AIR CONDITIONING & REFRIGERATION CENTER
ACRC
A NATIONAL SCIENCE FOUNDATION
INDUSTRY/UNIVERSITY COOPERATIVE RESEARCH CENTER

Transcritical CO_2 for Mobile Air-Conditioning and Heat Pump Systems

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Sustainable Technologies for Air Conditioning Workshop
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Before We Get Started…

Efficiency of CO_2 at high ambient temperatures

Cost of R1234yf

Technology to improve efficiency exists, but adds complexity (cost)

Cost of CO_2 system

Service & maintenance (training)

Patent situation

Low CO_2 production volumes (initially)

CO_2 systems requires re-design of each component (not a drop-in)

Safety concerns
- *Flammability*
- *Combustion byproducts (HF)*
- *Long-term environmental concerns (TFA)*

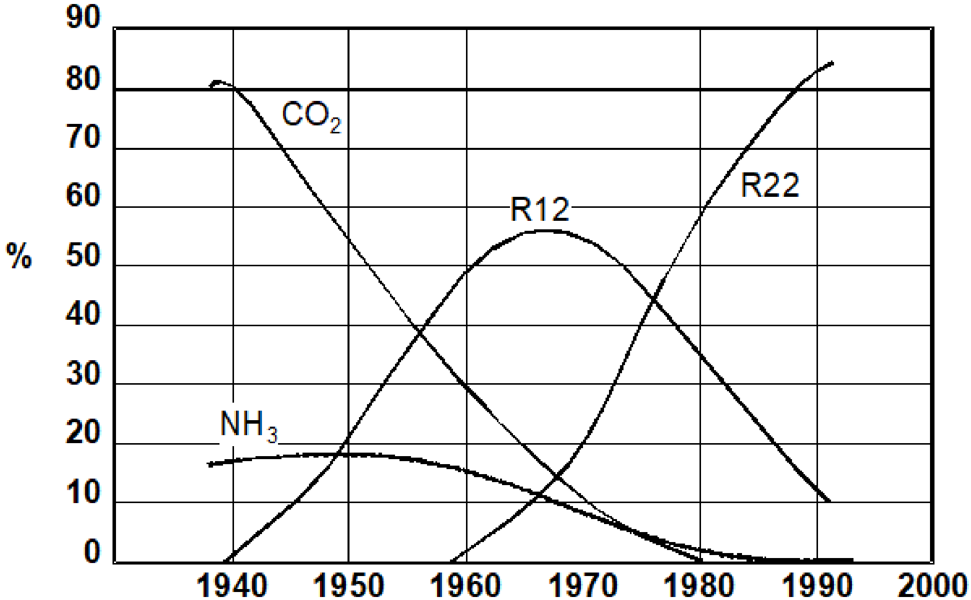
Need for heat pump in electric vehicles

Presentation Outline

- Brief History of CO_2 as Refrigerant
  - CO_2 used to be very popular. What made it disappear?
  - Why did it reappear? Why does transcritical CO_2 make sense for cars?
- What is so Different About CO_2?
  - What are the strengths of CO_2?
  - What technical challenges need to be overcome?
- Technology Examples that Paved the Road for CO_2
  - Microchannel gas cooler
  - Internal heat exchanger
  - Ejector for expansion work recovery
  - Heat pump for low ambient temperatures (hybrid / electric vehicles)
- Path to Successful Implementation
- Summary & Conclusions

CO_2 Used to be a Very Popular Refrigerant!

Percentage Use of Primary Refrigerants in Existing Marine Cargo Transport Classed by Lloyd's Register



Stera A.C., 1992, Ammonia Refrigerating Plant on Reefer Ships. Introduction to Ammonia as a Marine Refrigerant, Lloyd's Register Technical Seminar, London, UK

Advertisement in Ice & Refrigeration, 1922, Vol. 63

Fish Freezing, 1915

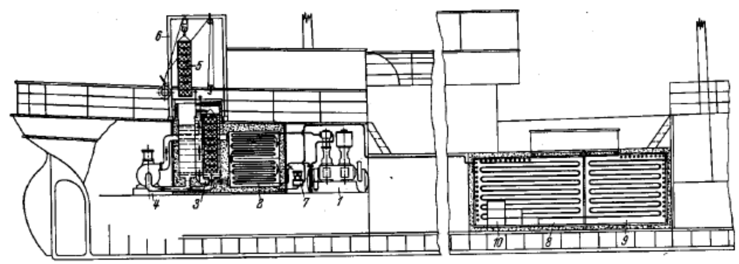
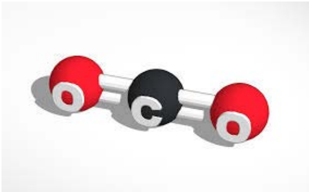


Abb. 102. Einbau einer OTTESEN-Fischgefrieranlage in den Dampfer „Karmøy" (Thomas Th. Sabroe, Aarhus, Dänemark).

1 Dampfmaschine und CO_2-Kompressor mit Kondensator, 2 Verdampfer, 3 Gefrierbehälter, 4 Solezirkulationspumpe, 5 galvanisierte Fischbehälter, 6 Hebevorrichtung für die Fischbehälter, 7 Solepumpe, 8, 9 Lagerräume, 10 gefrorene Fische versandfertig verpackt.

Pettersen J., 2002, CO_2 Vapour Compression Cycle in a Historical Perspective, Public Lecture (PhD Defense)

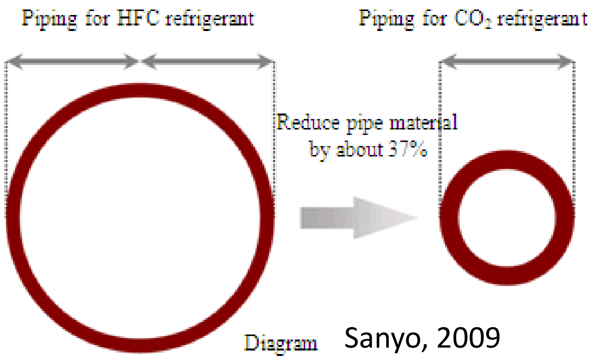


But What Made CO_2 Refrigeration Disappear?

- Containment problems (leaks)
- Perceived problems of high pressure
  - Production and material technology did not offer good options for high pressures
- Loss of capacity and efficiency at high temperatures
  - Cold cooling water not availabe or too hot in tropical seas
- CFC refrigerant development (”Freon”)

Why Did CO_2 Reappear? Why Does it Make Sense for Cars?

- Environmental issues: it appears CO_2 is the only ASHRAE A1 (non-toxic, non-flammable) low-GWP refrigerant available for mobile air-conditioning (not considering blends which have additional technical issues)
  - CO_2 is non-toxic to humans **and** plants (no phytotoxic breakdown products)
- Improved materials and technologies:
  - High pressure and containment issues have been resolved
  - Microchannel HXs offer great compactness at reasonable cost. Instead of thick walls use tubes with small diameter. Weight of HXs does not increase for CO_2!
  - Improvements in compressor technology and significantly smaller displacements make CO_2 systems more compact
- Increased need for heat pump and combined AC/HP applications where CO_2 has advantages (electric / hybrid vehicles)

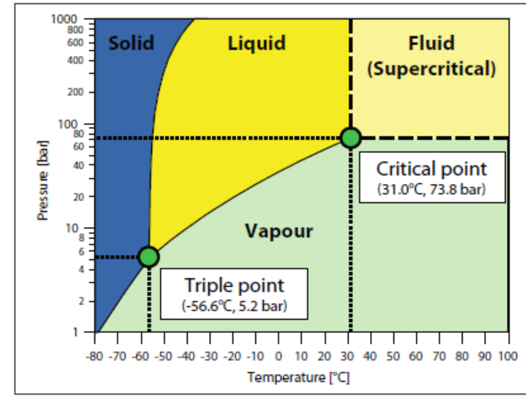


Sanyo, 2009

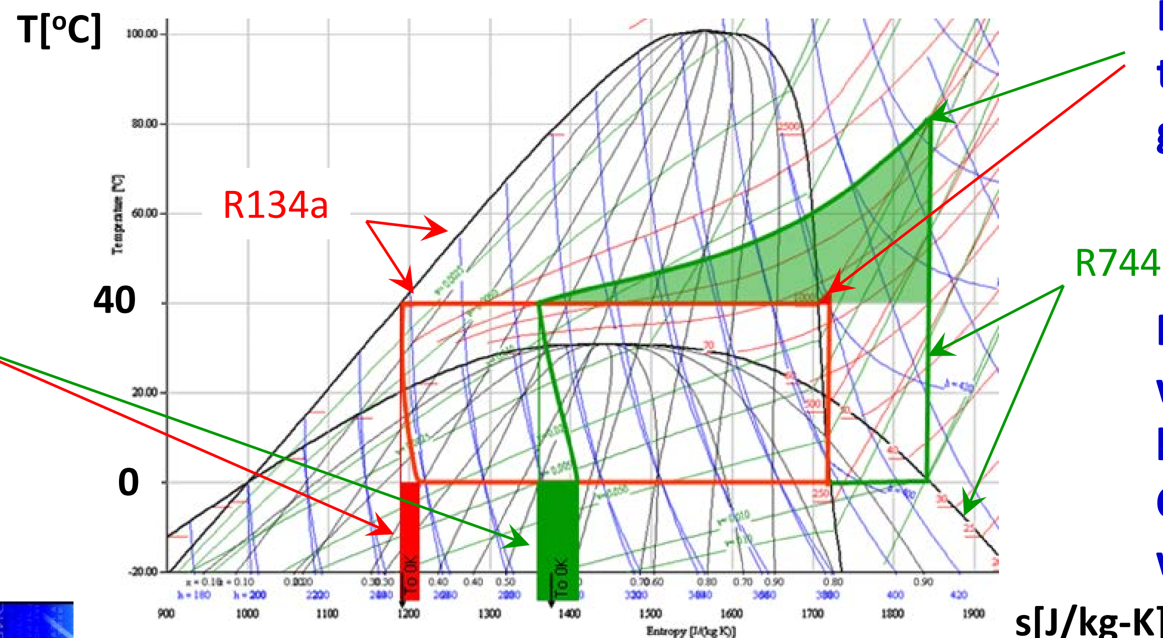
What is so Different About CO_2?

- Has excellent thermophysical properties
  - High thermal conductivity, low viscosity, …
- Has low critical temperature (only 31°C)
  - Cannot differentiate between vapor and liquid above critical point, i.e. no condensation but instead gas cooling
- Runs as a transcritical cycle at elevated ambient temperatures
  - That is what's causing the efficiency loss in AC operation

Source: www.Danfoss.com



Loss due to temperature glide



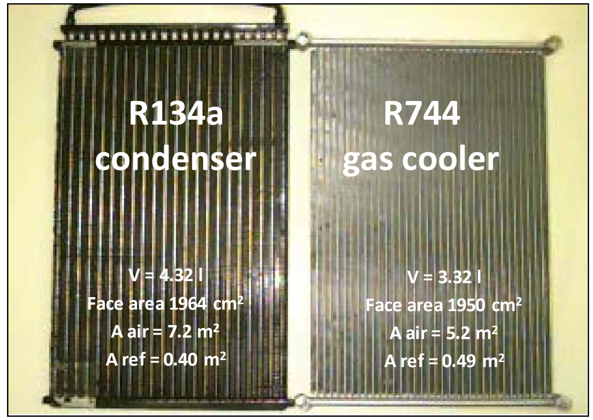
s[J/kg-K]

Additional losses due to isenthalpic expansion

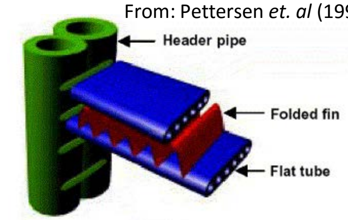
Rankine cycle with R134a looks more like Carnot than with R744

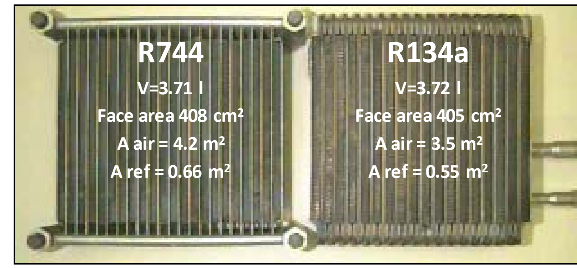
Initial Expectations Were Not Very High! But…

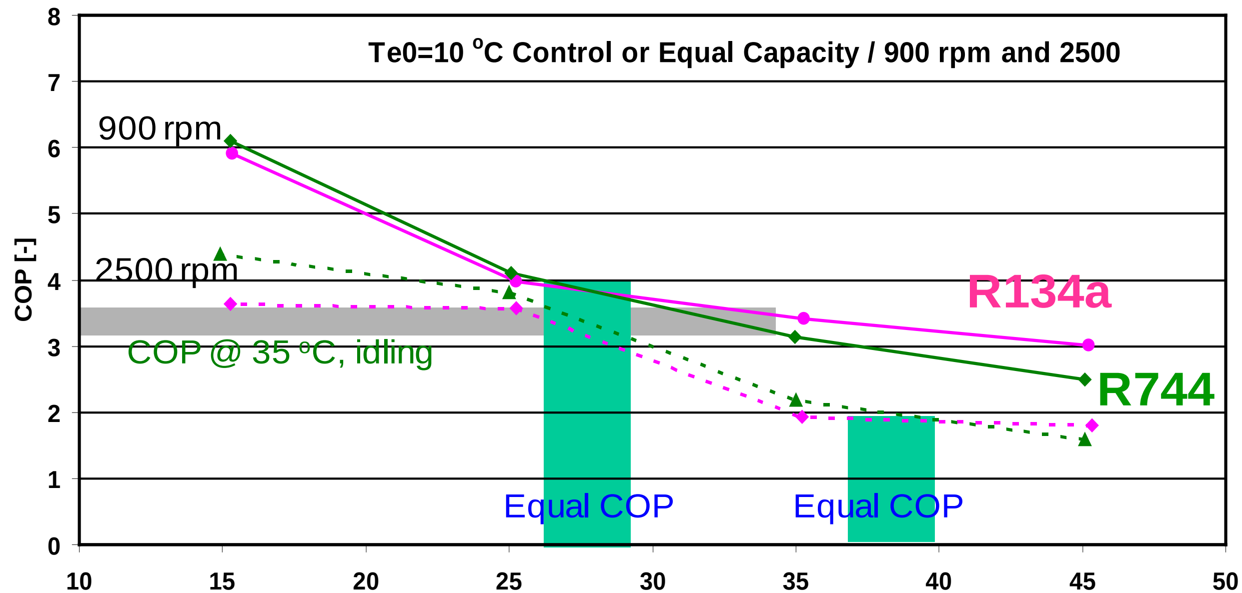
- Although initial modeling showed inferior performance for CO_2, even our first results (1996) showed surprisingly good results!
  - **CO_2 outperformed R134a!** (R134a only better at idle and > 35°C)
  - Good prototype compressors and microchannel HX



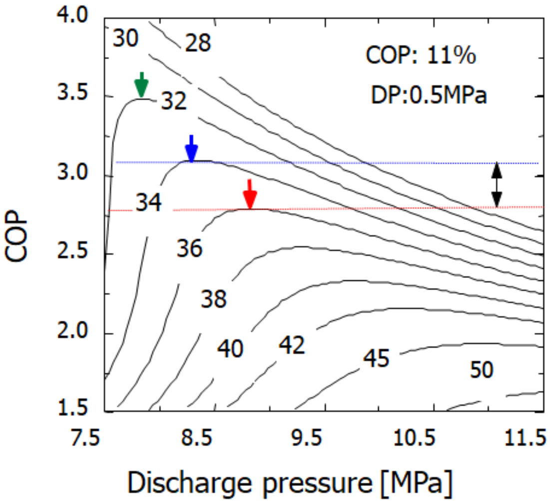
From: Pettersen *et. al* (1998)





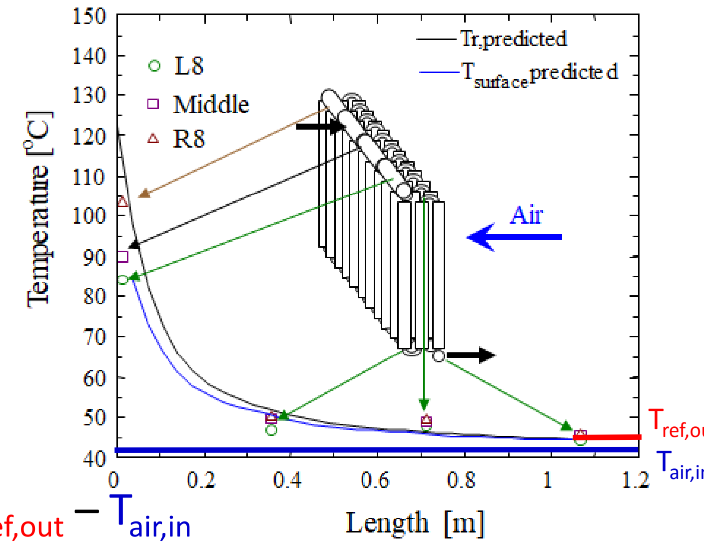


What Explains the Good CO_2 Performance?

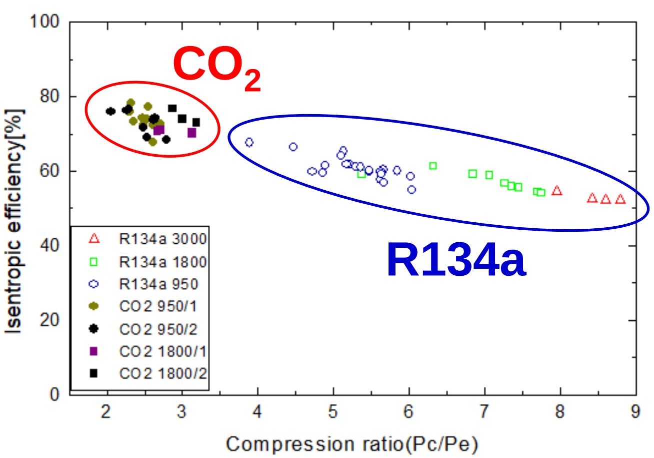


Optimized high-side pressure for maximum performance

Cross-counter-flow micro-channel gas cooler to minimize $\Delta T_{approach}$

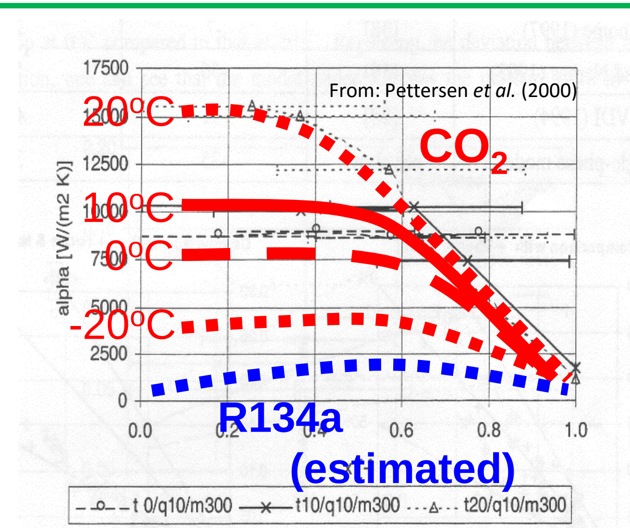


$\Delta T_{approach} = T_{ref,out} - T_{air,in}$



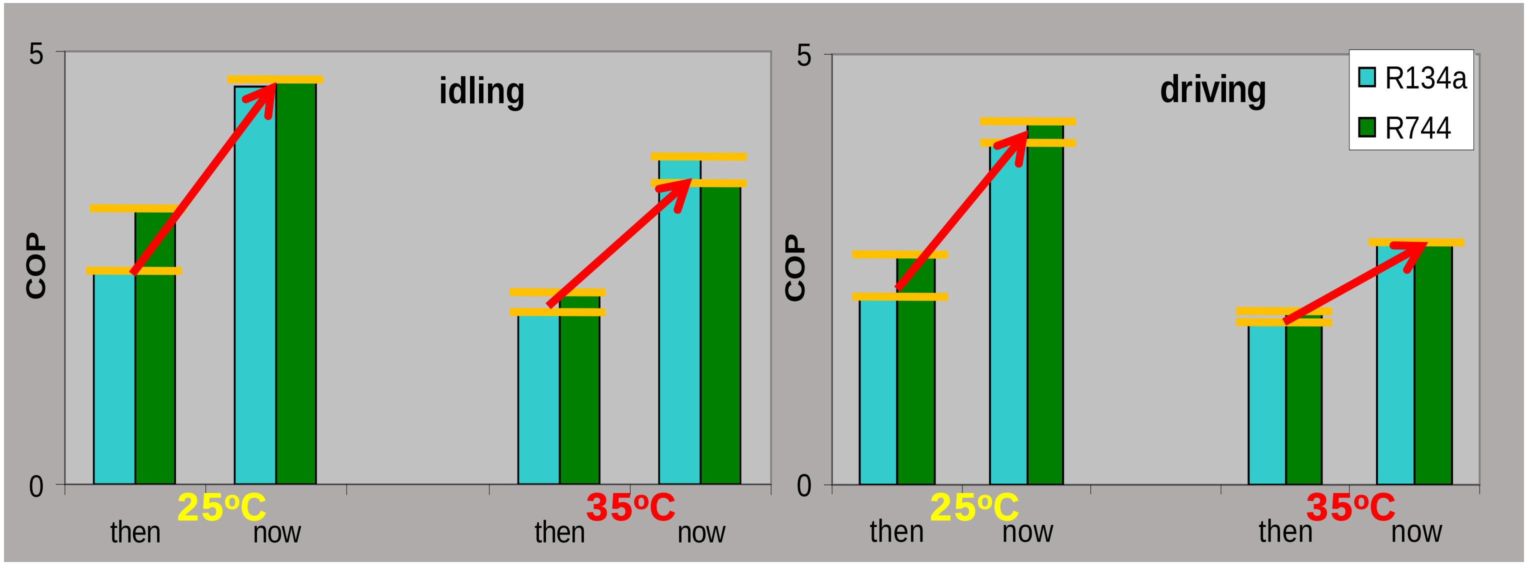
Higher $\eta_{compressor}$ due to lower pressure ratio

Much higher CO_2 convective heat transfer coefficients



20+ Years of Automotive CO_2 Research Resulted in Dramatically Improved COPs

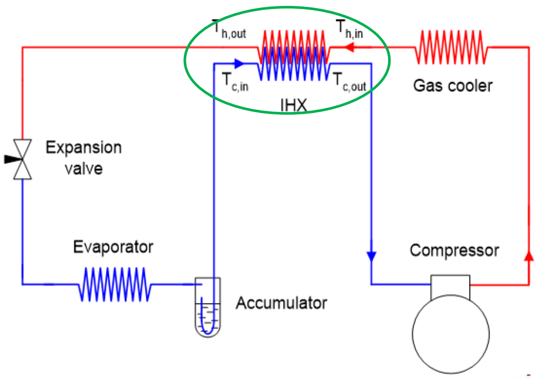
- But R134a (R1234yf) COPs also improved over time!

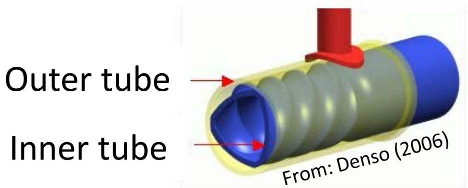


- For each condition: COP improvement in time larger than COP difference between R134a and CO_2
- Twenty years of intense research efforts lead to COP improvements of almost 100% for both fluids (at some conditions)

Technology Developed for CO_2 That is Now Used to Improve HFC/HFO

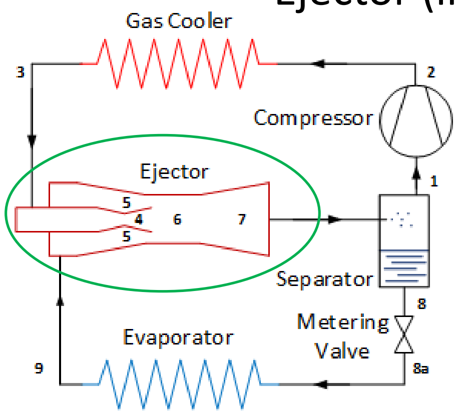
Internal Heat Exchanger

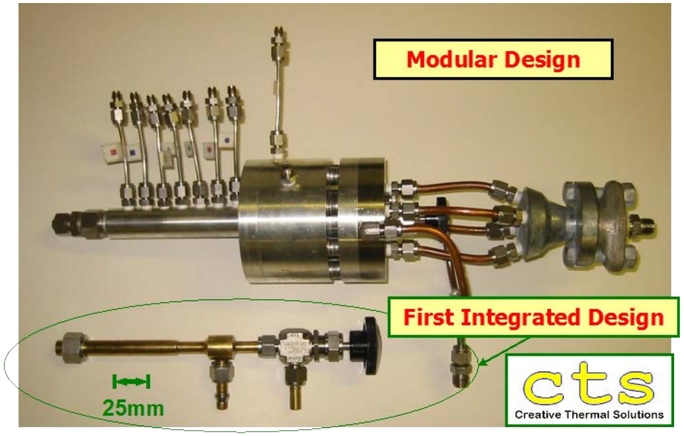


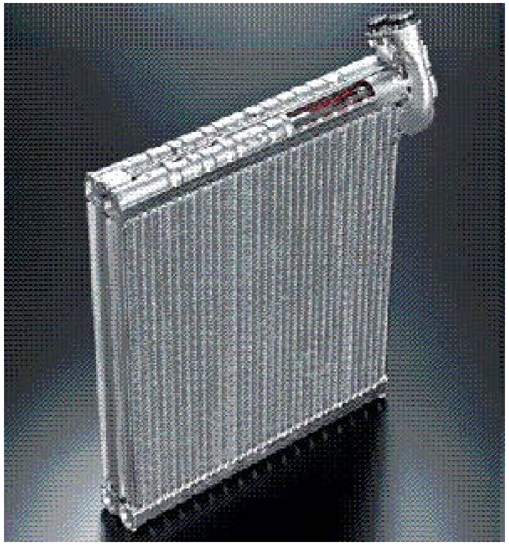


From: Denso (2006)

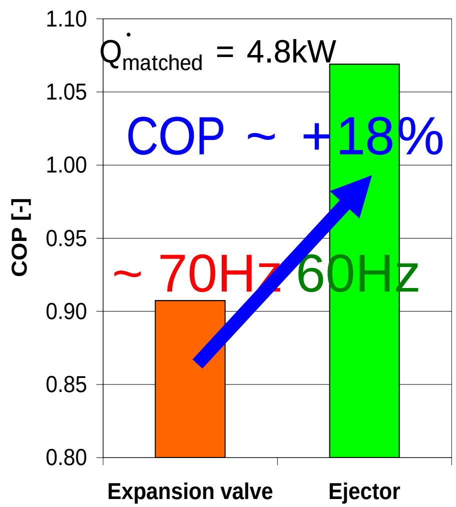
Ejector (instead of expansion valve)





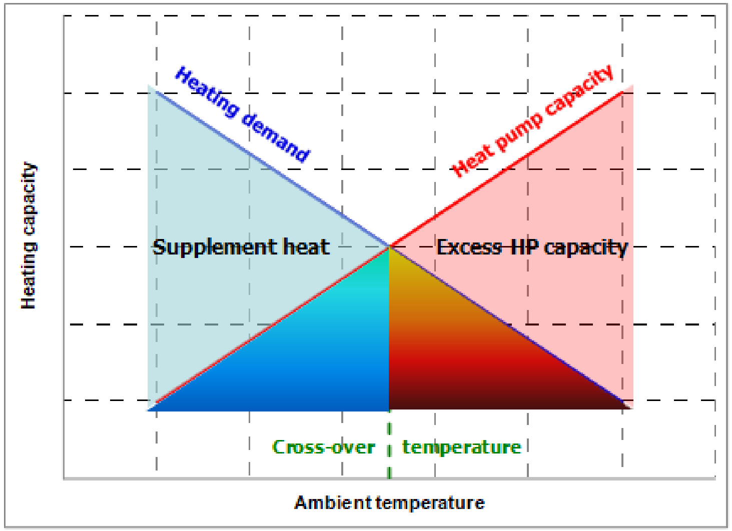


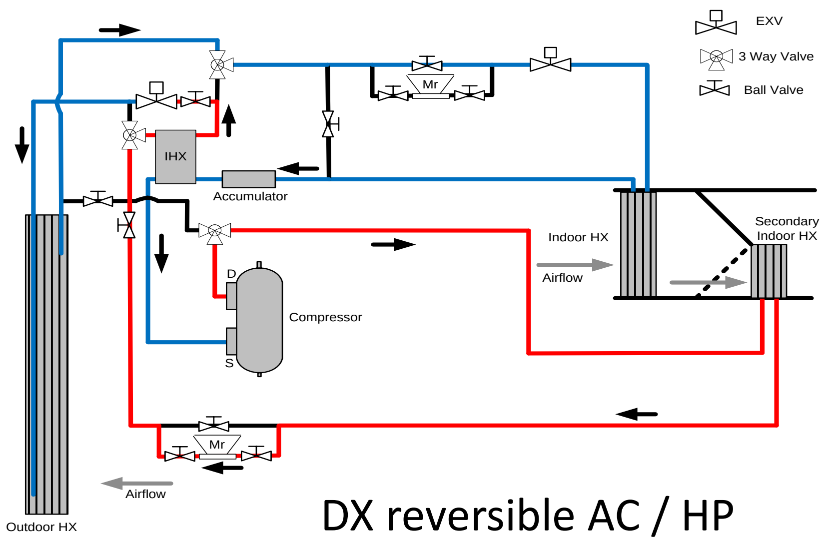
From: Denso (2010)



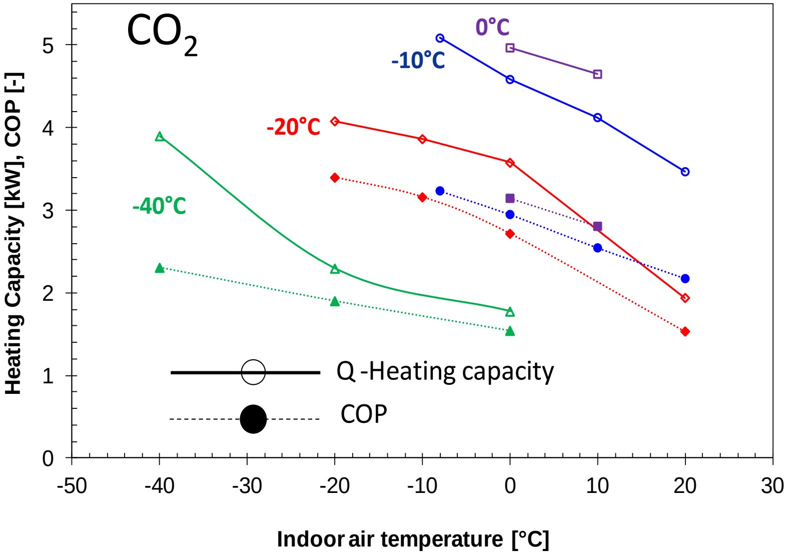
Advantages for CO_2 in Heat Pump Mode

- Increased need for heat pump in electric / hybrid vehicles
- Due to higher pressures, CO_2 can cover wider temperature range than R134a or R1234yf (CO_2 operates at -40°C with good COP)
- Temperature glide in gas cooler makes good heat exchanger for heat pumping





DX reversible AC / HP



Long Path to Successful Implementation of CO_2 Air Conditioning in Cars

R744 lab. prototype system (left) and BMW 520 CFC-12 system (right)

1989: First CO_2 systems at University labs


Schwäbische Zeitung 4.April 1998

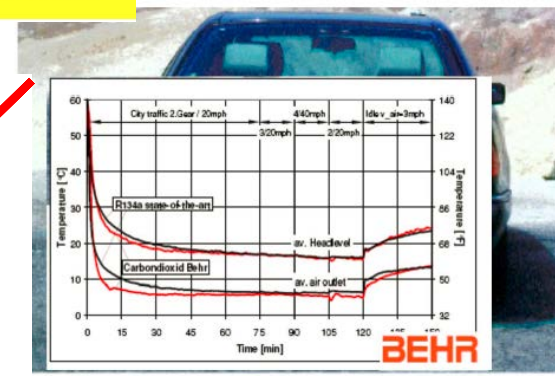
Schwäbische Zeitung

Samstag, 4. April 1998 / Nr. 79

Ökologische Klimaanlagen

…the greenhouse gas effect of the car AC system can be cut by a third when applying carbon dioxide as a refrigerant

1998: OEMs start equipping cars with CO_2 AC for wind tunnel and field testing

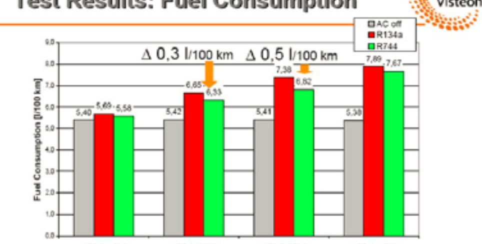


BEHR- Prototype Vehicle with CO_2 – Cycle, Death Valley 1998

2006: Numerous Asian and European OEMs and suppliers work on 2nd generation CO_2 with much improved performance

Fuel consumption of a Toyota Yaris (MY 2006) with different mobile AC systems when driving a NEDC at various ambient temperatures

Test Results: Fuel Consumption



⇨ Significant, absolut fuel reduction of 0,3 and 0,5 l/100 km at ambient temperature of 25°C and 35°C for R744

⇨ Add on fuel reduction of 25 % at 25°C and 35°C of R744 in comparison to R134a

- Engine 3 cylinders, 1,0 l, 51 kW
- Test vehicle with 15.000 km
- TXV system
- Compressor with external control valve (90 cc)

VDA Alternate Refrigerant Winter Meeting 2007, Saalfelden, Austria.

Images from: Hafner A., 2017, International Symposium on Natural Working Fluid CO2 Refrigeration and Heat Pump technology, Tianjin, China, Sep. 17-18

Long Path to Successful Implementation of CO_2 Air Conditioning in Cars

Source: www.uba.de

CO_2 car operated by German UBA between 2009 and 2017, accumulates more than 165,000 km

2009: CO_2 vehicles for long term fleet tests under real conditions

Source: www.daimler.com

Happy End for CO_2… More OEMs to Follow?

Source: www.sanden.jp

2017: First mass produced cars with CO_2 AC systems

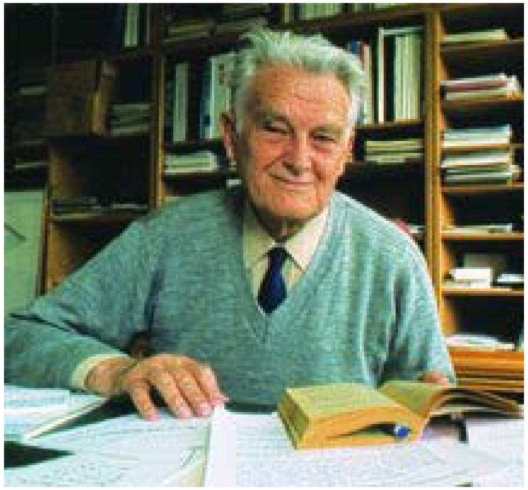
Conclusions

- Miracle refrigerant that can solve all our problems does not exist!
  - All fluids have pros & cons: environment, flammability, cost, performance, …
- For the past 75 years, our industry did not challenge mechanical engineers much, because chemists were able to provide refrigerants that allowed simple cycles
- CO_2 could be (for many applications) the "final" refrigerant selection, but it requires more effort to get good results
- Good news is that technology to make CO_2 work at high ambient temps exists
  - Microchannel HX, internal heat exchangers, ejectors, …
  - Eventually, prices will come down, but CO_2 systems are more complex
- Many examples of successful implementation of transcritical CO_2 exist
- Heat pumps for electric cars could bring the breakthrough for CO_2

In 1995, a Wise Man from Norway Wrote:

We have heard a great deal lately of the harmful effects to the environment when halocarbon refrigerants are lost to the atmosphere. This should not really have come as a surprise since similar problems have happened over and over again. Numerous cases are on record where new chemicals, believed to be a benefit to man, have turned out to be environmentally unacceptable, sometimes even in quite small quantities (DDT, PCB, Pb etc.). In the present situation, when the CFCs and in a little longer perspective the HCFCs are being banned by international agreement, it does not seem very logical to try to replace them by another family of related halocarbons, the HFCs, equally foreign to nature[1].

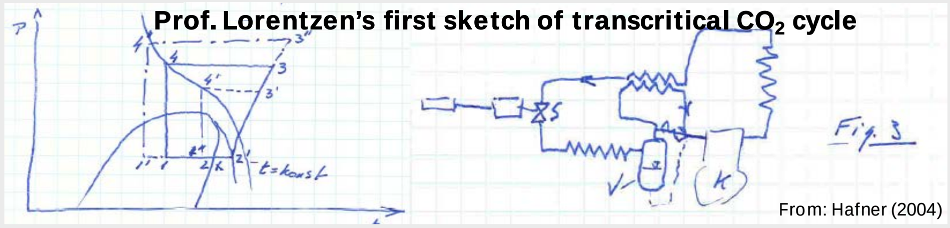
From: Int. J. Refrig., 1995, 18(3):190-197



Prof. Gustav Lorentzen
(1915- 1995)

Thank you for your attention!

elbel@illinois.edu



Prof. Lorentzen's first sketch of transcritical CO_2 cycle

From: Hafner (2004)