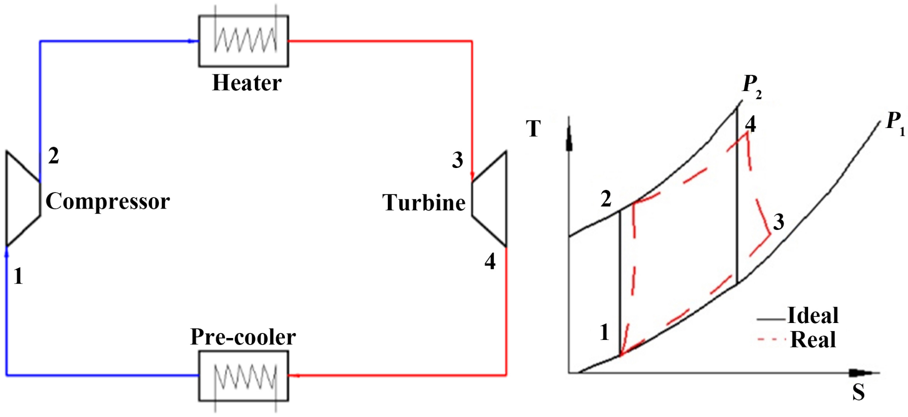

Figure 21. Flowchart and TS diagram of the basic Brayton cycle [148].

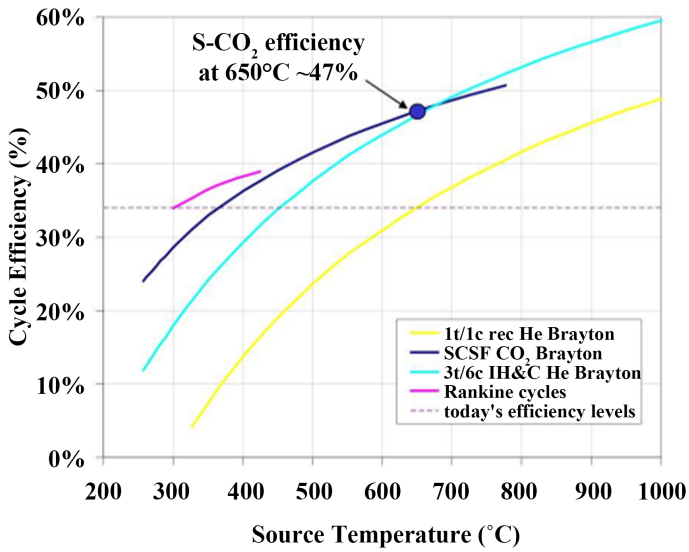

Figure 22. Thermal efficiency of the cycle as a function of the temperature of the heat source [149].

However, the supercritical CO_2 Brayton cycle still has some disadvantages such as the corrosive material with temperatures above 500˚C and the requirement of high pressure to achieve high efficiency. The following sections present the different modifications of the cycle carried out by the researchers.

- **Brayton SCO_2 cycle with reheat**

The work capacity of the turbine for several cycle configurations can be increased by adding a reheat process. Comparative performance studies for these different cycle configurations (SRBC, RCBC, pre-compression and expansion cycle) have been conducted by several researchers. Liao *et al.* [150] performed analyzes and comparison of the performance of these new configurations, the results showed that the RCBC has the highest efficiency up to 45%.

- **Brayton SCO_2 cycle with cogeneration of heat and electricity**

Although the Brayton SCO_2 cycle has proven to be a promising motor cycle for providing high efficiency in excess of 50%, it can still be improved by adding a suitable bottom cycle using its own waste heat, such as the Brayton CO_2 transcritical cycle (TCBC) [151], ORC [152]-[154], KC [155] and the organic flash cycle (OFC) [156]. This cycle can be applied to solar energy, nuclear energy, high temperature fuel cells, waste heat sources and CO_2 capture and storage in coal-fired power plants.

The Brayton cycle uses concentrated solar energy to directly heat supercritical CO_2 to power a turbine. Singh *et al.* [127] developed a control-oriented direct heating SRBC model varying with ambient temperature. Since the value of solar heat input varies with temperature, an extremum-seeking control strategy by regulating the CO_2 mass flow rate has been proposed to maximize the power output of a direct-fired SRBC system [157] which was also studied by Singh *et al.* [158] with dry cooling and a softer response.

SCBC replacement of other electrical or working fluid cycles applied to solar energy is competitive. Turchi [159] found that RCBC had higher thermal efficiency among helium BC. Muto *et al.* compared performance between PCBC (650˚C, 20 MPa) and Brayton subcritical cycle with two intercoolers (650˚C, 10 MPa), where each cycle was integrated with a 100 Mw centralized solar system. The thermal efficiency of PCBC was found to be around 48.9% compared to 45.3% for other cycles. Enriquez [160] revealed that the gross efficiency of the SRBC with reheating of two double loop solar fields was 44.4%, while the gross efficiency of the Rankine subcritical water power cycle was 41.8%. Saboora *et al.* evaluated the performance of a concentrated solar power plant using Brayton cycles with supercritical carbon dioxide [161], an optimization study was carried out on a solar tower energy production system with supercritical CO_2 integrated into the cycle Steam Rankine [162]. Thermodynamic optimization of supercritical carbon dioxide Brayton cycles for combined heat and power production is studied by Ruiqiang *et al.* [163]. For the application of the solar thermal power plant integrated into the air-cooled supercritical CO_2 Brayton cycle with concentrator, the GHG emissions of the s CO_2 cycle are 21% to 41% lower than those of the steam Rankine cycle [164].

5. Conclusion and Suggestions for Future Work

A review of technological advances, as well as recent technical obstacles and advancements in refrigeration and engine cycles using CO_2 as the working fluid is presented in this article. The study discusses the improvements in the performance of its systems operating on CO_2 compared to conventional working fluids and proposes solutions that can be applied. From the basic cycle to the improved cycle of transcritical CO_2 refrigeration, the additional functionalities necessary to further improve the performance of the system have been described, as well as the related issues highlighted. It shows that the technology of the CO_2 refrigeration cycle with ejectors is the most studied and has better performance than those of the others.

Various applications using CO_2 as a working fluid were also presented; unlike the refrigeration cycle, the efficiency of which collapses in a hot climate, the CO_2 engine cycle is more beneficial in these conditions and is of great interest for the recovery of heat, in particular in the Rankine and Brayton cycles of which this article presents recent advances in the operation of the cycle, as well as the various applications in the recovery and exploitation of low-grade heat for the production of electricity.

- A prospect for future improvement is to integrate modulating steam ejectors for low superheat operation and a semi-flooded evaporator for the transcritical CO_2 refrigeration cycle. So the compression stage MT can be disconnected from the evaporator and connected directly to the upper level of the CO_2 tank, this compression stage will have to compress the refrigerant flow to the gas cooler, then will go to one side towards the ejectors which will suck on the other side all the flow coming from the medium temperature cold station and precompress this flow towards the liquid reservoir;
- In order to improve the performance of the CO_2 refrigeration cycle, recovery of the expansion work can be carried out on the gas-cooler outlet pre-expansion valve in order to reduce the work input to the thermodynamic system;
- Another perspective is to use the free energy coming from the high HP pressure through the ejector to draw in and recompress the fluid coming from the evaporator. This will allow the system to be more efficient when outside temperatures are high and can therefore be a solution for the proper functioning of the CO_2 refrigeration system in all climates and for all seasons.
- CO_2, although it is a natural fluid with very low GWP and ODP suitable for the refrigeration cycle, has a major disadvantage which is operation in transcritical mode at external temperatures above 15˚C; Compared to other conventional refrigerants, at this temperature range or higher, the system operates in subcritical mode and good condensation of the fluid occurs, thus improving refrigeration production. This disadvantage linked to the thermodynamic properties of CO_2 in the refrigeration cycle, turns out to be rather advantageous in electrical power cycles, the study of which also presents the performances and the various technological advances in this area.

Although it is suitable for these two cycles, high dose inhalation by humans can be harmful to the body and requires a CO_2 level monitoring device in critical areas in the event of a possible leak.

With increasingly efficient improvements, it is expected that system technologies using CO_2 as the working fluid will become more competitive compared to those of conventional fluids. The combination of the refrigeration cycle and transcritical CO_2 engine cycle could be a practical option in the context of improving system performance, obtaining better efficiency and respecting the environment.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Abbreviations

CO_2 Carbon dioxide
TCBC Transcritical CO_2 Brayton Cycle
CFC Chlorofluorocarbon
PCBC Partial Cooling Brayton Cycle
HCFC HydroChloroFluoroCarbon
ECS Domestic hot water
HFC HydroChloroFluoroCarbon
HVAC Heating Ventilation and Air Conditioning
TCO_2 Transcritical carbon dioxide
COP Coefficient of performance
SCO_2 Supercritical carbon dioxide
Mpa Mega Pascal
SRBC Simple Recuperator Brayton Cycle
MT Medium temperature
RCBC Recompression CO_2 Brayton Cycle
HP High pressure
SCBC Supercritical CO_2 Brayton Cycle
REF Refrigeration