Refrigeration

Technologies under development

Themes

- Background
- Fundamental principles
- Secondary fluids
- Carbon dioxide refrigerant
- Ejectors
Background

For the past 20 years, the refrigeration industry has been hit hard by the environmental impacts of synthetic refrigerants.

Schedule for the Gradual Phase-Out of HCFCs

<table>
<thead>
<tr>
<th>Year</th>
<th>HCFC Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>1989</td>
<td>100.0%</td>
</tr>
<tr>
<td>2004</td>
<td>65.0% 2,000,000 kg</td>
</tr>
<tr>
<td>2010</td>
<td>35.0%</td>
</tr>
<tr>
<td>2015</td>
<td>10.0%</td>
</tr>
<tr>
<td>2020</td>
<td>0.5%</td>
</tr>
<tr>
<td>2030</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

In 2010, demand for HCFCs in the USA will exceed supply by 12.5 million kilograms in the refrigeration sector.

(U.S. Environmental Protection Agency)
Refrigerant leaks projected using a bottom-up approach suggest an annual global emission rate of 30% of the stored load.

- PRESERVATION OF THE OZONE LAYER AND THE EARTH'S CLIMATE SYSTEM
- Questions about hydrofluorocarbons and perfluorocarbons
- IPCC/TEAP, 2005 http://www.ipcc.ch/ipccreports/special-reports.htm

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**GWP (PRG) of HFC Refrigerants**

Tableau R30-1. Potentiel de réchauffement global (PRG) des halocarboneis par le Protocole de Montréal et par la CCMUC et son Protocole de Kyoto (évalués dans le rapport en relation avec le CO₂ à un horizon de 100 ans), avec leur durée de vie et le potentiel de réchauffement de la planète (PRG), utilisé par la CCNUCC. Les gaz sur fond blanc (clair) de la CCNUCC. [Tableaux 2.6 et 2.7]

<table>
<thead>
<tr>
<th>Gaz</th>
<th>PRG, Forçage radiatif direct</th>
<th>R404a = R125/143a/134a</th>
<th>R410a = R32/125</th>
<th>R507a = R125/143a</th>
</tr>
</thead>
<tbody>
<tr>
<td>HFC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HFC-23</td>
<td>14 310 ± 5 000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HFC-143a</td>
<td>4 700 ± 1 540</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HFC-125</td>
<td>3 450 ± 2 210</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HFC-227ea</td>
<td>5 410 ± 1 100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HFC-43-10mec</td>
<td>1 610 ± 5 600</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HFC-134a</td>
<td>1 410 ± 4 900</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HFC-245fa</td>
<td>1 020 ± 3 600</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HFC-365mfc</td>
<td>782 ± 2 700</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HFC-52</td>
<td>670 ± 2 400</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HFC-152a</td>
<td>122 ± 4 83</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Fundamental Principles

Refrigeration cycle

Refrigeration Cycle

Pressure

Enthalpy

CanmetENERGY

Leadership in ecoInnovation
Definition of COP

\[ Q_f + W = 4 \text{ kW} \]

\[ Q_f = 3 \text{ kW} \]

\[ W = 1 \text{ kW} \]

\[ \text{COP} = \frac{Q_f}{W} = 3 \]

Secondary Fluids
Indirect Refrigeration Systems
Secondary Fluid

HFCs

-25°F

-20°F

Refrigerant limited to the mechanical room

Secondary fluid

Mechanical room
Advantages of Indirect Systems

1. Much less synthetic refrigerant
2. Better functioning
3. Much less complex
4. Lower maintenance costs
5. Increase in the quality and longevity of food products (for systems in supermarkets)

Significant Reduction in Refrigerant

- 75 to 90% less synthetic refrigerant;
- At about $10/lb, could correspond to over $25,000 for an average supermarket;
- Dramatic reduction in the potential for refrigerant leaks.
Better Operation

- Less overheating of the compressor and therefore improved efficiency
- Better possibility of installing sub-cooling; again, improved efficiency
- More stable condensation pressure
- Better controllability
- No oil return problems

Less Complex

- Only one evaporator with two expansion valves, located in the mechanical room rather than 50 evaporators with as many expansion valves several dozen of metres away from it
- No pressure regulators to adjust or control. Secondary fluid balancing valves adjusted at start-up
- Low-pressure piping (often pre-isolated in synthetic material)
Less Expensive to Maintain

- Refrigerant leaks are limited to the mechanical room and therefore easier to detect and less expensive.
- Overall maintenance costs can be reduced by almost 50% compared to a conventional direct expansion (DX) system (FMI Energy).

Product Quality

- Less product loss
- A more stable product temperature (1°F rather than 2.5°F for DX)
- Shorter defrost cycle
The Disadvantages of Indirect Systems

- Change
- Expected loss of efficiency
- Cost

Change

- Not common practice
- New design and assessment criteria to learn and apply
- Making these changes must be planned far in advance (who is doing what?)
- Tenders from contractors do not reflect the anticipated benefits
- This job is added to the many tasks and responsibilities for all stakeholders in the construction project
Expected Loss of Efficiency

- Evaporation and condensation temperatures for secondary fluid systems are equal if not better than those for direct expansion (DX) systems.
- Overheating of compressors during suction is reduced to a minimum.
- Sub-cooling is very easy to integrate and it increases the refrigeration system’s efficiency by 10 to 25%.
- The thermal inertia of the secondary fluid contributes to stabilizing the operation of the system.
- Heat recovery is more effective and can meet the heating load of a building.

Cost

- There are several hundred installations in North America.
- The design criteria and choice of materials are increasingly being mastered.
- The cost is still higher than that of a DX system, but the difference is decreasing with time and will soon become a standard in the refrigeration industry.
- Operating costs are less than or equal to those of DX systems.
DX vs. Secondary Fluid

Types of Secondary Fluids

- Without phase change
  - Ethylene glycol (heat rejection in the condenser)
  - Propylene glycol (10 to 32°F)
  - Potassium formate (-30 to 0°F)
  - Other antifreezes

- With phase change
  - Carbon dioxide (CO₂) (-50 to +20°F)
  - Slurry (water, methanol, glycol, etc.) (0 to 32°F)
**CO₂: the Ideal Secondary Fluid**

Liquid CO₂ cools a fluid by evaporating in a heat exchanger. A simple liquid pump is used to circulate the CO₂

- No corrosion
- Negligible pumping power
- No oil management problems
- Minimal pipe diameter
- Exceptional heat transfer features

**CO₂: Breadboard Model**

-30°C, CO₂ Test chamber
Slurries: the Secondary Fluid that Stores Energy

- **Slurry?**
  - Fine ice crystals (<0.1 mm) in a water/antifreeze mixture containing about 30% solids

**Advantages**
- Lower pumping energy
- Lower pipe dimensions
- Cold storage for managing demand for energy
- Heat storage for managing thermal discharges (Net-Zero buildings, houses and communities)

- Test bench under construction
- Challenge: a simple, efficient slurry generator

Conclusions

Experience shows that a secondary fluid system:

- Decreases environmental impacts
- Decreases energy consumption
- Increases heat recovery potential
- Increases product quality
- Simplifies installation
- Decreases maintenance costs
- Decreases lifecycle costs
Carbon Dioxide

- Is present in the atmosphere in a proportion of **375 ppmv** (parts per million in volume)
- The concentration is increasing rapidly, by about **2 ppmv/year**
- R744 is a natural refrigerant, like water, air, ammonia and hydrocarbons
History of CO₂

1850
Initial concept of CO₂ as a refrigerant (Alexander Twining, British patent)

1920-1930
J&E Hall: first two-stage CO₂ refrigeration system

1960
First CO₂ refrigeration system: Carle Linde

1993
CO₂ transcritical cycle

Montreal protocol 1 Jan. 1, 1989

Reinvention of CO₂ in refrigeration (G. Lorentzen) of Norway

CFCs invented, 1928

Danfoss, Niels P Vestergaard Niels P Vestergaard Ver 2004-04-SI+US
### Properties

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>R404A</th>
<th>NH₃</th>
<th>CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural refrigerant</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Ozone Depletion Potential (ODP)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Global Warming Potential (GWP)</td>
<td>3260</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>Critical condition [psi/°F]</td>
<td>541/162</td>
<td>1640/270</td>
<td>1067/88</td>
</tr>
<tr>
<td>Boiling point at 15 psig [°F]</td>
<td>-51</td>
<td>-28</td>
<td>-69</td>
</tr>
<tr>
<td>Boiling point at 400 psig [°F]</td>
<td>137</td>
<td>144</td>
<td>16</td>
</tr>
<tr>
<td>BTU/cubic foot at -40 [°F]</td>
<td>36</td>
<td>24</td>
<td>226</td>
</tr>
<tr>
<td>Saturated ΔT / ΔP = 1 psi at -40 [°F]</td>
<td>2.1</td>
<td>3.4</td>
<td>0.3</td>
</tr>
<tr>
<td>Flammability</td>
<td>NO (slightly)</td>
<td>NO</td>
<td></td>
</tr>
<tr>
<td>Toxicity</td>
<td>NO</td>
<td>high</td>
<td>NO</td>
</tr>
</tbody>
</table>

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### 717- CO₂ Cascade System

![CO₂ Cascade System Diagram](image)

Danfoss, Niels P Vestergaard Niels P Vestergaard Ver 2004-04-51 US
HFC - CO₂ Cascade Systems

CO₂ as a Secondary Fluid
**Transcritical Cycle**

*The Eco-Cute hot water HP produces hot water at 180°F with a COP of 4 to 8!*

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**Why CO₂?**

<table>
<thead>
<tr>
<th>Strong arguments</th>
<th>Commercial</th>
<th>Industrial</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Environment</strong></td>
<td></td>
<td></td>
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<tr>
<td>Gradual elimination of substances that have an impact on the environment (HCFCs, HFCs): (ODP (Ozone Depletion Potential), GWP (Global Warming Potential))</td>
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</tr>
<tr>
<td><strong>Safety</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toxicity and flammability for systems using large quantities of ammonia</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Costs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Lower operating costs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• More efficient systems</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Lower refrigerant costs</td>
<td></td>
<td></td>
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<tr>
<td>• Lower component volume</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Conclusions

- In the last 10 years, products available for applications using CO₂ have become increasingly abundant. These applications cover all sectors.
- Low-temperature refrigeration and heat pumps are especially appealing.
- Operating pressures can be high, but the equipment is more compact and often more efficient.
- It is a natural refrigerant that is **safe** and inexpensive.
- Every refrigeration equipment manufacturer around the world is interested in CO₂ as a refrigerant.

Ejectors
What is an Ejector?

Ejectors convert kinetic energy into pressure and quantity of movement. It is a thermocompressor.

- Primary nozzle
- Secondary nozzle
- Actuating or primary fluid
- Entrained, or secondary fluid
- Mixing zone
- Diffuser
- No moving parts

Why Ejectors?

- They are simple
- They have no moving parts
- They use no oil
- There is a large variety of materials for building one
- They can use any gas or refrigerant
Weaknesses

- Operation is not a very flexible
- Low apparent efficiency
- Not well known; used primarily for recompressing vapour
- Complex design (supersonic flow)

Applications

- Using effluent as a source of energy for cooling
- Or to recover heat through heat pumping
- Trigeneration
Trithermal Combined Cycle

Ejector Cycle Output

\[ \eta_{eject} = \frac{Q_{evap}}{Q_{gen}} \approx 0.5 \]
Applications

Integration into the refrigeration cycle to recover the expansion energy and increase the COP

Ejector Regulator

COP 26% higher
Applications

Integration into the refrigeration cycle to recover the condensation energy to increase the thermal discharge temperature, thereby making it useful for heat recovery or increasing the COP of the refrigeration system.

Ejector Condenser

COP 20% higher
Thank you