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Carbon Dioxide as an Eco-Friendly Refrigerant for Electric Vehicles

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Executive Summary

Atmospheric carbon dioxide receives a lot of negative press for its role in global climate change. However, it offers significant benefits in vehicular thermal management. This study compares CO_2 with R134a, the most common organic refrigerant, and discusses the applicability of CO_2 to electric vehicle-specific applications.

The key of benefits of CO_2 are low global warming potential, low ambient temperature refrigerant properties, improved heat transfer and pressure drop over organic refrigerants, no requirement for refrigerant recovery, and small component sizes.

The primary challenges of CO_2 are high operating pressures, unique control strategies necessitated by pressure-enthalpy characteristics, system benefit requiring a suction-line heat exchanger, and lack of balance-of-system components (e.g. compressors) for the automotive industry. For electric vehicles (EVs), AC performance and rapid charging are also challenges to mass commercialization.

Inquiry Question

Is carbon dioxide (R744) a viable refrigerant option for electric vehicles at a range of climates? Chemical manufacturers are frequently unveiling new refrigerant blends that address the global warming potential (GWP) while providing sufficient cooling capacity.

For EVs, green technology appeals to their target consumer. While organic refrigerant manufacturers strive to reduce the GWP to 1, carbon dioxide sets the scale. But while the thermophysical properties of CO_2 are favorable for efficient heat transfer, its low critical temperature dictates that it must reject heat as a supercritical fluid and operate at high pressures to optimize system performance.

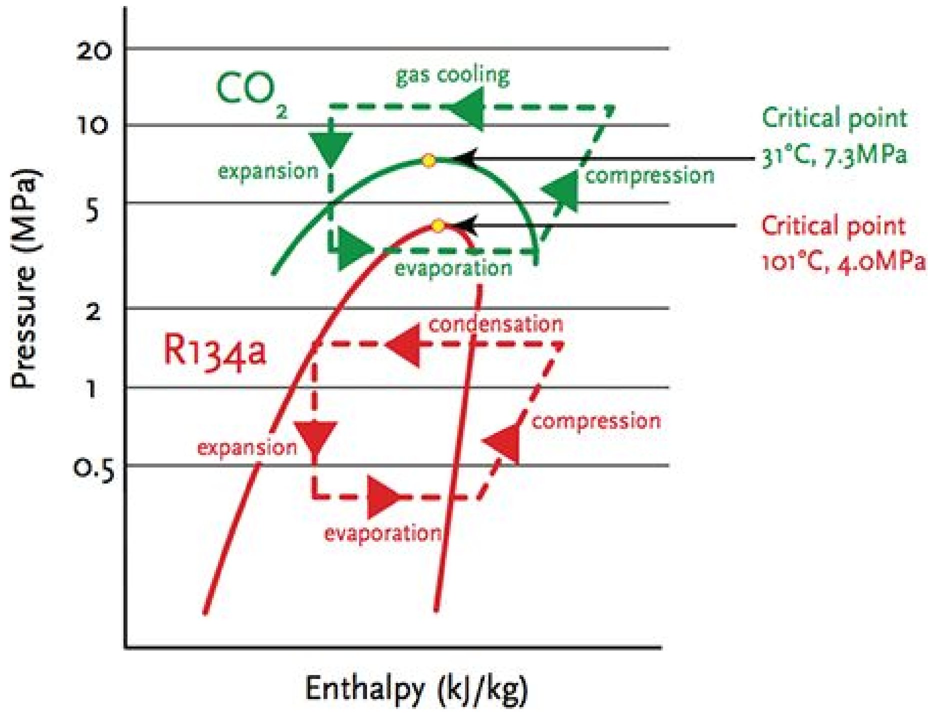


Image courtesy of CIBSE Journal

Key Results

1) **Thermophysical properties** – CO_2 has lower viscosity and higher vapor density and density ratio than R134a

2) **Refrigeration cycle** – temperature is decoupled from pressure above the vapor dome for CO_2, changing system control and optimization strategy

3) **Ambient temperature performance** – relative rate of cooling capacity and coefficient of performance (COP) decrease is smaller than R134a when varying saturation pressure and high-side pressure

4) **EV-specific** – while advantaged for low-ambient operation, CO_2 faces challenges in system component development (e.g. compressors and expansion devices) and competitive technology (e.g. electric heaters).

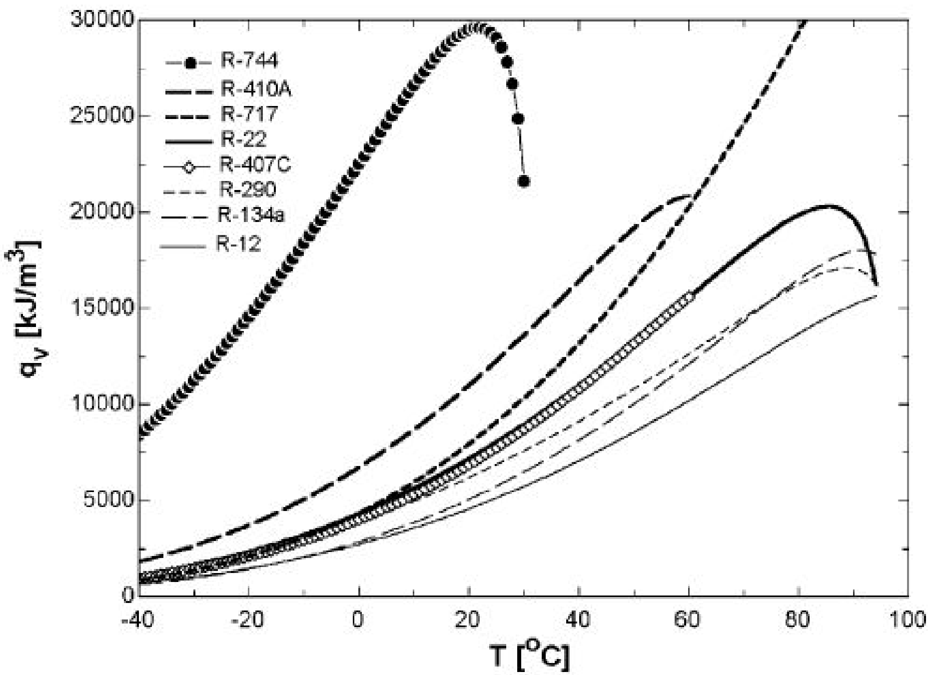
Supplementary Information

$$q_V\ [kJ/m^3] = \rho_{vap} \times \Delta H_{vap}$$

Volumetric Refrigeration Capacity (q_v)[1]

The product of vapor density and latent heat of vaporization provides the energy per unit volume.

CO_2 has a higher volumetric refrigeration capacity than many traditional refrigerants, which provides higher heat transfer and lower pressure drop as a result.

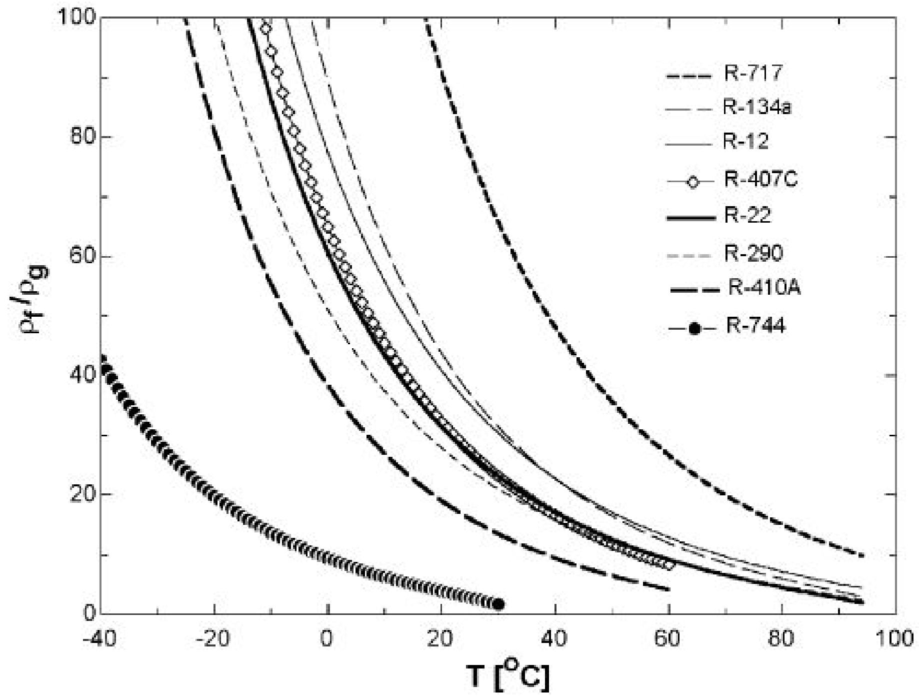


ρ_{vap} = vapor density
ΔH_{vap} = latent heat of vaporization

Density Ratio[1]

When defined as the ratio of liquid density to vapor density, CO_2 has a significantly lower density ratio than organic refrigerants.

A lower density ratio leads to a more homogeneous 2-phase flow, which in turn increases 2-phase heat transfer coefficients. Additionally, a more uniform 2-phase mixture improves the significant challenge of flow distribution. This is a critical pain point for evaporators to maximize cooling capacity.

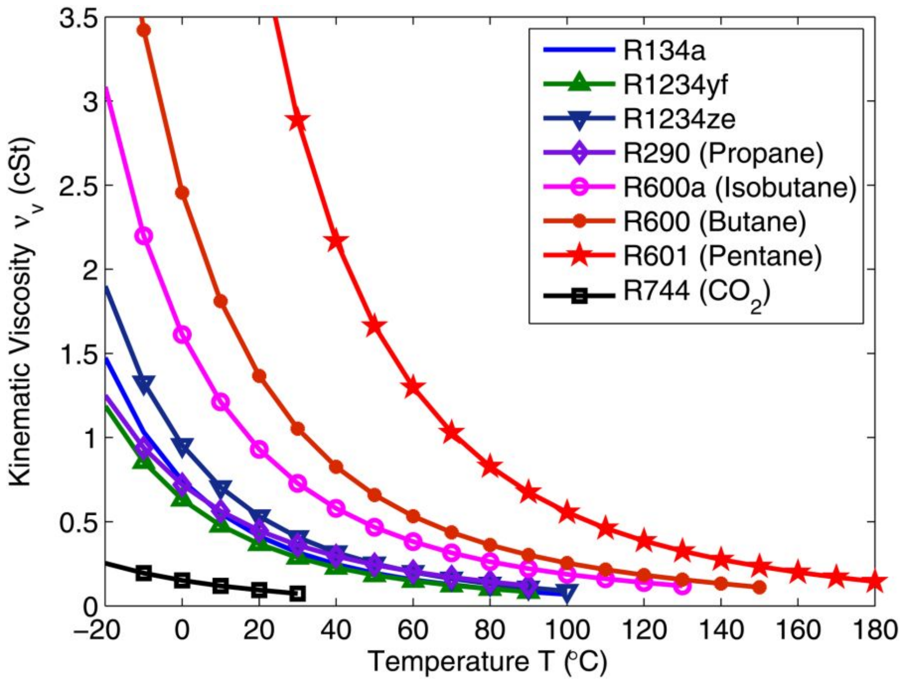


ρ_f = *liquid density*
ρ_g = *gas density*

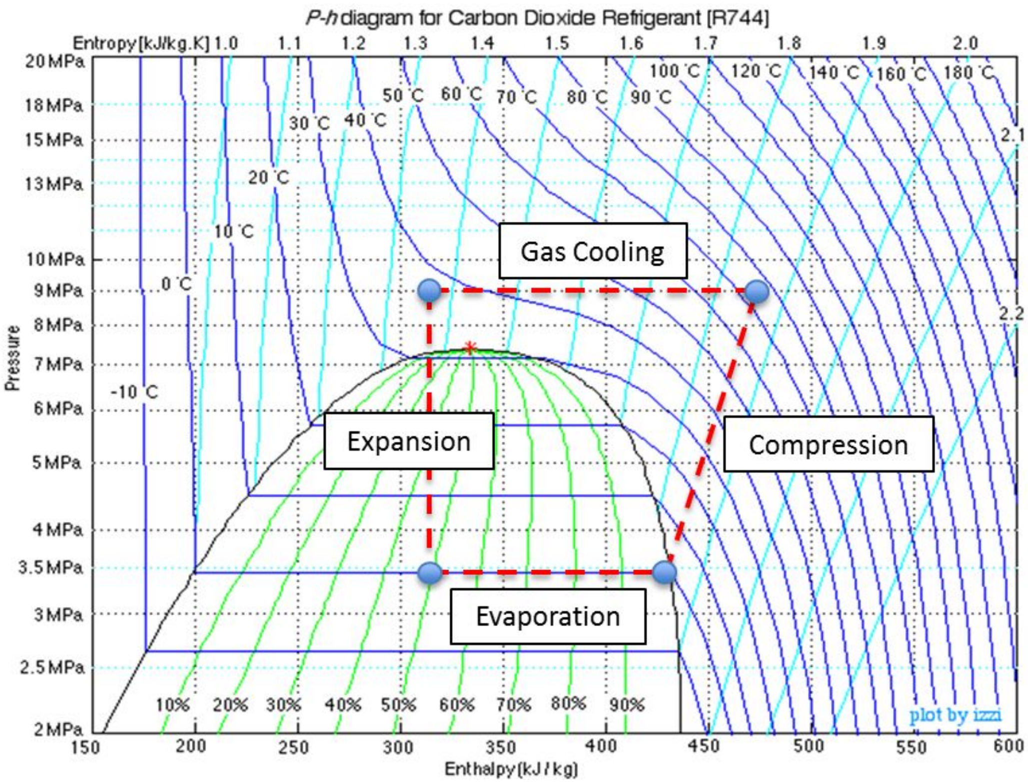
Viscosity[2]

Viscosity of carbon dioxide is also favorable over organic refrigerants, especially at low pressures.

A lower viscosity increases Reynold's number which increases heat transfer, and decreases pressure drop due to the reduced flow resistance.



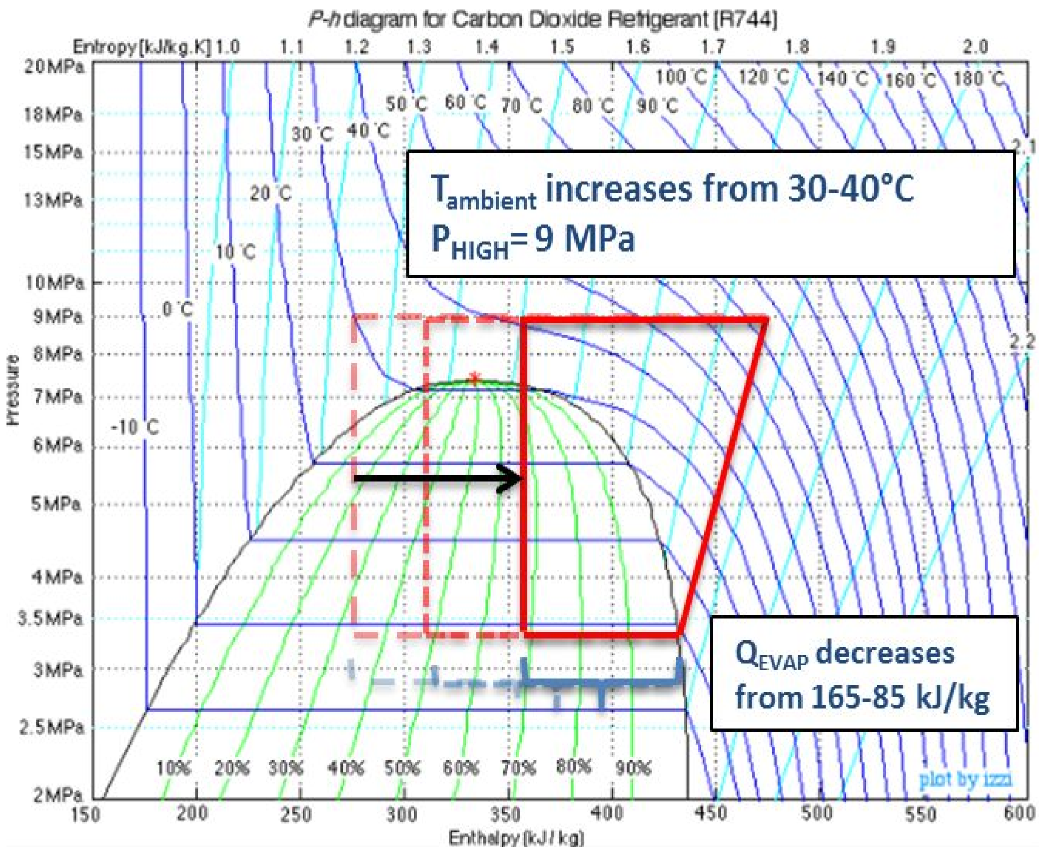
Transcritical Refrigeration Cycle



Transcritical cycles absorb heat within the vapor dome (subcritical) but reject the heat above it (supercritical). For a supercritical fluid, temperature is decoupled from pressure. Cooling capacity performance (ΔH_{EVAP}) improves as $T_{GC,exit}$ approaches the ambient. As a result, the gas cooler should be as effective as possible without creating excessive pressure drop (an optimization opportunity).

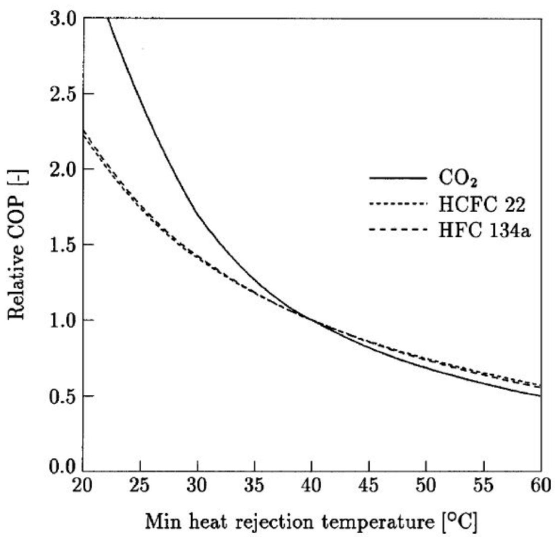
Transcritical Refrigeration Cycle

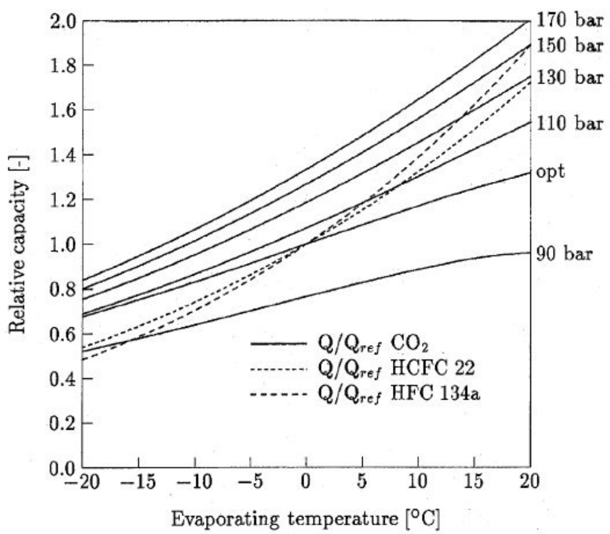
Higher ambient temperature and/or excessive pressure drop in the gas cooler decreases cooling capacity at fixed high-side pressure. This trend is due to the S-shape of isotherms above the vapor dome.

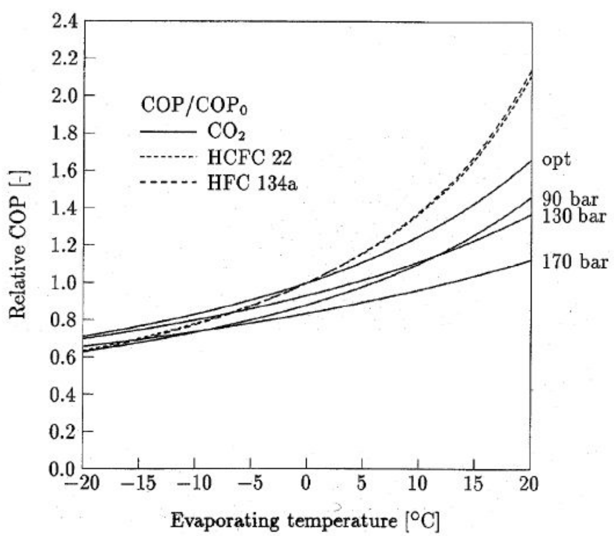


Ambient Temperature Performance[1]

The biggest advantage of CO_2 might be its performance at low ambient temperatures. The "S"-shape of the isotherms above the vapor dome impacts the CO_2 evaporator inlet enthalpy. This behavior shifts system optimization control from saturation temperature to high-side pressure.

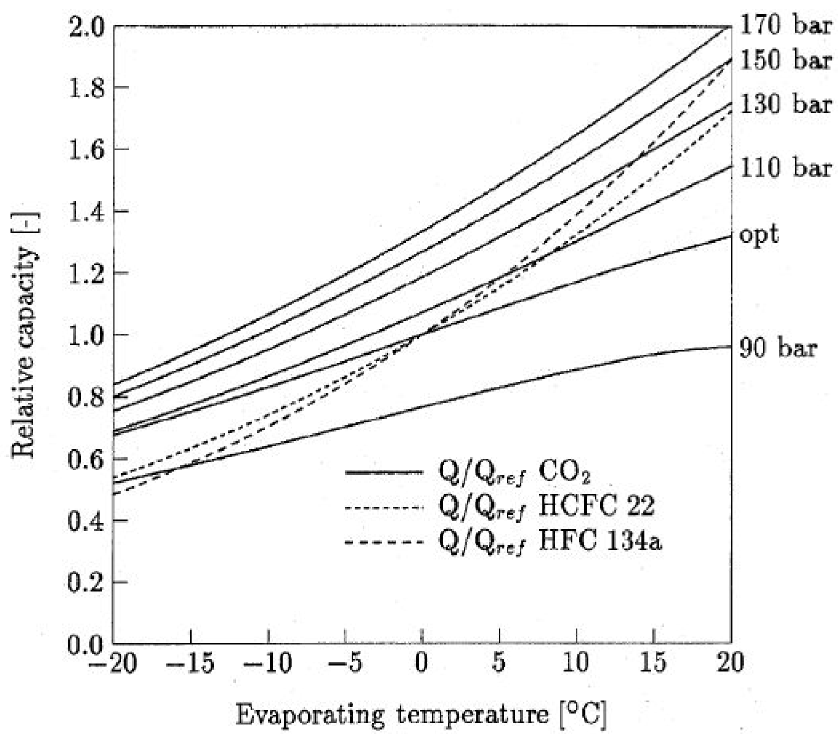






Air Conditioning Mode[1]

While CO_2 shows clear advantages in heating mode, air conditioning mode presents its own set of challenges. Carbon dioxide exhibits poor cooling performance at high ambient conditions, as shown by its shallower slope in the middle plot on slide 11 (and below). The graph shows that CO_2 has a general loss of performance when compared with organic refrigerants at higher ambient temperatures.



Rapid Charging[3]

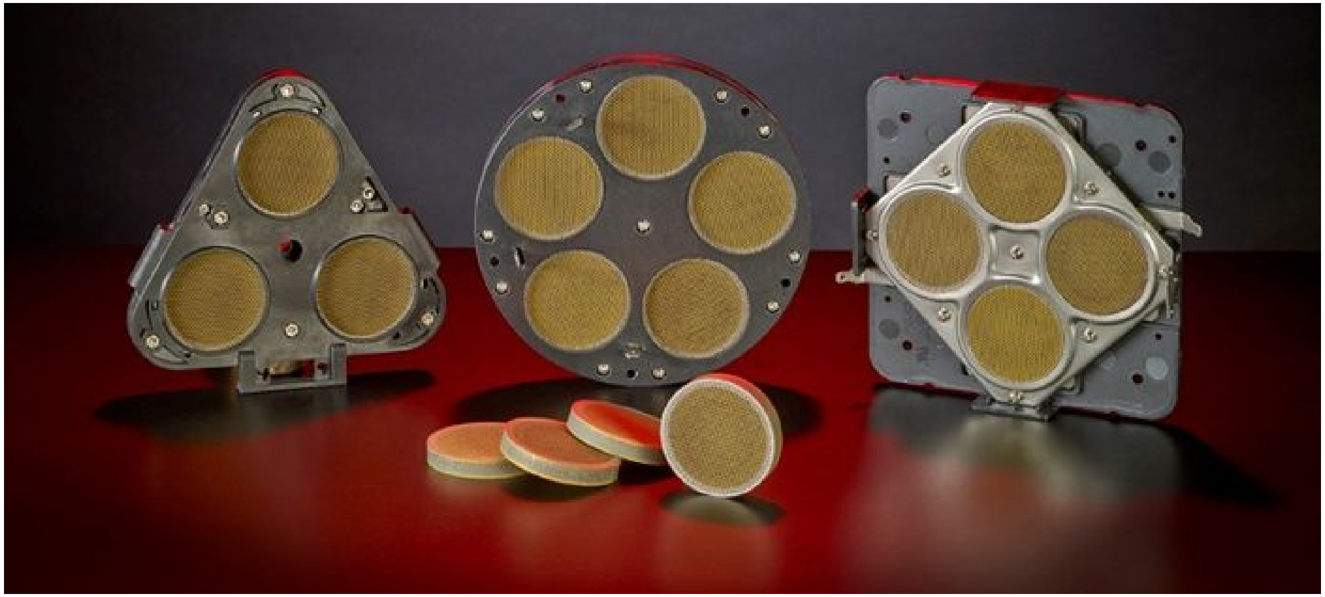
Currently, the size and capacity the vehicular cooling components is dictated by the intensity of charging. The table below shows the charging times at two power sources (“Level 1”, or standard wall outlet charging, was not included but adds about 2-5 miles of range per hour).

LEVEL 2 CHARGING (240V)	DC FAST CHARGING
→ Nissan Leaf: 11-22 miles per hour	→ Nissan Leaf: 60-95 miles in 30 minutes
→ Ford Focus Electric: 22 miles per hour	→ Ford Focus Electric: (no fast-charging)
→ Volkswagen e-Golf: 24 miles per hour	→ Volkswagen e-Golf: 60-83 miles in 30 minutes
→ BMW i3: 28 miles per hour	→ BMW i3: 60-82 miles in 30 minutes
→ Tesla Model S: 29-60 miles per hour	→ Tesla Model S: 170 miles in 30 minutes
→ Chevy Volt: 11 miles per hour	→ Chevy Volt: (no fast-charging)

Fast charging could require around 18-20 kW to simultaneously cool the passenger cabin and the battery. For that much capacity, CO_2 systems require a large compressor (not yet commercially available). This larger capacity drives size and weight, which is also increased by the pressure vessel requirements needed to contain the elevated CO_2 system pressures.

Alternative Heating Methods[4]

While CO_2 shows low ambient temperature benefits for heating, it is only useful down to around -10°C (14° F). However, in many geographic regions the temperature can get as low as -30°C, or lower. The conventional solution to bridge that gap is a Positive Temperature Coefficient (PTC) heater. This type of electric resistance heater uses ceramic in place of wire. Though expensive, they are required to meet the lowest ambient requirements in conjunction with CO_2 heat pumps. Battery development is ongoing to make PTC heaters economic enough to obsolete the heat pump.



Market Momentum Around CO_2

Low-ambient performance and favorable global warming potential are the current market pulls for CO_2 as a vehicular heating, ventilation and air conditioning (HVAC) refrigerant. Challenges are 1) that of the three primary modes of operation, heating, AC, and rapid charging, CO_2 is not favorable in the latter two, and 2) there are component development and competing technologies that impend its wide scale implementation.

The market is currently being driven toward heat pumps to improve driving range. So, there is near-term pull for CO_2 heat pump systems especially in cold climates. However, product development around battery technology, PTC heaters, additional waste heat system architectures and/or directional (targeted) heating are threatening the long-term viability of a CO_2 system that is not yet fully commercialized.

Conclusions and Outlook

The added complexity and weight of a CO_2 heat pump system must be traded-off against its benefit. For vehicles that would be driven only in the northern cold climates, it would make sense. But what about a cross-country trip? EVs are significantly cost-challenged, so for warm climates with no need to carry the excess heating equipment, consumers are unlikely to want to pay for the extra componentry. Geographically-specific vehicles within a country decrease the scale economies of parts not common to all designs.

Further, as organic refrigerants perform better in AC and fast charge modes, CO_2 is again at a disadvantage. It also seems unlikely that compressor suppliers will push to develop a high-pressure-capable product solution for a technology that could be made redundant in the intermediate term. Compressor development is in a race with PTC development for commercial viability at volume.

CO_2 definitely has a place in the near term due to improved low-ambient performance. But the complexity and cost with implementing it is a legitimate challenge to its use as a wide scale vehicular refrigerant solution.

References

1) Kim, M., Pettersen, J. and Bullard, C. (2004). Fundamental process and system design issues in CO2 vapor compression systems. Progress in Energy and Combustion Science, 30, 119-174.

2) Zhang, T. and Mohamed, S. (2014). Conceptual Design and Analysis of Hydrocarbon-Based Solar Thermal Power and Ejector Cooling Systems in Hot Climates. J. Sol. Energy Eng. 137(2), 021001.

3) https://www.fleetcarma.com/electric-vehicle-charging-guide/

4) https://www.pelonistechnologies.com/blog/three-benefits-of-ptc-heating-technology

Next Inquiries

Topic	Question	Deliverable
Related research	What US-based institutions are working on incorporating carbon dioxide in EV cooling systems?	Inquiry 2
Patent landscape	What's the patent landscape for carbon dioxide-based refrigerant solutions?	Inquiry 3
Other eco-friendly refrigerants	Look at adjacent industries for technologies related to eco-friendly refrigerants.	Inquiry 4
Outreach	Interview high interest targets anonymously	Inquiry 5
Market Analysis	Where are there new business or revenue streams for us to tap into?	Inquiry 6

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