

# INVESTIGATION OF R744 AC AND HEAT PUMP SYSTEMS FOR ELECTRIC VEHICLES WITH EJECTORS

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## ABSTRACT

R744 is considered a highly promising alternative to PFAS-based refrigerants in electric vehicle air conditioning/heat pump systems. However, the throttling loss in an AC/HP cycle using R744 is relatively higher than in a cycle using PFAS producing refrigerants. It is possible to address this challenge by using a two-phase ejector that uses the expansion work of the high-pressure refrigerant to boost and compress the low-pressure refrigerant. In this article, a thermodynamic analysis is carried out to investigate the advantages of integrating a two-phase ejector into the electric vehicle AC/HP cycle. In this study, three cabin cooling modes, two cabin heating modes, and one battery cooling mode are investigated. The results show that the ejector provides up to 10.5 bar pressure lift and 26% compressor power saving potential. Furthermore, the required compressor displacement is reduced by about 22%. With the same compressor for baseline and ejector systems, the ejector system provides 24% more cooling capacity.

Keywords: Carbon Dioxide, Ejector, Mobile Heat Pump, Electric Vehicle, Expansion Work Recovery

## 1. INTRODUCTION

The European Chemicals Agency (ECHA) submitted a proposal to ban the use and production of per- and polyfluoroalkyl (PFAS) producing refrigerants (Spyrakis & Dragani, 2023). This proposal will significantly impact the design of the electric vehicle thermal management system. The most common refrigerant used in the air conditioning/heat pump (AC/HP) of electric vehicles is currently R134a (Dan et al., 2023). With the PFAS proposal, R134a should be replaced with other alternatives that meet global warming concerns.

R744 is the most probable alternative for PFAS-producing refrigerants in the vehicle thermal management system (Junqi et al., 2021; Piesch et al., 2023; Prabakaran et al., 2023; Y. Song et al., 2022; Wang et al., 2018; Zhang et al., 2023). It is not only an environmentally friendly refrigerant but also non-flammable and low toxicity. The high thermal performance properties of R744 help design smaller heat exchangers for the refrigeration system (Ayad et al., 2012; Hafner, 2003). Furthermore, in cold climates, the heat pump system using R744 works very well (Qi, 2014; Wang et al., 2023). However, the performance of R744 air conditioning systems is reduced in hot climates (X. Song et al., 2022; Wang et al., 2022). This is due to the high throttling loss and exergy destruction in the high-

pressure expansion valve (Kim et al., 2004; Robinson & Groll, 1998). As a solution to decrease exergy destruction, a two-phase ejector can be employed to recover some part of the expansion work (Chen et al., 2015; Elbel & Hrnjak, 2008; Elbel & Lawrence, 2016). This study investigates the benefit of using a two-phase ejector instead of the high-pressure expansion valve in an AC/HP system of an electric vehicle. Modelica language has been used to simulate the refrigeration cycle and carry out the thermodynamic analysis of the AC/HP system.

## 2. SYSTEM DESCRIPTION

Figure 1 (a) shows the baseline R744 HP/AC system. In cabin cooling modes, the hot ambient air is directed toward the low-pressure heat exchanger to cool it down. Then, the cold air provides the cooling demand. In the case of the battery cooling mode, the coolant is directed to the chiller on the low-pressure side to reject the heat to the low-pressure refrigerant. In both cabin cooling and battery cooling modes, the heat is rejected to the atmosphere by the outside heat exchanger on the high-pressure side. In cabin heating modes, the cold ambient air is directed toward the cabin heater located on the high-pressure side. Then, the air absorbs the heat in the cabin heater and provides the heating demands of the cabin. For the cabin heating modes, the low-pressure refrigerant is directed to the outside heat exchanger to absorb the heat at low temperatures.

In the baseline system, the low-pressure refrigerant is provided by a high-pressure expansion valve. The isenthalpic expansion of the high-pressure R744 refrigerant leads to entropy generation and exergy destruction in the high-pressure valve, known as throttling loss. Throttling loss can significantly degrade cycle performance, especially for cycles that work with R744 refrigerant. As an alternative, the high-pressure expansion valve can be replaced by an ejector to decrease the losses and recover the expansion work of the high-pressure refrigerant to compress the low-pressure refrigerant. Figure 1 (b) presents the cycle equipped with a two-phase ejector. For a fair comparison, the refrigerant temperature at the outlet port of the gas cooler, the low-pressure refrigerant, the cooling demand for cabin cooling and battery cooling modes, and the heating demand for cabin heating modes are considered the same for both the baseline and the ejector cycle. Operating condition constraints are presented in Table 1.

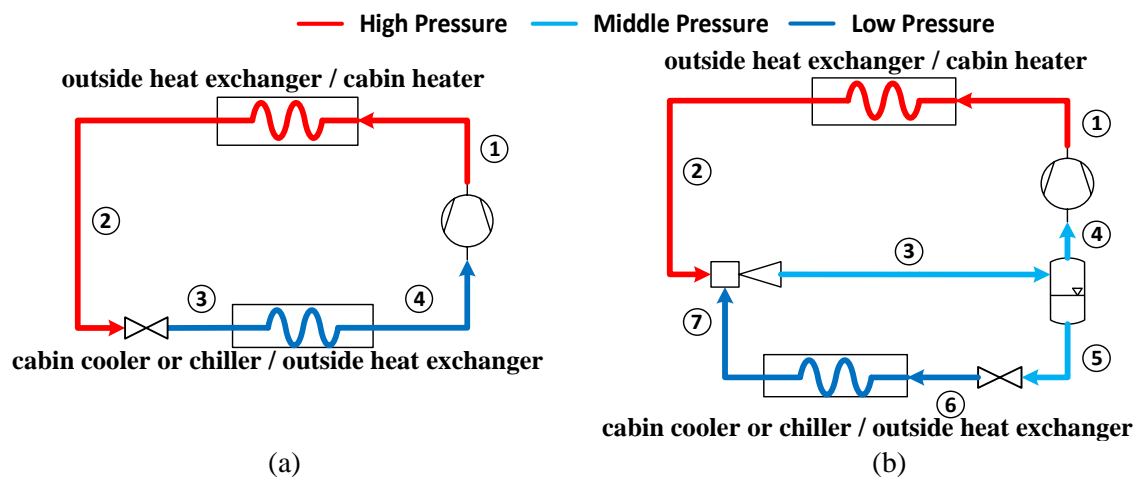


Figure 1: R744 AC/HP systems (a) baseline system (b) ejector-equipped system

**Table 1. Operational constraints for the AC/HP system**

Operating case	Mode	Heating/Cooling capacity (kW)	Temperature after gas cooler (°C)	Pressure after expansion (bar)
1	cabin cooling	5.5	45	40
2	cabin cooling	2.5	42	37
3	cabin cooling	1	32	37
4	cabin heating	7.5	32	15
5	cabin heating	5.5	38	21
6	battery cooling	12	45	40

### 3. SYSTEM MODELING AND FORMULATION

The high-pressure motive flow is expanded in the ejector and provides the driving force to compress the low-pressure refrigerant of the suction port. The ejector efficiency is defined according to the potential recoverable work in the motive flow and the recovered work by the suction flow as follows (Elbel & Hrnjak, 2008):

$$\eta_{ejector} = \dot{m}_s(h_{s,o,isen} - h_{s,i}) / \dot{m}_m(h_{m,i} - h_{m,o,isen}) \quad \text{Eq. (1)}$$

where  $h_{m,o,isen}$  represents the enthalpy of the motive flow at the outlet port, assuming an isentropic expansion.  $h_{s,o,isen}$  represents the enthalpy of the suction flow at the outlet port, assuming an isentropic compression. The ejector pressure lift is defined as follows:

$$P_{lift} = P_{mixed} - P_s \quad \text{Eq. (2)}$$

The isentropic efficiency and volumetric efficiency of the compressor are defined by the following equations (Yang et al., 2023):

$$\eta_{c,isen} = 0.9611 - 0.052(P_{c,o}/P_{c,i}) \quad \text{Eq. (3)}$$

$$\eta_{c,V} = 0.8882 - 0.04185(P_{c,o}/P_{c,i}) \quad \text{Eq. (4)}$$

The discharge pressure is adjusted according to Eq. (5) to provide the optimum cycle performance (Sarkar, 2008).

$$P_{c,o} = 22.7 + 0.21T_e + 1.06T_{g,o} + 0.0094T_e \times T_{g,o} + 0.0213T_{g,o}^2 \quad \text{Eq. (5)}$$

The compressor displacement is presented as follows:

$$\text{Compressor displacement} = \dot{V}_{c,s} / (\eta_V \times N_c) \quad \text{Eq. (6)}$$

where  $\dot{V}_{c,s}$  is the refrigerant volumetric flow rate at the suction port and  $N_c$  is the compressor rotational speed. The power-saving potential provided by replacing the high-pressure expansion valve with the ejector is defined as follows:

$$\text{Power saving} = (\dot{w}_{baseline} - \dot{w}_{ejector\ cycle}) / \dot{w}_{baseline} \quad \text{Eq. (7)}$$

where  $\dot{W}_{baseline}$  is the compressor power when running the baseline system and  $\dot{W}_{ejector\ cycle}$  is the compressor power when the ejector cycle is running with the same cooling/heating capacity.

The coefficient of performance of the system is defined as follows:

$$COP = \begin{cases} [\dot{m}_g(h_{g,i} - h_{g,o})]/[\dot{m}_c(h_{c,o} - h_{c,i})] & \text{heating mode} \\ [\dot{m}_e(h_{e,o} - h_{e,i})]/[\dot{m}_c(h_{c,o} - h_{c,i})] & \text{cooling mode} \end{cases} \quad \text{Eq. (8)}$$

#### 4. RESULTS AND DISCUSSION

In Figure 2, the P-H diagram of the baseline cycle is compared with that of the cycle equipped with a 25% efficient ejector for different operating cases. Points 4 and 1 show the compressor inlet and outlet, respectively. According to the results, the ejector cycle works at a higher suction pressure and lower discharge temperature. Table 2 Summarizes the ejector cycle improvements. Thanks to the ejector, the compressor suction pressure can be increased up to 8 bar. As a result of the pressure lift provided by the ejector, the compressor is partially unloaded, and the power consumption decreases. Results show that the ejector provides up to 20.5% and 15.9% power saving potential in cooling and heating modes, respectively. In general, there is a higher saving potential in cooling modes than in heating modes. In the case of using the same power as the baseline system in the ejector cycle, the cooling and heating capacities can increase by up to 25.8% and 18.9%, respectively. As the suction pressure increases, the refrigerant density increases at the compressor inlet. So, the compressor can provide a higher refrigerant mass flow rate with a fixed volume displacement. In order to compare the baseline cycle and the ejector cycle, the cooling and heating capacities were fixed to calculate the required volumetric flow rate. Results show the required volumetric flow rate for cooling and heating modes decreases by up to 15.7% and 13.6%, respectively. Thus, a smaller compressor can be used to provide the same demands. As it is shown Figure 2, the compressor pressure ratio decreases in the ejector cycle. In heating modes, this allows the system to work even at a lower ambient temperature. According to the results, the discharge temperature in cooling modes and heating modes decreases up to 10.2 °C and 22.2 °C, respectively. Avoiding a high refrigerant temperature in heating modes makes compressor and oil system operations safer. However, in cooling modes, the reduction of the refrigerant discharge temperature reduces the temperature driving force in the gas cooler to reject the heat to the ambient. So it may lead to a larger gas cooler.

Figure 3 shows how the ejector efficiency affects the COP of the cycle and the ejector pressure lift. According to the results, adding the ejector to the baseline system can increase the COP of the cycle by up to 35% in cooling modes and up to 25% in heating modes. Furthermore, the ejector provides up to 10.5 bar pressure lift in cooling modes and up to 8 bar in heating modes. Results show that the ejector is more beneficial in cooling modes than heating modes. Thanks to the pressure lift provided by the ejector and the increase in refrigerant density at the compressor inlet, the ejector-equipped system works with a lower power consumption. Figure 4 shows the power saving potential in the ejector cycle compared to the baseline system. Results show that if the ejector replaces the high-pressure valve, the required power to provide the same demand decreases by up to 26% in cooling modes and up to 20% in heating modes. In the case of using the same power as the baseline system for the ejector system, the cooling and heating capacities can increase by up to 35% and 25%, respectively.

The compressor is sized based on the battery cooling mode capacity. As the refrigerant density increases at the compressor inlet, the required compressor displacement to provide the cooling demand is decreased. Figure 5

shows how the ejector efficiency affects the required compressor displacement. The compressor rotational speed is assumed to be 8600 rpm. Results show that using a high ejector efficiency can make the compressor 22% smaller. When using a compressor with the same displacement for both the baseline and ejector systems, the ejector system can provide up to 24% more cooling capacity.

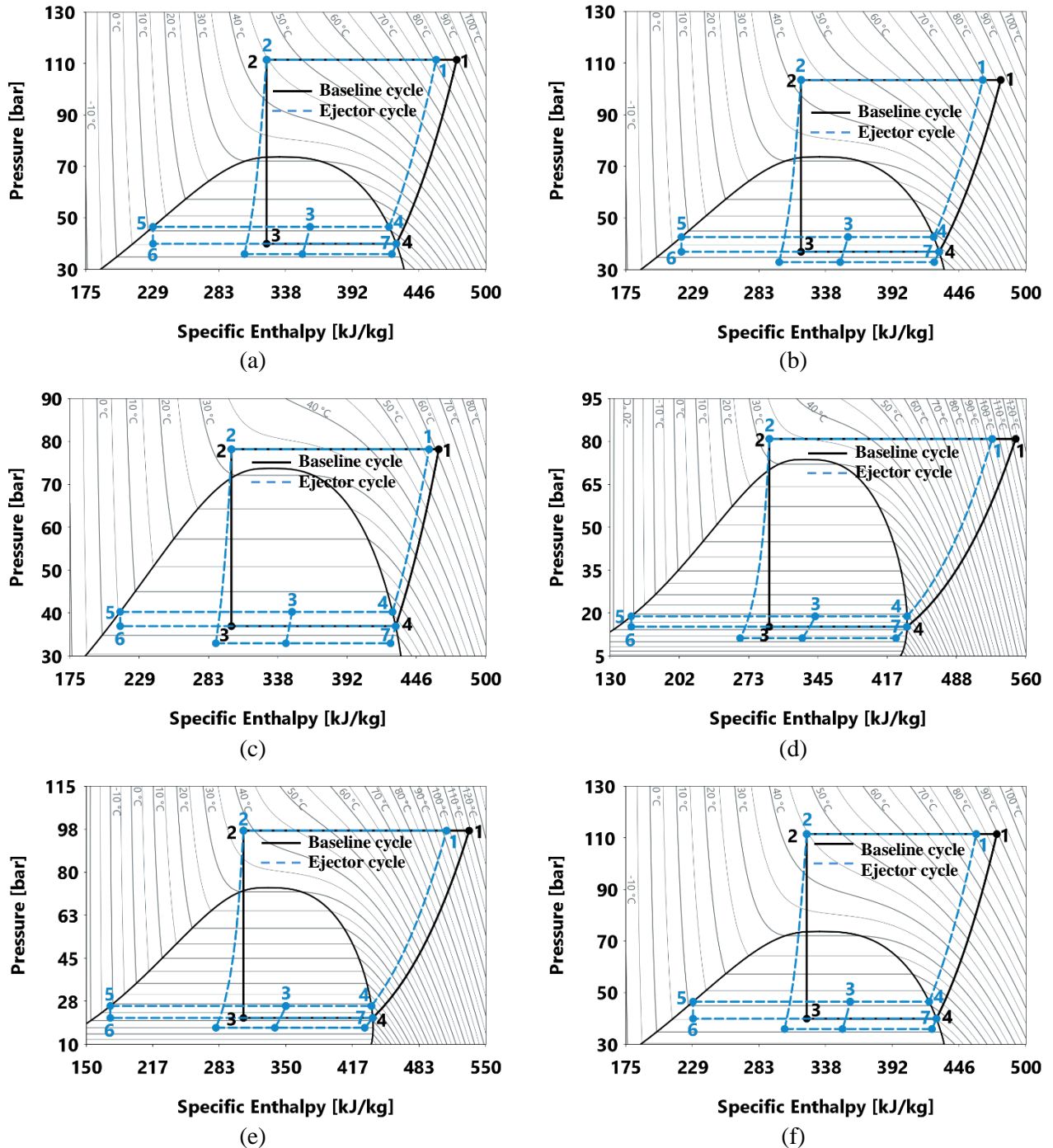
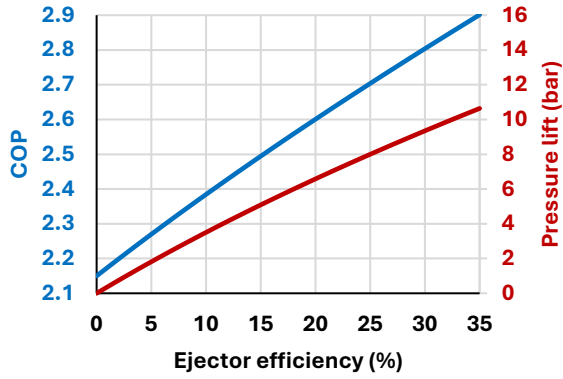


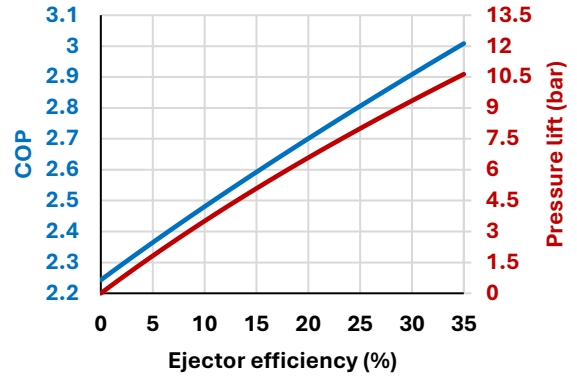
Figure 2: P-H diagram of the baseline cycle and the ejector cycle ( $\eta_{ejector} = 25\%$ )  
 (a) Mode 1 (cabin cooling) (b) Mode 2 (cabin cooling) (c) Mode 3 (cabin cooling)  
 (d) Mode 4 (cabin heating) (e) Mode 5 (cabin heating) (f) Mode 6 (battery cooling)

**Table 2. Benefits of using a two-phase ejector in the AC/HP system ( $\eta_{ejector} = 25\%$ )**

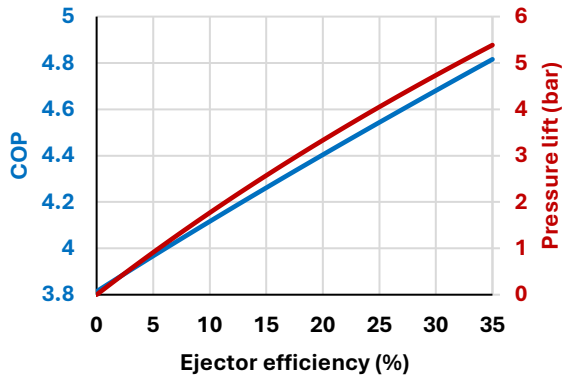
Operating case	1	2	3	4	5	6
$P_{lift}$ (bar)	8.0	7.0	4.1	4.4	5.9	8.0
Power saving (%)	20.5	20.1	16.1	15.9	15.9	20.5
Capacity improvement (%)	25.8	25.1	19.1	18.9	18.9	25.8
Volumetric flow reduction (%)	15.7	15.6	10.1	13.5	13.6	15.7



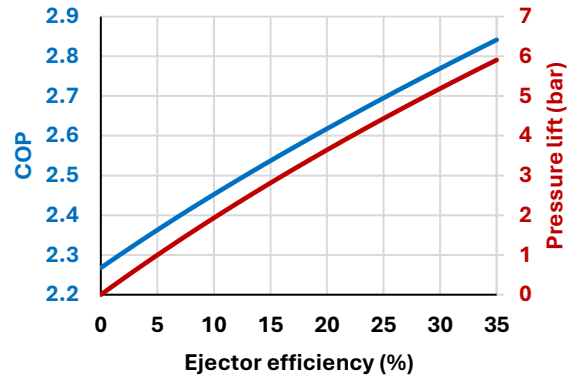
(a)



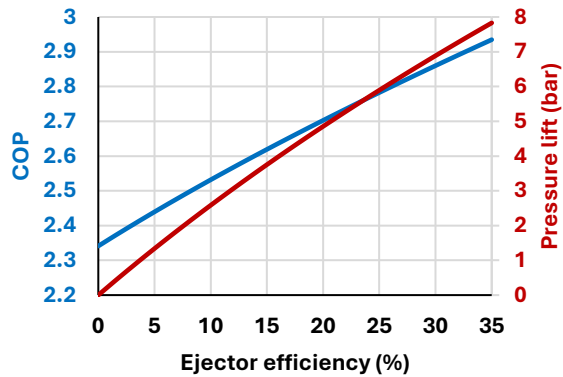
(b)



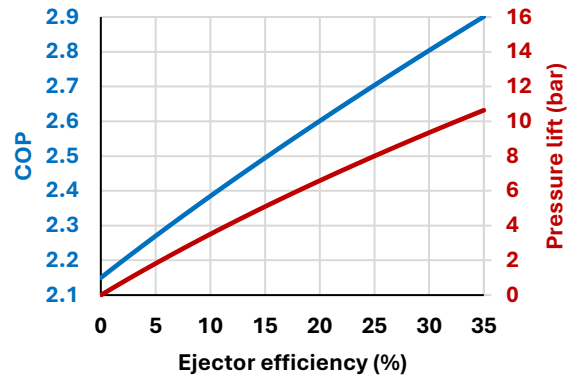
(c)



(d)

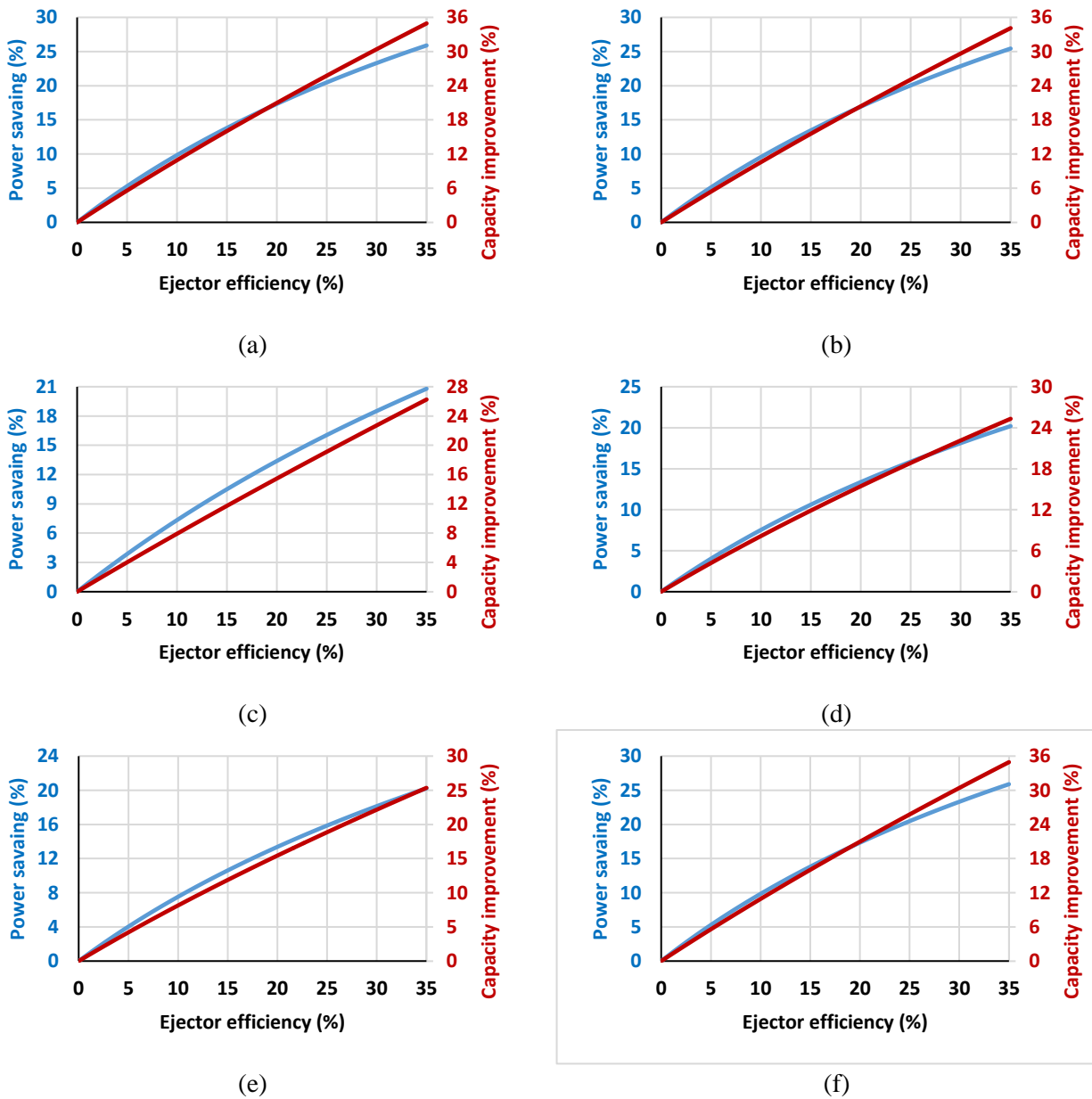


(e)

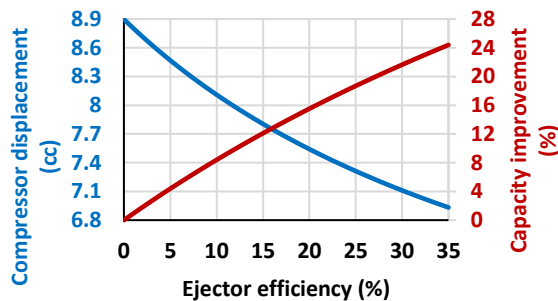


(f)

**Figure 3: The effect of ejector efficiency on the cycle COP and the ejector pressure lift**  
 (a) Mode 1 (cabin cooling) (b) Mode 2 (cabin cooling) (c) Mode 3 (cabin cooling)  
 (d) Mode 4 (cabin heating) (e) Mode 5 (cabin heating) (f) Mode 6 (battery cooling)



**Figure 4: The effect of ejector efficiency on the power saving potential and capacity improvement**  
 (a) Mode 1 (cabin cooling) (b) Mode 2 (cabin cooling) (c) Mode 3 (cabin cooling)  
 (d) Mode 4 (cabin heating) (e) Mode 5 (cabin heating) (f) Mode 6 (battery cooling)



**Figure 5: The effect of ejector efficiency on the compressor displacement and battery cooling capacity**

## 5. CONCLUSION

As global warming is increasing, there is a need to shift to environmentally friendly refrigerants, and new restrictions should be considered when designing next-generation AC/HP systems. R744 is the most promising environmentally friendly refrigerant for electric vehicle AC/HP systems. It is not only a natural refrigerant but also provides the opportunity to design more compact AC/HP systems. However, the R744 expansion in high-pressure valves imposes high exergy destruction on the system and leads to low cycle performance, especially in high ambient temperatures. This study employed a conceptual thermodynamic analysis to show how a two-phase ejector improves the electric vehicle AC/HP system. Results showed that the ejector helps to save the compressor power up to 26% and 20% in cooling and heating modes, respectively. In addition, the required compressor displacement could decrease up to 22% for the same cooling capacity. If the same compressor is used, cooling capacity could increase by 24%.

## NOMENCLATURE

$h$	enthalpy (kJ/kg)	<i>Subscripts</i>	
$\dot{m}$	mass flow rate (kg/s)	$c$	<i>compressor</i>
$N$	compressor rotational speed (revolutions per second)	$e$	<i>cabin cooler or chiller</i>
$P$	pressure (Pa)	$g$	<i>gas cooler</i>
$\dot{Q}$	heat transfer rate (J/s)	$i$	<i>inlet port</i>
$T$	temperature (°C)	$isen$	<i>isentropic</i>
$\dot{V}$	compressor volumetric flow rate (m <sup>3</sup> /s)	$m$	<i>motive port</i>
$\dot{w}$	compressor work (J/s)	$mixed$	<i>ejector outlet port</i>
		$o$	<i>outlet port</i>
		$s$	<i>suction port</i>
<i>Greek symbols</i>			
$\eta$	efficiency (%)		

## REFERENCES

- Ayad, F., Benelmir, R., & Souayed, A., 2012. CO<sub>2</sub> evaporators design for vehicle HVAC operation. *Applied Thermal Engineering*, 36, 330-344.
- Chen, J., Jarall, S., Havtun, H., & Palm, B., 2015. A review on versatile ejector applications in refrigeration systems. *Renewable and Sustainable Energy Reviews*, 49, 67-90.
- Dan, D., Zhao, Y., Wei, M., & Wang, X., 2023. Review of Thermal Management Technology for Electric Vehicles. *Energies*, 16(12), 4693.
- Elbel, S., & Hrnjak, P., 2008. Experimental validation of a prototype ejector designed to reduce throttling losses encountered in transcritical R744 system operation. *International Journal of Refrigeration*, 31(3), 411-422.
- Elbel, S., & Lawrence, N., 2016. Review of recent developments in advanced ejector technology. *International Journal of Refrigeration*, 62, 1-18.
- Hafner, A., 2003. Compact interior heat exchangers for CO<sub>2</sub> mobile heat pumping systems.
- Junqi, D., Yibiao, W., Shiwei, J., Xianhui, Z., & Linjie, H., 2021. Experimental study of R744 heat pump system for electric vehicle application. *Applied Thermal Engineering*, 183, 116191.
- Kim, M.-H., Pettersen, J., & Bullard, C. W., 2004. Fundamental process and system design issues in CO<sub>2</sub> vapor

compression systems. *Progress in energy and combustion science*, 30(2), 119-174.

Piesch, N., Niroomand, R., Hafner, A., Banasiak, K., & Ayad, F., 2023. R744 heat pump solutions for electric vehicles. 10th Conference on Ammonia and CO2 Refrigeration Technologies,

Prabakaran, R., Lal, D. M., & Kim, S. C., 2023. A state of art review on future low global warming potential refrigerants and performance augmentation methods for vapour compression based mobile air conditioning system. *Journal of Thermal Analysis and Calorimetry*, 148(2), 417-449.

Qi, Z., 2014. Advances on air conditioning and heat pump system in electric vehicles—A review. *Renewable and Sustainable Energy Reviews*, 38, 754-764.

Robinson, D. M., & Groll, E. A., 1998. Efficiencies of transcritical CO2 cycles with and without an expansion turbine: Rendement de cycles transcritiques au CO2 avec et sans turbine d'expansion. *International Journal of Refrigeration*, 21(7), 577-589.

Sarkar, J., 2008. Optimization of ejector-expansion transcritical CO2 heat pump cycle. *Energy*, 33(9), 1399-1406.

Song, X., Yu, B., Zhang, Y., Shi, J., & Chen, J., 2022. An investigation into the thermodynamic improvement potential of a transcritical automotive CO2 refrigeration cycle. *Applied Thermal Engineering*, 216, 119137.

Song, Y., Cui, C., Yin, X., & Cao, F., 2022. Advanced development and application of transcritical CO2 refrigeration and heat pump technology—A review. *Energy Reports*, 8, 7840-7869.

Spyrakakis, F., & Dragani, T. A., 2023. The EU's Per- and Polyfluoroalkyl Substances (PFAS) Ban: A Case of Policy over Science. *Toxics*, 11(9), 721.

Wang, D., Yu, B., Hu, J., Chen, L., Shi, J., & Chen, J., 2018. Heating performance characteristics of CO2 heat pump system for electrical vehicle in a cold climate. *International Journal of Refrigeration*, 85, 27-41.

Wang, L., Zhu, S.-L., & Zhang, X.-R., 2022. Performance and economic evaluation of CO2 (R744) air conditioning system driven by compressed air engine. *International Journal of Refrigeration*, 135, 189-197.

Wang, X., Xu, K., Huang, L., Cao, F., & Song, Y., 2023. The Experimental Study of an R744 Heat Pump System for an Electric Vehicle for Cabin Cooling or Heating and Battery Fast Charging Cooling. *Energies*, 16(4), 2061.

Yang, H., Wu, J., Chen, Y., & Xue, X., 2023. Pseudo-optimal discharge pressure analysis of different CO2 electric vehicle heat pumps based on cabin thermal model. *Applied Thermal Engineering*, 122069.

Zhang, N., Lu, Y., Ouderji, Z. H., & Yu, Z., 2023. Review of heat pump integrated energy systems for future zero-emission vehicles. *Energy*, 127101.