International Archive of Applied Sciences and Technology
Int. Arch. App. Sci. Technol; Vol 9 [2] June 2018 : 01-06

[ISO9001: 2008 Certified Organization]
www.soeagra.com/iaast.html

IAAST
ONLINE ISSN 2277- 1565
PRINT ISSN 0976 - 4828

CODEN: IAASCA REVIEW ARTICLE

DOI: .10.15515/iaast.0976-4828.9.2.16

Future of CO_2 as a Green Refrigerant : A Review

Manpreet Singh Brar[1], Rajesh Kumar[1*], Sarita[2] , Rajender Kumar[1], Amandeep Singh[3]
[1]Department of Basic Engineering, CCS Haryana Agricultural University, Hisar (INDIA)
[2]Department of Physics, Govt. (P.G.) College, Hisar(INDIA)
[3]Department of Soil water Engineering, CCS Haryana Agricultural University, Hisar(INDIA)
*Corresponding author: er.rajduhannit@gmail.com

ABSTRACT
All over the world, the scientists are putting efforts to make the environment more green and sustainable for the living things to survive over the generations. Along with the other factors, refrigeration and air conditioning is also responsible for the present condition of our environment. Ozone layer depletion and global warming are the effects caused by the leakage of chemical refrigerants like Chlorofluorocarbons (CFCs) and Hydrochloroflurocarbon (HCFCs). Hydroflurocarbon (HFCs) were introduced as substitute to ozone depleting substances at the end of 20th century but it has very high global warming potential. These days CO_2 is one of the key refrigerants which is natural and have zero ozone depletion and global warming potential. CO_2 is a colorless, odorless, non-toxic and natural gas with melting point -56.6°C at 101.325 kPa pressure. It is present in the atmosphere at a concentration of 350 ppm (parts per million) from so many years. CO_2 is proven as a best natural refrigerant for cold climatic conditions but it is not considered as a promising refrigerant for ambient conditions higher than its critical temperature (30.08°C). The purpose of this paper is to review the resent research to improve the performance of CO_2 based vapor compression systems in the last few years for subtropical climate conditions
***Key words**: Ozone layer depletion, Global warming, Natural refrigerant.*

Received 22/02/2018 Revised 20/03/2018 Accepted 09/05/2018

Citation of this article
Manpreet Singh Brar, Rajesh Kumar, Sarita , Rajender Kumar, Amandeep Singh. Future of CO_2 as a Green Refrigerant : A Review. Int. Arch. App. Sci. Technol; Vol 9 [2] June 2018. 01-06.

INTRODUCTION

At the end of nineteenth century, CO_2 based machines were used for refrigeration and air conditioning applications in Europe and America since other fluids like ammonia, sulphur dioxide were considered toxic and flammable and their use was legally restricted. But with the introduction of man-made synthetic chemical refrigerants in 1930s the use of natural refrigerants start reducing due to efficient thermo-physical and transport properties of synthetic refrigerants. Natural refrigerants refer to naturally occurring substances such as air, ammonia, carbon dioxide, isobutene, propane and water. The use of these substances is expected to have the minimum adverse effect on the environment because they remain in the atmosphere from thousands of years. In the entire twenty century, chemical refrigerants such as Chlorofluorocarbons (CFCs) and Hydrochloroflurocarbon (HCFCs) were used in almost all the applications of refrigeration and air conditioning. In 1974, Rowland and Molina confirmed by their research that chlorine from CFCs and HCFCs is depleting the ozone layer by catalyzing the formation of ClO and O_2. After the confirmation of high ozone depleting and global warming potential of CFCs and HCFCs, Hydroflurocarbon (HFCs) have emerged in last part of twenty century and actual usage began in twenty-first century. The leakage of CFCs and HCFCs in atmosphere causes ozone depletion and global warming due to presence of Chlorine and Fluorine respectively in these refrigerants. HFCs have zero

ozone depleting potential but contribute to the global warming due to presence of Fluorine in these refrigerants [1].
Due to high ozone depleting and global warming potential of the synthetic refrigerants, international treatises and national laws restricted the use of these refrigerants and made natural refrigerants, like CO_2 and NH_3, popular again to use in a large variety of applications since they have almost negligible impacts on the environment. The main focus in this paper is to study the resent research and development in refrigeration and air conditioning systems with CO_2 as refrigerant because CO_2 may become a good alternative to replace synthetic refrigerants in near future. CO_2 have zero ozone depleting potential and since we are getting it naturally from environment, hence it can also be said that global warming potential of CO_2 as a refrigerant is technically zero. CO_2 have other advantages also such as, its molecular weight is comparatively less which results in less power consumption, and compressor of smaller displacement capacity is required due to its high volumetric heat capacity. CO_2 have high specific heat which results in better heat transfer rate, and less surface tension in comparison to other refrigerants results in less pressure drop across the components of the system which save the power consumption.

LITERATURE REVIEW

Brown *et al.,* [2] evaluated the performance merits of CO_2 and R134a AMAC systems. The results from semi-theoretical models show that the COP of CO_2 was lower by 21% at 32.2 °C and by 34% at 48.9 °C. The COP disparity was even greater at high speeds and ambient temperatures.
Aprea and Maiorino [3] experimentally evaluated the transcritical CO_2 refrigerator performances using an internal heat exchanger for the ambient temperatures 25 ^oC to 40 ^oC. The comparison of the coefficients of performance of two cycles, working with and without the internal heat exchanger, is discussed and an increase of the coefficient of performance of 10% has been found with a suction line heat exchanger. The experimental plant employing a semi-hermetic compressor, plate-finned tube type heat exchangers, a back pressure valve electronically controlled and an expansion valve is used. An additional auxiliary compressor is also used which by-pass the flash vapour in the intermediate flash vessel to the gas cooler and ensures an entry of liquid CO_2 into the throttle valve of an evaporator. The addition of the auxiliary compressor and the pressure vessels etc. in the system increases the total weight and initial cost of the system.
Torrella *et al.* [4] analyzed the performance of an Internal Heat Exchanger (IHX) operating in a CO_2 transcritical refrigeration plant, for thermal effectiveness and energetic performance of the plant. The evaluation was based on experimental data collected by comparing the performance of the plant working with and without the IHX at the same operating conditions. The experimental evaluation covers three evaporating levels (-5, -10 and -15 ^oC), at two different gas-cooler outlet temperatures each (31, 34 ^oC), for a wide range of gas-cooler operating pressures (74.5 to 105.9 bar). In the results, It was verified experimentally that the use of the IHX increases both the efficiency and cooling capacity of the cycle up to 12% and increase on compressor discharge temperature, reaching increments up to 10.0 ^oC at the evaporating temperature of -15.0 ^oC with regard to the operation without the IHX, which limits the operation of the plant at low evaporating levels.
Sanchez *et al.* [5]compared the energetic behavior of a refrigerating plant working with several IHX configurations such as gas-cooler exit, liquid receiver exit, and in both positions at the same time. The energetic behavior including cooling capacity, power consumption and COP was analyzed along with the discharge temperature reached on each position. From the experimental results, a general improvement in COP and cooling capacity was observed regardless the position of the IHX. A maximum increment of 13% on COP was registered working with two IHX at the same time.
Lee *et al.* [6] suggested a cycle adopting an ejector to improve the performance of CO_2 transcritical air-conditioning system as compared to the conventional system. Experimental results of a CO_2 air-conditioning system using an ejector were compared for various outdoor temperatures and inverter frequencies. The COPs of an air-conditioning system using an ejector and conventional system were calculated and compared based on the pressures and temperatures of experiments. The cooling capacity and COP in the air-conditioning system using an ejector were higher than those in the conventional system at an entrainment ratio

greater than 0.76. In addition, better performance was shown at entrainment ratio greater than a certain value in other test conditions.

Kawamoto *et al.* [7] presented the study reports on a new generation ECS (Ejector Cycle System) for mobile air conditioning systems consisting of a nozzle, a suction section, a mixing section and a diffuser as a highly efficient ejector and a novel system configuration. The ejector was used as a fluid jet pump to recover expansion energy which gets wasted in the conventional refrigeration cycle decompression process, and converted the recovered expansion energy into pressure energy to raise the compressor suction pressure. In this way the ejector system reduced the power consumption of the compressor by using the above mentioned pressure-rising effect and improved energy efficiency of the refrigeration cycle. It was observed by the test results that the new generation ECS is better than the previous generation ECS which was reported in 2012 SAE World Congress1. The new generation ECS achieved higher energy efficiency through the development of ARC (Active flow Ratio Control. It means to control the refrigerant flow ratio of the suction flow to the total flow by separating gas-liquid two phase flow), improved design of each ejector part, and improved internal flow distribution inside the evaporator. The ejector is integrated into the tank of evaporator like the previous generation, so there is no impact to vehicle packaging space. Test results demonstrated that the new generation ECS reduced annual power consumption of compressor by 10% compared to previous generation and by 20% compared to conventional expansion valve systems. The new generation ejector technology can significantly improve actual fuel consumption of Mobile Air Conditioning systems and contribute to global greenhouse gas reduction.

He *et al.* [8] conducted the stability analysis of the basic transcritical CO_2 ejector expansion refrigeration cycle (EERC), and proposed a new system by introducing another evaporator downstream the ejector and a vapor feedback valve thus combining the two-stage evaporation cycle and vapor feedback cycle to increase the gas quality into the separator and decrease the exceed gas into the compressor respectively. The theoretical analysis of the new system is carried out based on the first and second laws of thermodynamics to show the effect of the parameters on the system performance, such as entrainment ratio, high-side pressure, outlet temperature of gas cooler, etc. The results by the first law show that, compared with basic EERC the new system can be used in wider range of working conditions, and the COP of the two-stage evaporation cycle is 28.6% higher and the vapor feedback cycle is lower slightly. By energy analysis at optimum high-side pressure, it is found that the energy destruction of ejector is the greatest part. The simulation results also give the working ranges of the two cycles, which can help to analyze the system control. Hence, it is observed that the improvement in the system is a promising method to reduce the restrain in basic EERC system but more study is still needed.

Llopis *et al.* [9] analyzed the modification of the optimum operating conditions of the CO_2 transcritical cycle by the use of the mechanical subcooling. The possibilities of improving the energy performance of the transcritical cycle with the mechanical subcooling for the optimum conditions are evaluated for three evaporating levels (5, -5 and -30^{o}C) for environment temperatures from 20 to 35 °C using propane as refrigerant for the subcooling cycle. In the results it has been observed that the cycle combination will allow increasing the COP up to a maximum of 20% and the cooling capacity up to a maximum of 28.8%, being both increments higher at high evaporating levels. Furthermore, the results indicate that this cycle is more convenient for environment temperatures above 25^{o}C. Finally, the results using different refrigerants for the mechanical subcooling cycle are presented, where no important differences are observed.

Llopis *et al.* [10] presented experimental evaluation of a CO_2 transcritical refrigeration plant in combination with mechanical subcooling cycle and found the improvement in the performance in the system in comparison to the conventional CO_2 transcritical refrigeration cycle. The combination of a R1234yf single-stage refrigeration cycle with a semihermetic compressor for the mechanical subcooling cycle is tested against the combination of a single-stage CO_2 transcritical refrigeration plant with a semihermetic compressor. The combination is evaluated at two evaporating levels of the CO_2 cycle (0 and -10 °C) and three heat rejection temperatures (24, 30 and 40 °C). The optimum operating conditions and capacity and COP improvements are analyzed with maximum increments on capacity of 55.7 % and 30.3 % on COP.

Bush *et al.* [11]described laboratory testing of a lab-scale transcritical booster system, with and without mechanical subcooling and in transcritical and subcritical operating modes. In addition, a new steady-state model for generalized vapor compression systems was developed and is used to simulate the transcritical CO_2 refrigeration system. The testing showed a significant improvement in both capacity and efficiency at all operating conditions with the subcooler. The solver was able to match capacity, power, and efficiency to within 3% for all test conditions. The model was used to perform a parametric study of subcooler capacity on the cycle; the results show that added subcooling substantially improves overall coefficient of performance and reduces the need for bypass flow, but the overall coefficient of performance benefit diminishes as the efficiency of the main cycle increases.

Yang *et al.* [12] investigated three different variations of transcritical carbon dioxide two-stage compression cycles with expanders by using thermodynamics analysis. These three variations are the two-stage compression at optimal intermediate pressure (TCOP) cycle, two-stage compression with expander driving high-pressure stage (TCDH) cycle and two-stage compression with expander driving low-pressure stage (TCDL) cycle, respectively. In the results it is found that the COP and energy efficiency of the TCOP cycle are on average 9% higher than those of the SCE cycle. At given design points, the COP of the TCDH cycle outperforms the other options, showing 11.32%, 9.65% and 0.72% performance improvement over the TCDL cycle, SCE cycle and the TCOP cycle, respectively. If design and structure are also taken into account, the TCDH cycle is a feasible option since the expander and the auxiliary compressor are integrated into one unit; thus, the transfer loss and leakage loss can be decreased greatly. The key problem is to adopt some measures that control the operating conditions to avoid deviating from the design point.

Yu *et al.* [13] presented the evaluation of performance of an automobile air conditioning system using CO_2-propane mixture as a refrigerant. Experiments have been carried out to see effects of various CO_2-propane mass fractions of 100/0, 90/10, 80/20, 70/30, 60/40, 50/50 on the system performance at different ambient temperatures and gas cooler frontal air velocities. In the results it is found that under the same compressor speed, system COP reaches highest at 60% of CO_2 mass fraction, which is 29.4% higher than pure CO_2 system and even achieves equal level of the R134a system, the optimum pressure and discharge temperature are reduced up to a maximum of 40% and 47 °C during the research range. Furthermore, comparison was carried out under the same cooling capacity by adjusting compressor speed for different mass fraction of CO_2, results demonstrate that the use of CO_2-propane mixtures yields a maximum COP rise of 22% even when cooling capacity is kept constant. A new optimum high pressure control algorithm for the transcritical CO_2-propane mixture cycle has been developed based on the experimental data within a deviation of 5%.

Hafner *et al.* [14] have compared efficiencies and capacities for an R-744 supermarket refrigeration system layout with ejectors and heat recovery for different climate conditions. A simulation models for two supermarket refrigeration systems with and without ejector neglecting the low temperature cabinets were implemented using the Modelica/Dymola based simulation tool TIL-Suite. A reference booster system with flash gas bypass and heat recovery and a similar system with a multi-ejector concept for a test rig facility are considered. Compared to the investigated reference system a COP increase between 10% at 15°C and 20% at 45°C ambient temperature is determined. First results show relevant improvements in system efficiency of up to 30%. For nearly all investigated boundary conditions the multiejector system shows significant COP increase compared to the reference system for both cooling and heating mode. The increase of COP depends highly on the system control strategy. Typical COP increase during the cooling mode of 17% in Athens, 16% in Frankfurt and 5% in Trondheim can be achieved during the summer. In the winter the typical COP increase is between 20% and 30%.

Gullo *et al.*[15] compared theoretically the energy consumption of a CO_2 refrigerating plant equipped with a multi-ejector unit with that of a R404A direct expansion system (DXS), of a conventional CO_2 booster configuration and of two CO_2 solutions using parallel compression. The energy benefits related to the adoption of low temperature (LT) overfed display cabinets were also assessed. Furthermore, various scenarios involving different sizes of the supermarket, integration and capacity of the air conditioning (AC) system and efficiency of the parallel compressors were investigated. The evaluations were carried out by considering different locations in Southern Europe. The results showed that, as a function of the selected boundary conditions, energy savings ranging from 15.6% to 27.3% could be accomplished with the multi-ejector concept over DXS.

Karampour and Sawalha [16] analyzed theoretically a CO_2 trans-critical booster system in which parallel compression, heat recovery and air conditioning are integrated. The performance of the system is studied in various running modes using flash gas by-pass (FGBP) or parallel compression (PC). These running modes include summer cases with or without air conditioning and winter case with heat recovery. The results show that parallel compression is more efficient than flash gas by-pass in summer cases; the increase in *COP* is up to 14% comparing the best cases for PC and FGBP. The increase in *COP* in winter heat recovery mode is marginal, less than 4-6% and hardly-feasible in practice. Comparing the AC function of the CO_2 system with a conventional HFC air conditioning system, it has been found that CO_2 system is more efficient in moderate ambient temperatures lower than 20-25°C. The CO_2 system's AC performance is less efficient than HFC solution in ambient temperatures higher than 25°C.

CONCLUSIONS

The applications of refrigeration and air conditioning devices are increasing drastically in recent years with the worldwide economic growth. Even though these machines are very useful in giving comfort to humans, they also cause energy problems and environmental pollution such as ozone layer depletion and global warming.. Hence, seeking ecofriendly refrigerants like CO_2 along with more efficient system has become a crucial topic today in refrigeration and air conditioning. Lot of researches are carried out in resent years to develop more efficient systems using CO_2 as a refrigerant. These systems are discussed in this paper to give an overview of the improvements which are achieved by introducing the new attachments such as heat exchangers, ejectors, multi-ejectors, two-stage evaporators, two-stage compressors, subcooling systems etc. and improving the design of the basic system. After studying these researches it is found that COP and energy efficiency of the refrigeration and air conditioning systems using CO_2 as a refrigerant is improved. In future it is expected that the performance of CO_2 as a refrigerant can be further increased by refining these systems and introducing new systems. In this way one can say that the future of CO_2 as a refrigerant is very good.

REFERENCES

1. A.D.Kadam, A S. Padalkar, (2014), Performance Assessment of Air Conditioner with CO2 as Refrigerant.http://hdl. handle.net/10603/91507.
2. J.S. Brown, S.F. Yana-Motta, P. (2002). Domanski, Comparative analysis of an automotive air conditioning systems operating with CO2 and R134, International Journal of Refrigeration, volume 25, pp. 19 - 22
3. Aprea, C. , Maiorino, A. , (2008). An experimental evaluation of the transcritical CO_2 refrigerator performances using an internal heat exchanger. Int. J. Refrig. 31, 1006–1011.
4. Torrella, E. , Sanchez, D. , Llopis, R. , Cabello, R. , (2011). Energetic evaluation of an internal heat exchanger in a CO 2 transcritical refrigeration plant using experimental data. Int. J. Refrig. 34, 40–49.
5. Sanchez, D. , Patino, J. , Llopis, R. , Cabello, R. , Torrella, E. , Fuentes, F.V. , (2014). New positions for an internal heat exchanger in a CO_2 supercritical refrigeration plant. Exp. Anal. Energ. Eval. Appl. Therm. Eng. 63, 129–139.
6. Lee, J.S. , Kim, M.S. , Kim, M.S. , (20140. Studies on the performance of a CO_2 air conditioning system using an ejector as an expansion device. Int. J. Refrig. 38, 140–152.
7. Kawamoto, Y., Ogata, G., Shan, Z., (2017). Ejector energy-saving technology for mobile air conditioning systems. SAE Int. J. Passeng. Cars - Mech. Syst. 10 (1). doi: 10. 4271/2017-01-0120.
8. He, Y. , Deng, J. , Zhang, Z. , (2014). Thermodynamic study on a new transcritical CO_2 ejector expansion refrigeration system with two-stage evaporation and vapor feedback. HVAC&R Res 20, 655–664.
9. Llopis, R. , Cabello, R. , Sánchez, D. , Torrella, E. , (2015). Energy improvements of CO_2 transcritical refrigeration cycles using dedicated mechanical subcooling. Int. J. Refrig. 55, 129–141.

10. Llopis, R., Nebot-Andrés, L., Cabello, R., Sánchez, D., Catalán-Gil, J., (2016). Experimental evaluation of a CO_2 transcritical refrigeration plant with dedicated mechanical subcooling. Int. J. Refrig. 69, 361–368. doi:10.1016/j.ijrefrig.2016.06.009
11. Bush, J., Beshr, M., Aute, V., Radermacher, R., (2017). Experimental evaluation of transcritical CO_2 refrigeration with mechanical sub-cooling. Science and Technology for the Built Environment 23 (6), 1013–1025. doi: 10.1080/23744731.2017. 1289056.
12. Yang, J.L. , Ma, Y.T. , Liu, S.C. , (2007). Performance investigation of transcritical carbon dioxide two-stage compression cycle with expander. Energy 32, 237–245.
13. Yu, B. , Wang, D. , Liu, C. , Jiang, F. , Shi, J. , Chen, J. ,(2018). Performance improvements evaluation of an automobile air conditioning system using CO_2-propane mixture as a refrigerant. International Journal of Refrigeration 88, 172–181
14. Hafner, A., Försterling, S., Banasiak, K., (2014). Multi-ejector concept for R-744 supermarket refrigeration. Int. J. Refrigeration 43, 1–13. doi: 10.1016/j.ijrefrig.2013.10. 015.
15. Gullo, P., Hafner, A., Cortella, G., (2017). Multi-ejector R744 booster refrigerating plant and air conditioning system integration –a theoretical evaluation of energy benefits for supermarket applications. Int. J. Refrigeration 75, 164–176. doi: 10.1016/j.ijrefrig.2016.12.009.
16. Karampour, M. , Sawalha, S. , (2015). Theoretical analysis of CO_2 transcritical system with parallel compression for heat recovery and air conditioning in supermarkets. In: Proceedings of the 24th IIR Refrigeration Congress of Refrigeration. IIF/IIR. Yokohama, Japan.

