27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COBEM2023-0880
CO_2 TRANCRITICAL REFRIGERATION SYSTEMS USING EJECTOR: A-STATE-OF-THE-ART REVIEW.

Frank Wiliam Adolfo Blanco Ojeda
Enio Pedone Bandarra Filho
Federal University of Uberlândia
e-mails: frank_blanco@ufu.br; bandarra@ufu.br.

Abstract. *The concern with the environment associated with the restrictions imposed by international agreements such as the Kyoto protocol and the Kigali Amendment, have driven the use of natural refrigerants as alternatives to synthetic fluids, mainly HCFCs and HFCs in refrigeration systems. Carbon dioxide (CO_2) is a very promising natural fluid due to its properties: low viscosity, high heat transfer coefficient, non-flammable, non-toxic, and is widely used in cold climate countries. However, due to technological development, transcritical systems that operate with CO_2 are being applied in temperate countries with the use of ejectors, which substantially increase the efficiency of these systems. Since this device can save a part of the energy consumption in the compressor by recovering the energy losses in the throttling process in a refrigeration system. In this review, the complex thermodynamic phenomena that occur within the two-phase ejector are described from a macro perspective, and the operating conditions are reported, thus geometric parameters that increase the efficiency of the ejector as a function of entrainment rate and pressure rise rate. Finally, the main results obtained from transcritical refrigeration systems using the ejector as an expansion device are compared. The results found in the literature indicate that the use of the ejector increases the performance of transcritical refrigeration systems due to the utilization of kinetic energy in the throttling process, raising the suction pressure of the compressor and consequently reducing energy consumption. However, it was observed that most of the works available in the literature are theoretical and numerical, demonstrating the need for experimental studies to substantiate the importance of ejectors in refrigeration systems.*

Keywords: *Ejector, Transcritical, CO_2, Refrigeration.*

1. INTRODUCTION

The rising costs of energy, the destruction of the ozone layer, and global warming have made the future uncertain for environmental conservation. Consequently, coping with and stopping global warming has become one of the main challenges in mitigating greenhouse gas emissions. From the point of view of refrigeration systems, the compressor is widely related to the high consumption of electrical power, realizing that the power consumption of this equipment is about 20% of the total electricity used worldwide (IIR, 2019), contributing directly to a high environmental impact associated with the burning of fossil fuels or coal, used to generate electricity (indirect impacts). In this perspective, intergovernmental policies such as the Kyoto protocol and the Montreal treaty seek to reduce the environmental impacts caused by refrigeration systems, supporting the generation of new technologies that allow for greater energy efficiency allied to the use of alternative fluids that support the preservation of the environment.

In this sense, Brazil recently ratified the Kigali Amendment to combat global warming, foreseeing the reduction in the consumption of hydrofluorocarbons (HFCs) in a phased manner up to 80% by the year 2045 iCs, (2022). With the fulfillment of this agreement, the expectation is that there will be a decrease of up to 0.4 °C in global temperature. Besides the benefits to the environment, the ratification of this amendment will allow the Brazilian industry access to international resources to upgrade production lines and national competitiveness by increasing efficiency. Additionally, with the implementation of the Regulation (EU) N° 517/2014, (2014) the costs of high GWP refrigerants are increased in order to reduce the competitiveness of systems that operate with HFCs. Furthermore, the Kigali Amendment encourages Brazil to foster and implement new technologies in the refrigeration industry that are environmentally sustainable. Even if the development of an energy-efficient refrigeration system has a high initial cost, this will be supported by the different regulations that aim to reduce environmental impact.

Lorentzen, (1994a, 1994b) verified that the use of CO_2 proved to be a favorable solution since it is a natural refrigerant fluid with zero ODP and unitary GWP. In addition, this fluid is readily available, non-toxic, and is compatible with materials commonly used in conventional refrigeration systems Sarkar; Bhattacharyya; Gopal, (2004). On the other hand, CO_2 has desirable thermodynamic and transport properties, being characterized by its high viscosity in the liquid phase and high thermal conductivity, these parameters are fundamental to estimate the pressure drop and heat transfer Kim; Pettersen; Bullard, (2004). Additionally, CO_2 has a high specific mass, allowing heat exchangers, compressors and piping to be smaller in size compared to components designed with conventional refrigerants Gautam & Sahoo, (2022).

However, the use of CO_2 at high ambient temperatures causes the refrigeration system to operate in the transcritical condition, due to the low critical temperature of CO_2 (31.1 °C). The conventional transcritical refrigeration cycle (CTRC), is characterized by high pressures in the cooler gas above, being 5 to 6 times higher than a vapor compression refrigeration cycle (VCRC), this reflects on the cost of equipment to ensure reliability and safety in the system (Yu et al., 2019). The large difference between the high and low pressure side causes a large pressure drop in the isoenthalpic throttling process, causing the vapor quality in the expansion device to be high, causing significant irreversibility losses and low performance in the refrigeration system (Zhu, Li, et al., 2017). In this sense, the ejector is considered a promising device to increase the efficiency of the system, since this device can recover the work that is normally wasted, in the throttling process in a typical expansion device. Therefore, the transcritical refrigeration cycle with ejector (TRCE), proved to be an energy efficient system, as the use of the ejector contributes in reducing energy consumption, which results in a lower discharge temperature, contributing in the lifetime and better lubrication of the compressor.

Yu et al., (2019) conducted a literature review on technologies applied to the CTRC, finding that the ejector can increase system efficiency by 7 to 36%.Sutthivitode; Thongtip, (2022) experimentally evaluated TRCE with VCRC, these systems being designed to produce different chilled water temperatures at different cooling loads. The authors concluded that TRCE can increase the COP of the system by up to 12.7% when the cooling temperature is reduced to 2 °C. Liu et al., (2021) exergetically modeled the components of TRCE operating with a thermoelectric subcooler. The authors found that the compressor, thermoelectric subcooler, and ejector showed exergy destruction rates of 28.88%, 22.03%, and 19.65%, respectively, and are the main components that need to be improved to increase the efficiency of the cooling system. Nakagawa et al., (2011) experimentally evaluated the behavior of the TRCE in conjunction with an internal heat exchanger (IHX). The authors observed that the use of the IHX is desirable in the tested gas cooler pressure range for evaporation and gas cooler outlet temperatures of 0 and 42 °C. In addition, they reported an increase in COP by up to 27% compared to CTRC Gautam & Sahoo, (2022).

Although in the literature there are several comprehensive studies aimed at the behavior and efficiency of the two-phase ejector. In this work, it was found that there are still no summarized researches that analyze the efficiency of the ejector as a function of the entrainment rate and the pressure rise rate, from the point of view of geometric parameters and operating conditions. Therefore, this review intends to fill this gap, providing the reader in a summarized and comprehensive way with the main results obtained in the literature about the ejector efficiency, to be consequently analyzed in the overall performance of TRCE.

2. EJECTOR

The ejector is a crucial component in TRCE performance, consisting mainly of a primary nozzle, a secondary nozzle, a suction chamber, a mixing chamber, and a diffuser. The operation of the ejector consists of throttling the incoming primary fluid at a high pressure and being accelerated through the primary nozzle at supersonic speed. The high velocity of the primary fluid creates a pressure difference, which drags the secondary fluid that is connected to the outlet of the evaporator. This pressure difference causes a compression of the evaporated refrigerant. Once the primary and secondary fluid are in contact, after a certain length they are mixed within the mixing chamber. Finally, the diffuser slows down the flow of the mixture and at the same time increases the outlet pressure of the ejector (Y. Li et al., 2018). Figure 1a shows in detail the geometrical parameters and operation of the ejector that correspond to the velocity and pressure profiles.

The efficiency of the ejector is defined as the amount of expansion work recovered divided by the maximum amount of work that can be recovered. To this end, there are two important indicators that define ejector performance, being the entrainment ratio (ER) and the pressure lifting ratio (PLR). The ER is defined as the ratio of the mass flow rate of the secondary fluid to the mass flow rate of the primary fluid, while the PLR is the ratio of the outlet pressure to the secondary pressure of the ejector (Y. Li et al., 2022). However, it has been observed in the literature that the back pressure effect degrades the efficiency of the ejector, since there is a reduction in the pressure difference between the inlet and outlet of the ejector, which reflects in a lower suction of the secondary fluid. Therefore, when sizing the ejector, this limitation should be considered, so that the useful ejector design is robust and effective for different operating conditions (Yazdani et al., 2012). Yan et al., (2023) have highlighted that not only with the increase of the primary and secondary fluid pressure the performance of the ejector will increase, but also the reduction of the back pressure must be taken into account for the ejector to operate with better performance. The main results found in the literature on the operating conditions and geometric parameters that increase the efficiency of the ejector are presented in detail below.

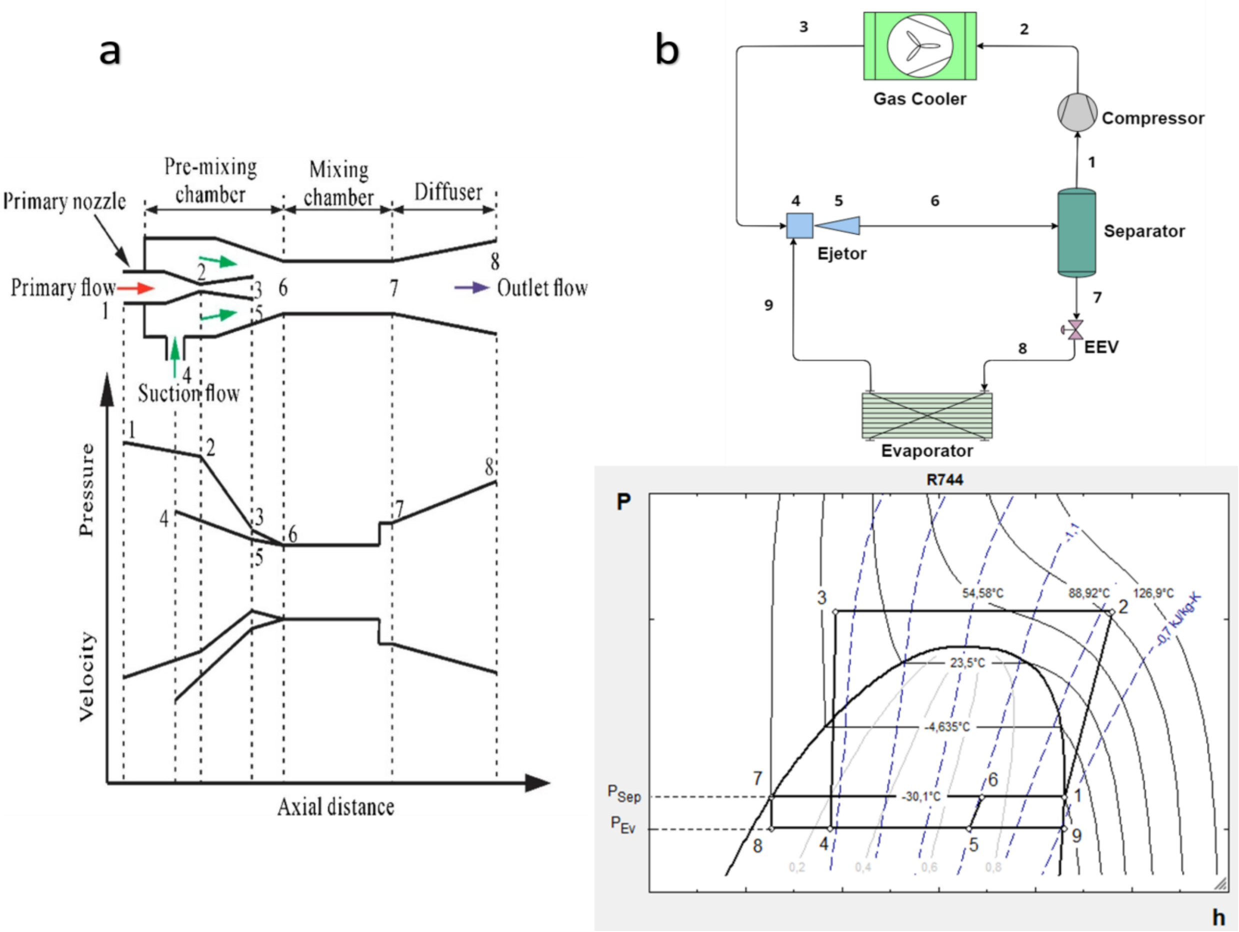


Figure 1a. geometric parameters of the ejector Y. Li et al., (2018). Figure 1b. transcritical refrigeration cycle with ejector, P-h diagram.

2.1 OPERATING CONDITIONS

Yan et al., (2023) the increase in backpressure and decrease in primary fluid pressure together cause the mass flow rate of the secondary fluid to decrease, causing the ER to decrease. On the other hand, with decreasing back pressure and increasing secondary fluid pressure jointly reflect an increase in the secondary fluid mass flow rate and consequently the ER.

Yan et al., (2023) found that with the variation of the primary fluid temperature there is a decrease of the primary fluid mass flow rate, while there is an optimum point of the secondary fluid mass flow rate and ER. On the other hand, with the variation of the secondary fluid pressure the authors observed a similar behavior with a decrease of the primary fluid mass flow rate, while there is a maximum point of the secondary fluid mass flow rate and ER.

Jeon et al., (2022) observed that as the ER increases, the pressure rise decreases, due to the reduction in the conversion of pressure energy to kinetic energy, being caused by the reduction in mass flow rate caused by the nozzle. On the other hand, when the ER decreases the work recovery potential increases due to the increase in the mass flow rate of the driving stream. Therefore, a balance point is required to find the proper ER that provides good ejector performance.

Y. Song et al., (2020) conducted a literature review aimed at equating and simulating 1D, 2D, and 3D models focused on ejector operation and behavior. The authors found in their research the difficulty of validating numerical results with experimental studies, due to the impediment of accurately measuring the transonic and transcritical flow characteristics in a small-sized ejector. On the other hand, the deviations obtained are larger when the priming pressure is lower than the critical pressure, specifically when the pressure is close to the saturation line.

Taslimi Taleghani et al., (2019) developed a simulation model of a heat pump that uses the ejector as the expansion device, to numerically investigate the effects of the ejector design parameters on system performance. The authors observed that the ER of the ejector increases with the increase in the cooler gas pressure and the heat transfer area in the cooler gas, however there is the opposite effect with the pressure rise being decreased with their increase. On the other hand, the highest ejector efficiency occurred at a pressure lower than the optimum cooler gas pressure corresponding to a smaller heat transfer area.

Zhu et al., (2018) experimentally evaluated the ejector in a transcritical heat pump, the authors observed that increasing the primary pressure causes the primary flow rate to rise, while the secondary flow rate remains constant for pressures above 11 Mpa, causing the ER to also decrease.

Zhu & Jiang, (2018) performed a theoretical model to predict the primary and secondary flow in a two-phase ejector. The authors, found the increase in primary and secondary flow with increasing ejector inlet pressure. However, with increasing back pressure the primary flow is kept relatively constant while the secondary flow is decreasing, this is because the ejector is operating in the subcritical mode.

L. Wang et al., (2017) conducted an experimental study to verify the effects of primary pressure and back pressure on the ER of the ejector. The authors observed that an increase in the primary pressure causes an increase in the critical back pressure, which causes a decrease in the ER. Similarly, for fixed back pressure and evaporating pressure conditions, they found that there is an optimal primary pressure value that maximizes the optimal ER.

Zhu, Li, et al., (2017) theoretically proven that the efficiency of TRCE decreases with increasing back pressure, this effect is observed by the decrease in ER, which in turn is inversely proportional to PLR when the primary fluid pressure is kept constant.

Zhu, Wang, et al., (2017) found that the primary fluid pressure significantly affects the ejector performance, being a sensitive parameter in the ER when the ejector operates in subcritical mode. On the other hand, increasing the primary and secondary pressure causes the primary and secondary flow rates to increase. Furthermore, the ER is inversely proportional to the angle of expansion.

Figure 2a summarizes the main works found in the literature, illustrating the effects of backpressure as a function of ER, while Figure 2b illustrates the effects of the cooler gas pressure as a function of ER. In this graph, it can be concluded that the backpressure is a negative effect that degrades the ejector performance, while the cooler gas pressure is a parameter that needs to be optimized as a function of ambient temperature.

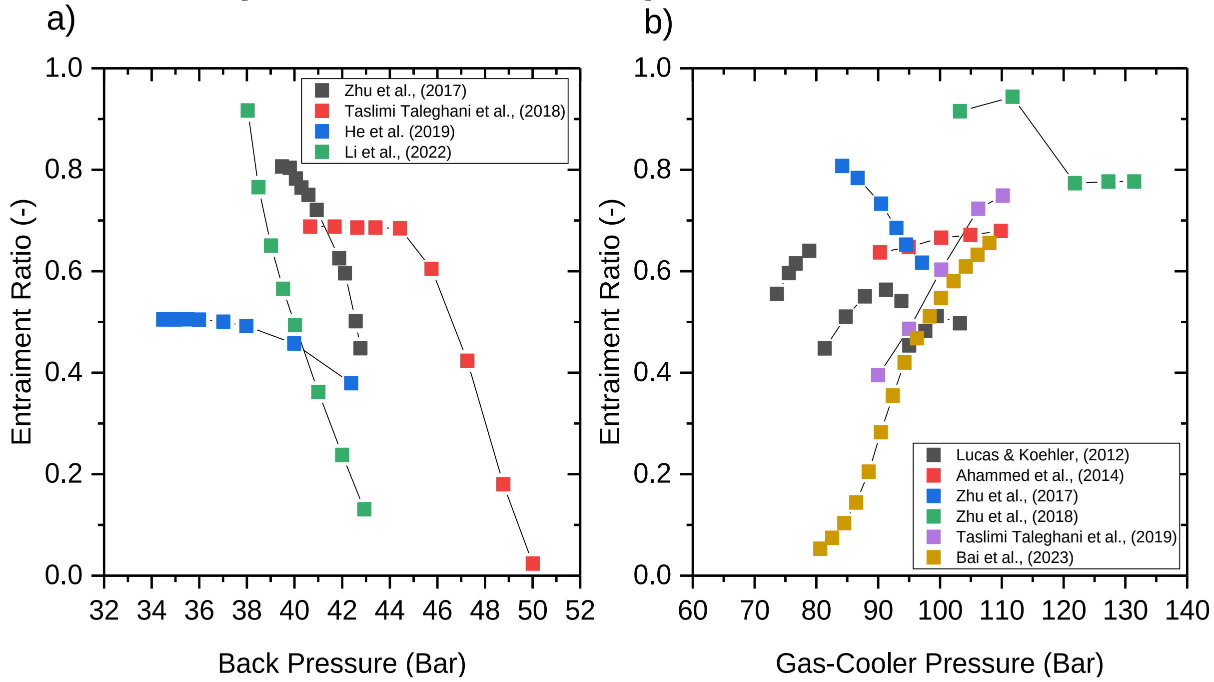


Figure 2a. effect of back pressure on the ER. Figure 2b. effect of gas cooler pressure on the ER

2.2 GEOMETRICAL PARAMETERS

Mathew & Smart, (2023) analyzed the effects that maximize efficiency in the convergent-divergent ejector, finding that as the gap between the nozzle exit and the mixing chamber increases the ER is also increased. On the other hand, ER decreases when the divergence angle of the primary nozzle increases or with increasing throat diameter.

Yan et al., (2023) simulated in CFD to theoretically verify which are the sensitive geometrical parameters that increase the ejector performance. In this regard, the authors found that by optimizing the aspect ratio the ER can increase by up to 44.5%, while by optimizing the nozzle position and constant area mixing chamber length, the ER can increase by up to 16.6 and 7.5%, respectively.

Bumrungthaichaichan et al., (2022) performed a comparison using a CFD simulation of the constant rate of momentum change ejector with the constant pressure mixing ejector, keeping the same rations of area and total length of the ejector. In the result analysis, the authors observed that the constant rate of momentum change ejector showed higher ER compared to the constant pressure mixing ejector due to the lower losses presented in this device.

Jeon et al., (2022) optimized the exit position of the driving nozzle of an adjustable ejector in a dual evaporation CTRC using an artificial neural network model based on experimental data. In their analysis of results, the authors found that reducing the diameter of the mixing section produces an expressive increase in pressure rise, while the ER was slightly increased. Similarly, the authors observed that the pressure rise increases relative to the ER as the nozzle outlet position decreases, causing the suction section space to be reduced and consequently the secondary flow passage to be narrower with the nozzle exit position being a highly sensitive parameter in cooling system performance.

Y. Li & Deng, (2022) performed a sensitivity study by performing a CFD simulation of a rectangular ejector, in the numerical study the authors observed an increase and decrease of the ER with increasing diffuser angle, width and length of the mixing chamber, obtaining optimum values of 6 °, 4.62 mm, 28 mm, respectively, these values provide a maximum ER.

Y. Li et al., (2022) carried out a numerical study of a rectangular ejector for different operating conditions of pressure and temperature of the primary fluid, using genetic algorithm and CFD simulation. In the sensitivity analysis, the authors observed that there is an optimum point where the ER is maximum, in relation to the nozzle outlet position they obtained an optimum value of 4 mm, while the angle in the suction chamber of the secondary fluid was 10°.

Yan et al., (2020) simulated a model in CFD to analyze the geometric parameters of two convergent-nozzle and convergent-divergent-nozzle ejectors. Analyzing the convergent nozzle ejector, they observed that there is a value of the optimal nozzle diameter and throat length that maximizes the ER, likewise they found that the smaller the convergence angle at the nozzle the ER increases. On the other hand, there is an optimal nozzle exit position that combined with the smaller convergence angle and shorter nozzle length maximizes the ER. Similarly, there is an optimum nozzle exit position value that combined with longer nozzle length maximizes the ER.

He et al., (2019) numerically evaluated the TRCE to verify the effects of the needle located in the suction chamber of an adjustable ejector. The authors, observed that the needle has an even greater gradual effect on ER with increasing back pressure. On the other hand, the introduction of the needle weakens the expansion of the primary flow, causing a reduction of the ER in the suction chamber.

Taslimi Taleghani et al., (2018) developed a thermodynamic model to calculate the geometry for certain operational conditions of the ejector inlet and outlet, considering different values of the polytropic efficiencies in the diffuser, primary and secondary nozzle. In the result analysis, the authors observed that decreasing the polytropic efficiency of the primary nozzle, increases its diameter and length. On the other hand, decreasing the polytropic efficiencies of the diffusers and primary and secondary nozzles cause the length of the constant area duct to decrease.

Y. Li et al., (2018) conducted an experimental study to visualize and interpret the phenomena in the single-phase and two-phase flow of the divergent convergent nozzle, using the methods of pressure measurement and direct photography, the flows are distinguished by the difference of the amount of light inserted using a high-speed camera. The authors observed, that for a pressure above 8.5 MPa, the position of the phase change is behind the local throat, concluding that the phase change can start before or after the throat depending on the operating conditions. Furthermore, they found that increasing the primary pressure results in a significant increase in refrigerant quality.

Lucas & Koehler, (2012) found in their experimental work that the maximum ejector efficiency was 22%, observing a decrease in ejector efficiency as the cooler gas outlet temperature is varied for low evaporation pressures, the authors consider that this undesired effect may be related to the length of the mixing chamber, which can cause pressure losses in the ejector.

3. TRANSCRITICAL REFRIGERATION CYCLE WITH EJECTOR

In temperate climate applications, CO_2 needs to be operated in transcritical mode, because heat rejection occurs above the critical point. In this transcritical region, pressure is independent of temperature, decoupled from each other, leading to the existence of an optimal heat rejection pressure, where the efficiency of the refrigeration cycle is maximum (Sarkar et al., 2004). Because of this phenomenon, in both the CTRC and TRCE the optimal discharge pressure conditions that maximize the system efficiency depending on the gas cooler outlet temperature have been determined. Importantly, the outlet temperature of the gas cooler is limited by the inlet temperature of the secondary fluid in a countercurrent heat exchanger, while for an air-cooled gas cooler it will depend on the ambient temperature. The advantage of using the ejector is that it allows the TRCE to have higher energy performance under high ambient temperature conditions compared to the CTRC. The following are the main results observed in the literature in terms of energy performance on the TRCE.

Surwase et al., (2023) simulated a gas evaporative cooler in the TRCE with the intention of reducing the gas cooler temperature and thus improving the system performance. However, although the authors had the same trends when comparing the simulated results with the experimental results obtained from the literature, they obtained a maximum error of 22.66% this high value is justified by the thermodynamic assumptions made by the authors to simplify the model analysis.

Bai et al., (2023) used an ejector in a parallel compression system, using a heat exchanger to ensure superheat in the auxiliary compressor. In the results analysis, the configuration with ejector showed a higher system performance compared to the conventional parallel compression refrigeration cycle.

Zeng et al., (2022) performed modeling to compare the performance of TRCE with a CTRC using a subcooler, finding that the transcritical refrigeration cycle with ejector increased the COP of the system by 18.2 to 21.6 %, for gas cooler outlet temperatures of 45 to 35 °C, respectively.

Jeon et al., (2022) verified that the COP values present the same trend as the PLR in relation to the nozzle output position, there being a point of maximum efficiency in the system. Likewise, the authors observed a linear increase in COP, obtaining higher efficiency values in the system when the rotation in the compressor is lower for a nozzle output position lower than 2 mm.

X. Liu et al., (2019) analyzed thermodynamic effects of TRCE using a thermoelectric subcooler, finding that this system increases system performance by up to 39.3% compared to CTRC. Furthermore, the implementation of thermoelectric subcooling in TRCE allows for lower discharge temperatures, contributing to longer compressor life.

F. Liu et al., (2016) experimentally evaluated an adjustable ejector, observing that as the throat diameter is decreased the cooling capacity increases. However, the COP of the system is oscillatory, and it is necessary to optimize the throat diameter to maximize the efficiency of the system. On the other hand, there is also an optimum point between the distance from the motor nozzle outlet and the mixing section inlet, which maximizes the efficiency in the refrigeration cycle. In addition, decreasing the frequency in the compressor increases the COP of the system due to the lower compression ratio in the system.

Zheng et al., (2016) performed a CTRC simulation using an adjustable ejector implementing a two-stage evaporator, varying the compressor speed, expansion valve opening, ejector throat area, and chilled water flow rate of the evaporators. The authors observed that the expansion valve opening modifies the evaporator pressure as well as the PLR in the ejector. In addition, they found that changing the throat area of the ejector contributes in changing the gas cooler pressure and the ER between the primary and secondary fluids in the ejector. From the trends of the theoretical results Zheng and Deng., (2017) experimentally evaluated this system, finding that the implementation of the two-stage evaporator helped regulate the balance and quality of the refrigerant, reducing excessive accumulation of refrigerant in the liquid phase in the separator, as well as improving performance in the system, concluding that the second evaporator plays a significant role in increasing system efficiency in lower entrainment ratio applications compared to the CTRC.

He et al., (2017a) implemented a control system to determine the optimum gas cooler pressure in a CTRC operating with an adjustable ejector by installing a needle in the driving nozzle to regulate the throat area, while aiming for maximum system efficiency under varying operating conditions. However, the authors observed that the system performance differs at different compressor speeds. Consequently,He et al., (2017b) experimentally evaluated the CTRC operating with an adjustable ejector, proposing a multivariable controller that tracks the gas cooler pressure in conjunction with the cooling capacity (by modifying the speed in the compressor), making the system operate stably.

Ahammed et al., (2014) numerically modeled the performance of TRCE, noting that ER is a key parameter in ejector performance. In addition, the authors observed a 21% increase in system performance when compared to CTRC.

Zhang et al., (2013) suggest that the application of the internal heat exchanger (IHX) in a TRCE is applicable in cases where the isentropic efficiency of the ejector is low, since the IHX brings an increase in the ER of the ejector and the cooling capacity in the system, however, it is not always advisable to add this component, as it entails a reduction in pressure recovery, resulting in a higher compression ratio.

Manjili & Yavari, (2012) theoretically analyzed the performance of TRCE with and without IHX, considering nozzle and diffuser efficiencies of 70% and 80%, respectively. The authors concluded that the addition of IHX brings with it a COP increment of 4.3% to TRCE.

Lucas & Koehler, (2012) experimentally evaluated the TRCE by comparing the results with a CTRC operating with an electronic expansion valve (EEV). In the comparison performed, the authors observed that due to the heat recovery from the ejector, the efficiency of the system is increased compared to the traditional system as the evaporating pressure and the outlet temperature of the gas cooler are increased.

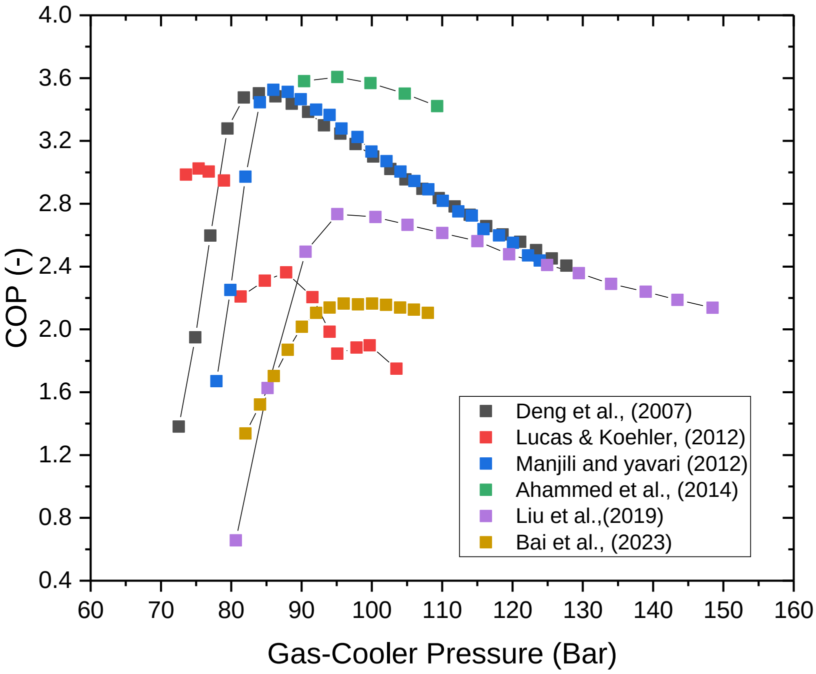
Fangtian & Yitai, (2011) thermodynamically analyzed the TRCE, observing there is an increase in the CO_2 mixing quality as the gas cooler outlet temperature is raised. On the other hand, the efficiency of the TRCE is higher for different heat rejection pressures compared to the CTRC operating with EEV.

Yari, (2009) theoretically analyzed the efficiency of TRCE operating with an IHX, finding that this configuration reduces the discharge temperature at the compressor, extending compressor life compared to CTRC with IHX.

Deng et al., (2007) analyzed theoretically the TRCE, verifying that the system achieves satisfactory results for an ER of 0.5 to 0.6. In addition, this system showed a 22% increase in efficiency compared to CTRC.

D. Li & Groll, (2005) have theoretically analyzed the TRCE for a typical air conditioning operation application, noting that the system efficiency is strongly influenced by the PLR in the system. On the other hand, increasing the superheat in the evaporator increases the specific cooling capacity, however due to the lower refrigerant flowing in the evaporator the cooling capacity of the system will be lower compared to the CTRC, leading to lower TRCE performance.

In Figure 3. the main TRCE performance work as a function of gas cooler pressure is summarized, finding that the work of Ahammed et al., (2014) This can be explained by the fact that the authors used a convergent-divergent ejector, considering the efficiency of the diffuser and the primary and secondary nozzles to be 85%, so that the performance of the ejector is kept constant for the different operating conditions of the TRCE.



r

Figure 3. COP values as a function of TRCE gas-cooler pressure.

4. CONCLUSIONS

In this paper a detailed review of the ejector was presented from the point of view of operating conditions and geometric parameters that increase the efficiency of the TRCE. In these conditions, the main conclusions are as follows:

- The feasibility of the ejector as an expansion device was verified since it increases the performance of the TCRE, due to the recovery in the throttling loss of the expansion process, contributing directly in the decrease of the pressure ratio in the compressor.
- From the point of operating conditions, it is observed that increasing back pressure is a negative effect that degrades the ejector performance, causing a lower ER. On the other hand, a balance point is needed to find the proper ER according to the PLR that provides good ejector performance, directly increasing the efficiency of the TRCE.
- Geometric parameters such as nozzle exit position, aspect ratio, mixing chamber length, suction chamber angle, and diffuser angle were found to have a significant influence on the efficiency of the ejector.
- It was observed the strong influence of the cooler gas pressure on the TRCE behavior, existing an optimum point that maximizes the TRCE efficiency as a function of the ambient temperature. Furthermore, it was observed that the separator is a fundamental component in the system performance, since this device provides the balance of the refrigerant quality, making the system operate in a stable way without changing the ejector behavior for different operating conditions.
- In the bibliographic review carried out, it was found that most of the studies used thermodynamic and CFD models to understand the internal behavior of the ejector. However, it was noted that only 26% of the research reviewed on TRCE systems operating with CO2 was experimental. Therefore, due to the limited experimental verification, empirical studies are needed to help corroborate the application of the ejector in this type of system.

5. ACKNOWLEDGEMENTS

The authors thank the CAPES, FAPEMIG and CNPq for the financial support.

6. REFERENCES

Ahammed, M. E., Bhattacharyya, S., & Ramgopal, M. (2014). Thermodynamic design and simulation of a CO2 based transcritical vapour compression refrigeration system with an ejector. *Energy Economics*, *45*, 177–188. https://doi.org/10.1016/j.ijrefrig.2014.06.010

Bai, T., Shi, R., & Yu, J. (2023). Thermodynamic performance evaluation of an ejector-enhanced transcritical CO2 parallel compression refrigeration cycle. *International Journal of Refrigeration*, *149*(October 2022), 49–61.

https://doi.org/10.1016/j.ijrefrig.2022.12.014
Bumrungthaichaichan, E., Ruangtrakoon, N., & Thongtip, T. (2022). Performance investigation for CRMC and CPM ejectors applied in refrigeration under equivalent ejector geometry by CFD simulation. *Energy Reports*, *8*, 12598–12617. https://doi.org/10.1016/j.egyr.2022.09.042
Deng, J. qiang, Jiang, P. xue, Lu, T., & Lu, W. (2007). Particular characteristics of transcritical CO2 refrigeration cycle with an ejector. In *Applied Thermal Engineering* (Vol. 27, Issues 2–3, pp. 381–388). https://doi.org/10.1016/j.applthermaleng.2006.07.016
Fangtian, S., & Yitai, M. (2011). Thermodynamic analysis of transcritical CO2 refrigeration cycle with an ejector. *Applied Thermal Engineering*, *31*(6–7), 1184–1189. https://doi.org/10.1016/j.applthermaleng.2010.12.018
Gautam, & Sahoo, S. (2022). A comprehensive thermodynamic analysis and performance evaluation of a transcritical ejector expansion CO2 adsorption refrigeration system integrated with thermoelectric sub-cooler. *Journal of Supercritical Fluids*, *182*(November 2021), 105517. https://doi.org/10.1016/j.supflu.2022.105517
He, Y., Deng, J., Li, Y., & Ma, L. (2019). A numerical contrast on the adjustable and fixed transcritical CO2 ejector using exergy flux distribution analysis. *Energy Conversion and Management*, *196*(November 2018), 729–738. https://doi.org/10.1016/j.enconman.2019.06.031
He, Y., Deng, J., Yang, F., & Zhang, Z. (2017). An optimal multivariable controller for transcritical CO2 refrigeration cycle with an adjustable ejector. *Energy Conversion and Management*, *142*, 466–476. https://doi.org/10.1016/j.enconman.2017.03.070
He, Y., Deng, J., Zheng, L., & Zhang, Z. (2017). Performance optimization of a transcritical CO2 refrigeration system using a controlled ejector. *International Journal of Refrigeration*, *75*, 250–261. https://doi.org/10.1016/j.ijrefrig.2016.12.015
iCs. (2022). *Emenda de Kigali é aprovada na Câmara dos Deputados*. https://climaesociedade.org/emenda-de-kigali-e-aprovada-na-camara-dos-deputados/
IIR. (2019). *The Role of Refrigeration in the Global Economy* (p. 12). https://iifiir.org/en/fridoc/the-role-of-refrigeration-in-the-global-economy-2019-142028#:~:text=Global annual sales of such,the overall electricity used worldwide.
Jeon, Y., Lee, D., & Cho, H. (2022). Optimization of motive nozzle position in a modified two-phase ejector expansion household refrigeration cycle using an artificial neural network. *Energy Reports*, *8*, 1114–1123. https://doi.org/10.1016/j.egyr.2021.12.033
Kim, M. H., Pettersen, J., & Bullard, C. W. (2004). Fundamental process and system design issues in CO2 vapor compression systems. In *Progress in Energy and Combustion Science* (Vol. 30, Issue 2). https://doi.org/10.1016/j.pecs.2003.09.002
Li, D., & Groll, E. A. (2005). Transcritical CO2 refrigeration cycle with ejector-expansion device. *International Journal of Refrigeration*, *28*(5), 766–773. https://doi.org/10.1016/j.ijrefrig.2004.10.008
Li, Y., & Deng, J. (2022). Numerical investigation on the performance of transcritical CO2 two-phase ejector with a novel non-equilibrium CFD model. *Energy*, *238*, 121995. https://doi.org/10.1016/j.energy.2021.121995
Li, Y., Deng, J., & He, Y. (2022). Numerical study on the interaction of geometric parameters of a transcritical CO2 two-phase ejector using response surface methodology and genetic algorithm. *Applied Thermal Engineering*, *214*(May), 118799. https://doi.org/10.1016/j.applthermaleng.2022.118799
Li, Y., Deng, J., Ma, L., & Zhang, Y. (2018). Visualization of two-phase flow in primary nozzle of a transcritical CO2 ejector. *Energy Conversion and Management*, *171*(June), 729–741. https://doi.org/10.1016/j.enconman.2018.06.022
Liu, F., Groll, E. A., & Ren, J. (2016). Comprehensive experimental performance analyses of an ejector expansion transcritical CO2 system. *Applied Thermal Engineering*, *98*, 1061–1069. https://doi.org/10.1016/j.applthermaleng.2015.12.017
Liu, X., Fu, R., Wang, Z., Lin, L., Sun, Z., & Li, X. (2019). Thermodynamic analysis of transcritical CO2 refrigeration cycle integrated with thermoelectric subcooler and ejector. *Energy Conversion and Management*, *188*(February), 354–365. https://doi.org/10.1016/j.enconman.2019.02.088
Liu, X., Yu, K., Wan, X., Zheng, M., & Li, X. (2021). Conventional and advanced exergy analyses of transcritical CO2 ejector refrigeration system equipped with thermoelectric subcooler. *Energy Reports*, *7*, 1765–1779. https://doi.org/10.1016/j.egyr.2021.03.023
Lorentzen, G. (1994a). Revival of carbon dioxide as a refrigerant. *H and V Engineer*, *66*(721), 9–14.
Lorentzen, G. (1994b). The use of natural refrigerants : a complete solution to the CFC/HCFC predicament (Utilisation des frigorigénes naturels : une solution complete au probl me des CFC et des HCFC). *Int. J. Refrig. Vol.*, *18*(3), 190–197.
Lucas, C., & Koehler, J. (2012). Experimental investigation of the COP improvement of a refrigeration cycle by use of an ejector. *International Journal of Refrigeration*, *35*(6), 1595–1603. https://doi.org/10.1016/j.ijrefrig.2012.05.010
Manjili, F. E., & Yavari, M. A. (2012). Performance of a new two-stage multi-intercooling transcritical CO 2 ejector refrigeration cycle. *Applied Thermal Engineering*, *40*, 202–209.

https://doi.org/10.1016/j.applthermaleng.2012.02.014

Mathew, V., & Smart, D. S. R. (2023). Materials Today : Proceedings Investigation and development of improved methods for the design of ejector. *Materials Today: Proceedings*, *xxxx*. https://doi.org/10.1016/j.matpr.2023.05.122

Regulation of the European Parliament and the Council of 16 April 2014 on fluorinated greenhouse gases and replealing Regulation (EC) N° 842/2006., 2014 Official Journal of the European Union L150/195 (2014). http://eur-lex.europa.eu/eli/reg/2014/517/oj

Nakagawa, M., Marasigan, A. R., & Matsukawa, T. (2011). Experimental analysis on the effect of internal heat exchanger in transcritical CO2 refrigeration cycle with two-phase ejector. *International Journal of Refrigeration*, *34*(7), 1577–1586. https://doi.org/10.1016/j.ijrefrig.2010.03.007

Sarkar, J., Bhattacharyya, S., & Gopal, M. R. (2004). Optimization of a transcritical CO2 heat pump cycle for simultaneous cooling and heating applications. *International Journal of Refrigeration*, *27*(8), 830–838. https://doi.org/10.1016/j.ijrefrig.2004.03.006

Song, Y., Ma, Y., Wang, H., Yin, X., & Cao, F. (2020). Review on the simulation models of the two-phase-ejector used in the transcritical carbon dioxide systems. *International Journal of Refrigeration*, *119*, 434–447. https://doi.org/10.1016/j.ijrefrig.2020.04.029

Surwase, S. A., Singh, S., & Maiya, M. P. (2023). Performance evaluation of an ejector based transcritical R-744 refrigeration system with evaporative gascooler. *Thermal Science and Engineering Progress*, *39*(November 2022), 101728. https://doi.org/10.1016/j.tsep.2023.101728

Sutthivirode, K., & Thongtip, T. (2022). Experimental investigation of a two-phase ejector installed into the refrigeration system for performance enhancement. *Energy Reports*, *8*, 7263–7273. https://doi.org/10.1016/j.egyr.2022.05.236

Taslimi Taleghani, S., Sorin, M., & Poncet, S. (2018). Modeling of two-phase transcritical CO2 ejectors for on-design and off-design conditions. *International Journal of Refrigeration*, *87*, 91–105. https://doi.org/10.1016/j.ijrefrig.2017.10.025

Taslimi Taleghani, S., Sorin, M., Poncet, S., & Nesreddine, H. (2019). Performance investigation of a two-phase transcritical CO2 ejector heat pump system. *Energy Conversion and Management*, *185*(February), 442–454. https://doi.org/10.1016/j.enconman.2019.02.004

Wang, L., Wang, C., Hou, W., Zhao, H., & Zhang, H. (2017). Experimental investigation on ejector performance near critical back pressure. *International Journal of Refrigeration*, *80*, 158–168. https://doi.org/10.1016/j.ijrefrig.2017.05.010

Yan, J., Li, S., & Liu, Z. (2020). Numerical investigation on optimization of ejector primary nozzle geometries with fixed/varied nozzle exit position. *Applied Thermal Engineering*, *175*(April), 115426. https://doi.org/10.1016/j.applthermaleng.2020.115426

Yan, J., Li, Z., & Zhang, H. (2023). Investigation on key geometries optimization and effect of variable operating conditions of a transcritical R744 two-phase ejector. *Applied Thermal Engineering*, *230*(PA), 120733. https://doi.org/10.1016/j.applthermaleng.2023.120733

Yari, M. (2009). Performance analysis and optimization of a new two-stage ejector-expansion transcritical CO2 refrigeration cycle. *International Journal of Thermal Sciences*, *48*(10), 1997–2005. https://doi.org/10.1016/j.ijthermalsci.2009.01.013

Yazdani, M., Alahyari, A. A., & Radcliff, T. D. (2012). Numerical modeling of two-phase supersonic ejectors for work-recovery applications. *International Journal of Heat and Mass Transfer*, *55*(21–22), 5744–5753. https://doi.org/10.1016/j.ijheatmasstransfer.2012.05.071

Yu, B., Yang, J., Wang, D., Shi, J., & Chen, J. (2019). An updated review of recent advances on modified technologies in transcritical CO2 refrigeration cycle. *Energy*, *189*, 116147. https://doi.org/10.1016/j.energy.2019.116147

Zeng, M. Q., Zheng, Q. Y., Zhang, X. L., Mo, F. Y., & Zhang, X. R. (2022). Thermodynamic analysis of a novel multi-target temperature transcritical CO2 ejector-expansion refrigeration cycle with vapor-injection. *Energy*, *259*(July), 125016. https://doi.org/10.1016/j.energy.2022.125016

Zhang, Z. Y., Ma, Y. T., Wang, H. L., & Li, M. X. (2013). Theoretical evaluation on effect of internal heat exchanger in ejector expansion transcritical CO2 refrigeration cycle. *Applied Thermal Engineering*, *50*(1), 932–938. https://doi.org/10.1016/j.applthermaleng.2012.08.022

Zheng, L., & Deng, J. (2017). Experimental investigation on a transcritical CO2 ejector expansion refrigeration system with two-stage evaporation. *Applied Thermal Engineering*, *125*, 919–927. https://doi.org/10.1016/j.applthermaleng.2017.07.056

Zheng, L., Deng, J., & Zhang, Z. (2016). Dynamic simulation of an improved transcritical CO2 ejector expansion refrigeration cycle. *Energy Conversion and Management*, *114*, 278–289. https://doi.org/10.1016/j.enconman.2016.01.069

Zhu, Y., Huang, Y., Li, C., Zhang, F., & Jiang, P. X. (2018). Experimental investigation on the performance of transcritical CO2 ejector-expansion heat pump water heater system. *Energy Conversion and Management*, *167*(December 2017), 147–155. https://doi.org/10.1016/j.enconman.2018.04.081

Zhu, Y., & Jiang, P. (2018). Theoretical model of transcritical CO2 ejector with non-equilibrium phase change correlation. *International Journal of Refrigeration*, *86*, 218–227. https://doi.org/10.1016/j.ijrefrig.2017.10.033

Zhu, Y., Li, C., Zhang, F., & Jiang, P. X. (2017). Comprehensive experimental study on a transcritical CO2 ejector-expansion refrigeration system. *Energy Conversion and Management*, *151*(August), 98–106. https://doi.org/10.1016/j.enconman.2017.08.061

Zhu, Y., Wang, Z., Yang, Y., & Jiang, P. X. (2017). Flow visualization of supersonic two-phase transcritical flow of CO2 in an ejector of a refrigeration system. *International Journal of Refrigeration*, *74*, 352–359. https://doi.org/10.1016/j.ijrefrig.2016.11.012

7. RESPONSIBILITY NOTICE

The author(s) is (are) the only responsible for the printed material included in this paper.