Supermarket Refrigeration and Heat Recovery Systems using CO\textsubscript{2} as the Refrigerant

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Outline

• Introduction
  • Supermarkets – facts & figures
  • CO₂ in supermarket refrigeration systems
• Project overview and objectives
• Main studies and findings
• Ongoing and future research plans
• Introduction

Supermarkets – facts & figures

Introduction
Supermarkets – facts & figures
CO₂ in supermarket refrigeration systems

• Project overview and objectives
• Main studies and findings
• Ongoing and future research plans
Supermarkets
Rapid Growth

• Supermarkets have become one of the vital service facilities of our modern society.
• The total area (m²) of supermarkets are increasing in developed and developing countries.

• Main driving forces (Trail, 2006):
  - Rapid urbanization
  - Emerging middle class
  - Globalization and taste convergence
  - More female labour in market
  - Openness to inward foreign investment

— Rapid growth example: frozen food global market is estimated to grow in sale value by 30% comparing predicted 2020 sales with 2014 values. (Persistence market research, 2014).

Photos ref.: National geographic
Supermarkets
Energy use (I)

- Share of national energy use of electricity
  - **Sweden:** 3% (Sjöberg, 1997), **USA:** 4% (Orphelin, 1997), **UK:** 3% (Tassou, 2011), **France:** 4% (Orphelin, 1997), and **Denmark:** 4% (Reinholdt and Madsen, 2010)

- Supermarkets: largest consumer of energy than any other commercial building in Sweden and other industrialized countries.

Ref.: (STIL2, 2010), (Energy star, 2012), (Enova, 2007), (BCA, 2014)
Supermarkets
Energy use (I)

- Supermarkets refrigeration system: consumer of about **50% of electricity** in supermarkets

Ref.: (Arias, 2005), (STIL2, 2010), (Kauffeld, 2007), (EPA, 2014)
Supermarkets
Refrigeration

- Supermarkets are **largest consumers** of HFC gases in Europe.

- Supermarkets are **largest emitters** of HFC gases in the world.
  - Hundreds of Kgs of refrigerant charge
  - High leakage rate

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**Figure ES 6: GHG Refrigerant Consumption, Mtonnes CO2**

All Refrigerants, Scenario A, EU 27

- 7 - Mobile AC
- 6 - Chillers & Hydronic Heat Pumps
- 5 - Stationary Air Conditioning (SAC) and Heat Pumps
- 4 - Industrial Refrigeration
- 3 - Transport Refrigeration
- 2 - Commercial Refrigeration
- 1 - Domestic Refrigeration

The **Commercial Refrigeration Sector** represents **40%** of 2010 refrigerant GHG consumption. The largest part of this consumption (**85%**) is for large refrigeration systems in supermarkets, most of which utilise the high GWP refrigerant **HFC 404A**. The remaining consumption is split between small hermetic systems and single condensing unit systems.

**Table 4.8. Leakage rates of supermarket refrigeration systems.**

<table>
<thead>
<tr>
<th>Country</th>
<th>Year(s)</th>
<th>Annual Refrig. Loss</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Netherlands</td>
<td>1999</td>
<td>3.2</td>
<td>Hoogen <em>et al.</em>, 2002</td>
</tr>
<tr>
<td>Denmark</td>
<td>2003</td>
<td>10%</td>
<td>Pedersen, 2003</td>
</tr>
<tr>
<td>Norway</td>
<td>2002–2003</td>
<td>14%</td>
<td>Bivens and Gage, 2004</td>
</tr>
<tr>
<td>Sweden</td>
<td>1993</td>
<td>14%</td>
<td>Bivens and Gage, 2004</td>
</tr>
<tr>
<td></td>
<td>1998</td>
<td>12.5%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>10.4%</td>
<td></td>
</tr>
<tr>
<td>United Kingdom</td>
<td>1998</td>
<td>14.4%</td>
<td>Radford, 1998</td>
</tr>
<tr>
<td>USA</td>
<td>2000–2002</td>
<td>13%, 18%, 19%, 22%</td>
<td>Bivens and Gage, 2004</td>
</tr>
</tbody>
</table>

Ref.: **SKM Enviros, 2012**

Ref.: **IPCC, 2005**
Supermarkets
Conventional refrigeration system in Sweden

- Indirect at medium temperature level and direct expansion at low temperature level, Typical refrigerant: R404A (GWP=3200)
- 2300-2400 supermarkets in Sweden

![Diagram showing refrigeration system with R404A and brine]

**Distribution of carbon dioxide emissions, %**
- ICA 49%
- COOP 25%
- AXFOOD 10%
- Bergendahl 7%
- Lidl 5%
- Netto 4%

Ref.: (DELFI, 2015), (ICA, 2014), (COOP, 2014)
F-gas regulation

REGULATION (EU) No 517/2014 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL
of 16 April 2014

on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006

Service and maintenance bans

<table>
<thead>
<tr>
<th>Service</th>
<th>GWP</th>
<th>Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>HFC’s</td>
<td>2,500</td>
<td>Jan. 2020</td>
</tr>
<tr>
<td>‘Placing on the market’ (new equipment) bans</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Domestic refrigerators and freezers</td>
<td>150</td>
<td>Jan. 2015</td>
</tr>
<tr>
<td>Refrigerators and freezers for commercial use (hermetically sealed systems)</td>
<td>2,500</td>
<td>Jan. 2020</td>
</tr>
<tr>
<td>Refrigerators and freezers for commercial use (hermetically sealed systems)</td>
<td>150</td>
<td>Jan. 2022</td>
</tr>
<tr>
<td>Stationary refrigeration equipment</td>
<td>2,500</td>
<td>Jan. 2020</td>
</tr>
<tr>
<td>(except equipment for temperatures below -50 °C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multipack centralized refrigeration systems for commercial use with a capacity of ≥ 40 kW (140 kBTU/hr) (except in the primary refrigerant circuit of cascade systems, where fluorinated greenhouse gases with a GWP of less than 1,500 may be used)</td>
<td>150</td>
<td>Jan. 2022</td>
</tr>
<tr>
<td>Movable room air-conditioning appliances (hermetically sealed equipment which is movable between rooms by the end user)</td>
<td>150</td>
<td>Jan. 2020</td>
</tr>
<tr>
<td>Single split air-conditioning systems containing &lt; 3 kg</td>
<td>770</td>
<td>Jan. 2025</td>
</tr>
</tbody>
</table>

Not a long-term solution!

Ref.: (Emesron, 2015)
• Introduction

CO₂ in supermarket refrigeration systems

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  Supermarkets – facts & figures
  CO₂ in supermarket refrigeration systems

• Project overview and objectives
• Main studies and findings
• Ongoing and future research plans
CO$_2$ as refrigerant

Properties:
- GWP=1, ODP=0
- Good safety: non-flammable, non-toxic
- High cooling effect: compact system - smaller pipe sizes than conventional systems
- High operating pressure
- Low critical temperature 31°C @ 73 bar
CO₂ in supermarket refrigeration systems:

CO₂ trans-critical booster system
**CO₂ in supermarket refrigeration systems market trends**

Ref.: Shecco guides, 2014 & 2015
• Project overview and objectives:
Supermarket refrigeration and heat recovery systems using CO₂ as the refrigerant

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Research Project overview

- KTH research on “supermarket refrigeration” has been ongoing for more than 15 years.

The two latest projects:
- Effsys+ (2011-2014): A comprehensive evaluation of refrigeration and heating systems in supermarkets based on field measurements and modelling

- Focus of both projects: Supermarket refrigeration and heat recovery systems using CO₂ as the refrigerant

- Partners:
Objectives

- **Evaluate the present supermarket refrigeration systems: focus on CO₂ systems**
  
  **Computer modelling**
  - Analyse CO₂ systems and components
  - Compare different system solutions
  - Heating and air conditioning integration

  **Field measurements analysis**
  - Performance of CO₂ systems in Swedish supermarkets
  - Guidelines for instrumentation, field measurements and systems evaluation

- **Evaluate & propose the “state-of-the-art” supermarket refrigeration system in Sweden; computer simulation + field measurements analysis**
  
  - key features of a modern refrigeration system
  - Definition of a state-of-the-art system, case studies
  - Compare with emerging alternative system solutions
  - Perform economic and environmental analysis of the suggested system
• Main studies and findings

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## Main studies and findings publications

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<th>References</th>
<th>Title</th>
<th>Authors</th>
<th>Conference/Journal/Report</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Karampour et al., 2013)</td>
<td>Field measurements and performance evaluation of CO2 supermarket refrigeration systems</td>
<td>Karampour, M., Sawalha, S., Rogstam, J.</td>
<td>2nd IIR International Conference on Sustainability and the Cold Chain. IIF/IIR, Paris, France</td>
</tr>
<tr>
<td>(Karampour and Sawalha, 2014a)</td>
<td>Performance and control strategies analysis of a CO2 trans-critical booster system</td>
<td>Karampour, M., Sawalha, S.</td>
<td>3rd IIR International Conference on Sustainability and the Cold Chain, IIF/IIR, London, UK</td>
</tr>
<tr>
<td>(Karampour and Sawalha, 2014b)</td>
<td>Investigation of using Internal Heat Exchangers in CO2 Trans-critical Booster System</td>
<td>Karampour, M., Sawalha, S.</td>
<td>11th IIR Gustav Lorentzen Conference on Natural Refrigerants. IIF/IIR, Hangzhou, China</td>
</tr>
<tr>
<td>(Abdi et al., 2014)</td>
<td>Heat recovery investigation of a supermarket refrigeration system using carbon dioxide as refrigerant</td>
<td>Abdi, A., Sawalha, S., Karampour, M.</td>
<td>11th IIR Gustav Lorentzen Conference on Natural Refrigerants. IIF/IIR, Hangzhou, China</td>
</tr>
<tr>
<td>(Karampour and Sawalha, 2014c)</td>
<td>Supermarket refrigeration and heat recovery using CO2 as refrigerant: A comprehensive evaluation based on field measurements and modelling</td>
<td>Karampour, M., Sawalha, S.</td>
<td><strong>Effsys plus final report</strong>, Stockholm, Sweden</td>
</tr>
<tr>
<td>(Karampour and Sawalha, 2015)</td>
<td>Theoretical analysis of CO2 trans-critical system with parallel compression for heat recovery and air conditioning in supermarkets</td>
<td>Karampour, M., Sawalha, S.</td>
<td>24th IIR Refrigeration Congress of Refrigeration. IIF/IIR, Yokohama, Japan</td>
</tr>
</tbody>
</table>
Study 1

Q: How energy-efficient is a CO$_2$ supermarket refrigeration system comparing with a conventional R404A system?
Field measurement analysis (Part of an earlier project)

- 8 supermarkets in Sweden have been compared.
  - 3 HFC systems
  - 5 \( \text{CO}_2 \) systems

**Conclusion:** \( \text{CO}_2 \) systems have COPs **higher or comparable** with advanced HFC conventional systems.
Field measurement analysis

- Some of the main reasons for 35-40% improvement in the newer CO₂ systems performance have been found/discussed.

**Conclusion: main factors**
- **System:** Receiver + Flash gas by-pass
- **Component:** More energy-efficient cabinets, compressors, ...

![Graph showing COP and T-cond variations](attachment:image.png)
Study 2

**Q:** How about integrating **heating** into the **refrigeration** system?

Is **CO₂** system an energy-efficient system regarding **heat recovery**?
CO$_2$ Trans-critical Booster System with heat recovery

- By increasing the discharge pressure and switching from sub-critical to trans-critical, the amount of available heat increases considerably.
Heat recovery

- The following example shows the CO$_2$ system operation in winter based on the suggested control strategy.
Standard CO$_2$ Trans-critical Booster System

**winter & summer control strategy**

**Summer**

1. Sub-critical operation: floating condensing

2. Trans-critical operation
   \[ P_{\text{optimum}} = 2.7 \ T_{\text{gas cooler exit}} - 6.1 \]

**Winter**

1. Gas cooler full capacity- $P_{\text{discharge}}$ regulation

2. Fixed max optimum $P_{\text{discharge}}$
   \[ P_{\text{optimum}} = 2.7 \ T_{\text{DSH,exit}} - 6.1 \]

   2.1 Fans slowed-down
   2.2 Fans off
   2.3 Gas cooler bypass
Summer and winter operation

\[
\text{COP}_{HR} = \frac{Q_{HR}}{E_{HS} - E_{HS,fc}}
\]
**Annual energy use and SPF (seasonal performance factor)**

\[ SPF = \frac{\Sigma Q_{HR}}{\Sigma (E_{HS} - E_{HS,fc})} \]

\[ SPF = \frac{417 \text{ MWh}}{104 \text{ MWh}} = 4 \]

Heating demand: 40-190 kW for ambient temperatures 10 to -20°C

**Conclusion**: Heat recovery by CO₂ trans-critical booster system has high and comparable SPF to other commercial size heat pumps.

**Avoiding the cost** of new heating system installation is another advantage of heat recovery from CO₂ system.

Ref.: (Miara et al., 2011)
Study 3

Q: how about modifying the system design? What is the effect of using internal heat exchanger in CO$_2$ “refrigeration + heat recovery” system?
Internal Heat Exchanger (IHX)

- Internal heat exchanger or liquid-suction heat exchanger main functions:
  - Sub-cooling the warm liquid flow
  - Superheating the suction flow
Internal Heat Exchanger (IHX) Positioning

- 36 cases are studied:
  - 9 IHX cases have been compared: NO IHX, A, B, C, D, AC, AD, BC, BD
  - 2 design alternatives: **WBP**: with by-pass - **WOBP**: without by-pass
  - (I) Refrigeration-only function (II) Refrigeration + heat recovery function
• 36 cases are studied:
  • 9 IHX cases have been compared: NO IHX, A, B, C, D, AC, AD, BC, BD
  • 2 design alternatives: **WBP**: with by-pass - **WOBP**: without by-pass
  • (I) Refrigeration-only function (II) Refrigeration + heat recovery function

• Conclusion: no significant impact in refrigeration-only mode
Internal Heat Exchanger (IHX) Positioning

- Example: $Q_{HR}$ Normalization – reference: $85[kW]@65[bar]$
- By using IHX AD, 3.8 bar decrease in discharge pressure, 11.8% increase in COP

NO IHX

\[\text{COP}_{\text{tot}} = 3.6\]
\[Q_{HR} = 85\]
\[P_{\text{discharge}} = 65\]

IHX AD

\[\text{COP}_{\text{tot}} = 4\]
\[Q_{HR} = 85\]
\[P_{\text{discharge}} = 61.2\]
Internal Heat Exchanger positioning

- Example: $Q_{HR}$ Normalization – reference: NO IHX-WBP-85[kW]@ 65[bar]

**Conclusion**

<table>
<thead>
<tr>
<th>IHX impact on $\text{COP}_{\text{tot}}$ increase</th>
<th>Refrigeration [COP$_{\text{ref}}$]</th>
<th>Refrigeration + heat recovery [COP$<em>{\text{ref}}$, COP$</em>{\text{tot}}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sub-critical</strong></td>
<td>No impact</td>
<td><strong>Positive effect, up to 12%</strong></td>
</tr>
<tr>
<td><strong>Trans-critical</strong></td>
<td>No impact</td>
<td>No impact</td>
</tr>
</tbody>
</table>
Q: How about modifying the system design and more system integration? What is the effect of using parallel compression in CO$_2$ “refrigeration + heat recovery + air conditioning” system?
Parallel compression (PC) vs Flash gas by-pass expansion (FGBP) comparison in an integrated CO₂ trans-critical booster refrigeration system + heat recovery (HR) + air conditioning (AC)

Case 1: PC vs FGBP: summer case (floating condensing mode) – no air conditioning
Case 2: PC vs FGBP: summer case (floating condensing mode) – with air conditioning
Case 3: PC vs FGBP: winter case (heat recovery mode) – no air conditioning
COP increase% PC vs FGBP without AC (Summer)

\[
COP_{tot} = \frac{Q_{MT} + Q_{LT} + Q_{HR} + Q_{AC}}{E_{HS} + E_{LS} + E_{PC} + E_{fan}}
\]

\[
\Delta p_{rec} = P_{rec} - P_{MT}
\]

Conclusion: 5-15 % increase

Increase in COP\text{\textsubscript{tot}} using PC compared to FGBP, summer with No AC case (left)  
Best cases comparison between PC-\(\Delta P_{rec}=13\) and FGBP-\(\Delta P_{rec}=3\) (right)
COP increase% PC vs FGBP with HR (Winter)

• Conclusion: Up to 6% improvement, but in very low ambient temperatures

Increase in COP\textsubscript{tot} using PC instead of FGBP, winter No AC case with heat recovery
Air conditioning comparison: Integrated CO₂ vs Separate R410A

COPₐc = Qₐc / (Eₜot_AC - Eₜot_No AC)

Conclusion: High COPₐc_CO₂ for Tamb < 25°C

COPₐc comparison of integrated CO₂ and separate R410A air conditioning systems
Parallel compression: Annual energy saving

- Annual energy savings by using **parallel compression** instead of the **standard flash gas by-pass**

![Energy Savings Chart](chart.png)

**Conclusion:** 6-9% annual savings

Annual energy savings % for 12 cities (DP=8 [bar])
Summary of main findings (I)

- Field measurements analysis of 8 supermarkets (continuation of a previous study at KTH)
  - CO\textsubscript{2} new systems have higher or equal energy-efficiency compared with HFC systems.
  - CO\textsubscript{2} new systems are 35-40\% more efficient than the old ones. Main reasons:
    - Receiver + flash gas by-pass
    - More efficient compressors and cabinets

- CO\textsubscript{2} booster system + heat recovery study
  - A suggested heat recovery control strategy has been used in an annual energy use modelling.
  - CO\textsubscript{2} booster system is able to provide the entire or a great share of supermarket heating demands with high SPF and COP.
Summary of main findings (II)

- **IHX study**
  - 36 cases have been evaluated to find the effect of IHX on $\text{COP}_{\text{tot}}$ increase.
  - Using some configurations in subcritical refrigeration + heat recovery mode increase the $\text{COP}_{\text{tot}}$ by 11-12%.

- **Parallel compression + Air conditioning study**
  - Integration of air conditioning and parallel compression into standard CO$_2$ booster system + heat recovery have been evaluated for summer and winter:
    - 5-15% $\text{COP}_{\text{tot}}$ increase in summer case, up to 6% increase in very low ambient temperatures of winter case
    - CO$_2$ integrated air conditioning is more efficient than conventional AC systems for ambient temperatures lower than 25°C.
  - Using parallel compression instead of flash gas by-pass have been evaluated in 12 European cities:
    - 6-9% annual electricity savings
• Ongoing and future research plans

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Ongoing/future research plans (I)

• **State-of-the-art system features; computer modeling and field measurements analysis**
  • Heat recovery at multiple temperature levels
  • Parallel compression
  • Air conditioning integration
  • Ejector
  • Ground thermal storage
  • Internal heat exchanger (continuation of the previous study)
  • Control strategies for integrated CO$_2$ trans-critical booster system
  • Evaporative cooling on gas cooler / evaporative condenser
  • New emerging solutions?
An example for State-of-the-art system

Features being studied/to be studied

1- tap water heating
2- space heating
3- parallel compression
4- air conditioning
5- ejector
6- ground source coupling
7- LT de-superheating or heat recovery
Ongoing/future research plans (II)

• Comparative studies of different system solutions in different climatic conditions
  • Energy efficiency comparison of (1) standard CO\textsubscript{2} booster, (2) state-of-the-art CO\textsubscript{2} booster, (3) direct and indirect new HFC/HFO systems
  • Environmental and economical aspects of the above-mentioned systems
  • Most energy-efficient system solutions for cold, mild and warm climates

• Defining and analysis of a “State-of-the-art” system
• **Comparative studies** of different system solutions in different climatic conditions
  • Energy efficiency comparison of (1) standard CO$_2$ booster, (2) state-of-the-art CO$_2$ booster, (3) direct and indirect new HFC/HFO systems
  • Environmental and economical aspects of the above-mentioned systems
  • Most energy-efficient system solutions for cold, mild and warm climates

• **Defining and analysis** of a “State-of-the-art” system
Thank you
Questions?