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New Energy Lean Refrigeration Technologies for the Future

Classification of Refrigeration Systems for Food Engineering Applications

In terms of prime mover

- **Electrically driven**
  - Vapour compression
  - Air cycle
  - Thermoelectric
  - Thermoacoustic
  - Magnetic
- **Thermally driven**
  - Sorption systems (absorption, adsorption)
  - Ejector (jet-pump systems)
  - Thermoacoustic
- **Hybrid**
  - Heat/Electricity
  - Solar/Electricity
  - Biomass/Engine
  - Biomass/Heat
  - Solar/Biomass/engine

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Classification of Refrigeration System for Food Engineering Applications

In terms of temperature range

- High temperature: above $3^{o}C$
- Medium temperature: $0^{o}C$ to $-10^{o}C$
- Low temperature: $-18^{o}C$ to $-35^{o}C$
- Very low temperature: $-50^{o}C$ to $-90^{o}C$

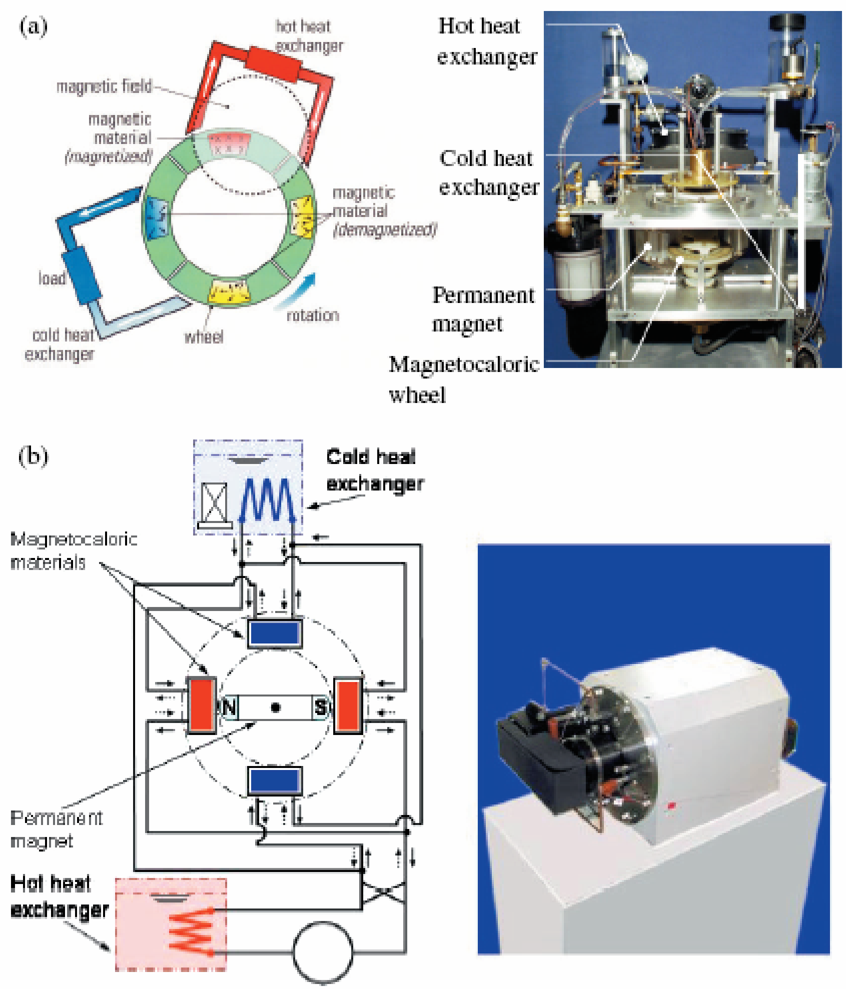
In terms of application

- Constant temperature
  - Transport refrigeration
  - Food storage and display
    - Display cabinets (integral and remote)
    - Cold storage
- Food processing

Alternative and Emerging Refrigeration Technologies

- Magnetic
- Thermoacoustic
- Thermoelectric
- Sterling cycle
- Air cycle
- Tri-generation
- Sorption technologies (absorption and adsorption)
- CO_2 refrigeration systems

Magnetic Refrigeration



(a) A magnetic refrigeration cycle employs a solid-state magnetic material as the working refrigerant. The material warms-up in the presence of a magnetic field and cools down when the field is removed.

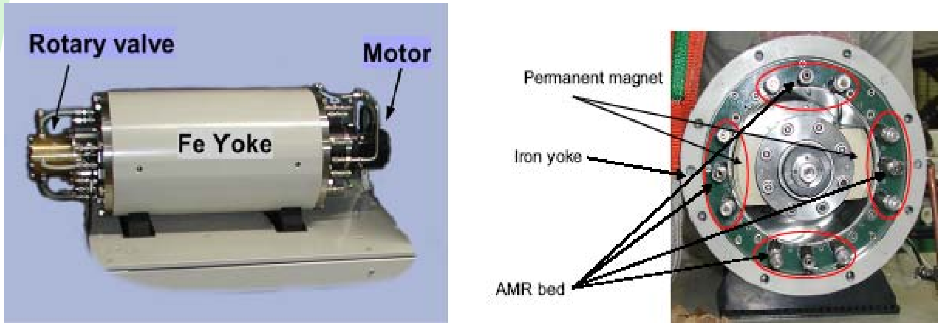
(c) Heat absorption and heat rejection are facilitated by thermally linking the magnetic material with the cold source and hot sink respectively, using a heat transfer fluid.

(d) The forces involved in applying and removing the magnetic field provide the necessary work input to the cycle for heat pumping from the source to the sink.

Magnetic Refrigeration

State of development

- Magnetic refrigeration technology for operating temperatures near to room temperatureis under active development.
- Magnetic refrigeration has the potential for use across the whole refrigeration temperature range, down to cryogenic temperatures.



Chubu Electric rotary magnetic refrigerator system *(from Okamura et al, 2006)*

Applications in the food sector

- A number of prototype systems have been announced. Cooling capacities of prototypes are low, maximum reported to date is 540 W, with a COP of 1.8 at room temperature.
- It is anticipated that the first commercial applications will be for low capacity stationary and mobile refrigeration systems. Time to commercialisation is estimated to be greater than ten years.

Thermoacoustic Refrigeration

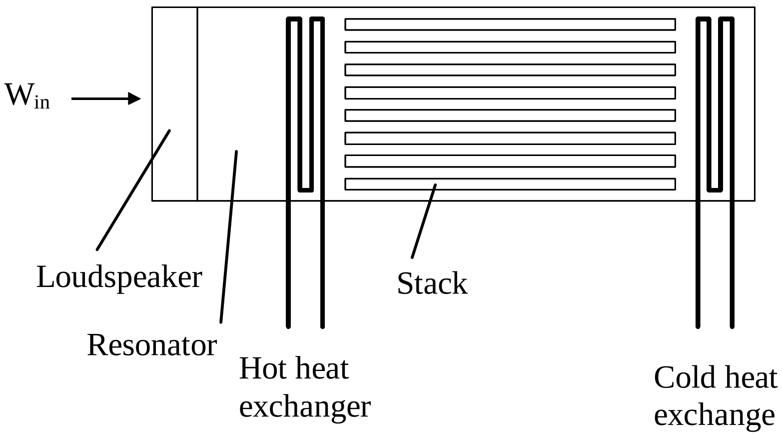


Figure 1 Sound wave Thermoacoustic engine

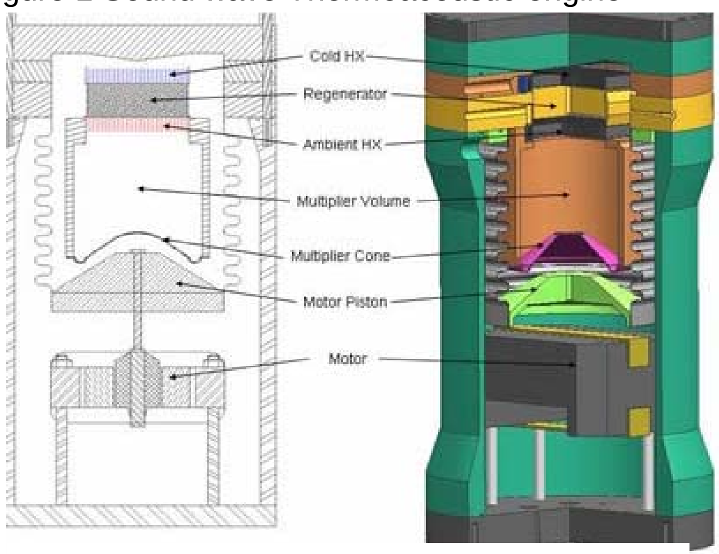


Figure 2. A travelling-wave thermoacoustic refrigerator (Source: Sounds Cool! The Ben & Jerry's Project, 2005)

(a) Thermoacoustic refrigeration systems operate by using sound waves and inert gas in a resonator to produce cooling. Thermoacoustic devices are typically characterised as either 'standing-wave' or 'travelling-wave'.

(b) Application of acoustic waves through a driver such as a loud speaker, makes the gas resonant. As the gas oscillates back and forth, it creates a temperature difference along the length of the stack.

(c) Thermoacoustic refrigerators have the potential to cover the whole spectrum of refrigeration down to cryogenic temperatures.

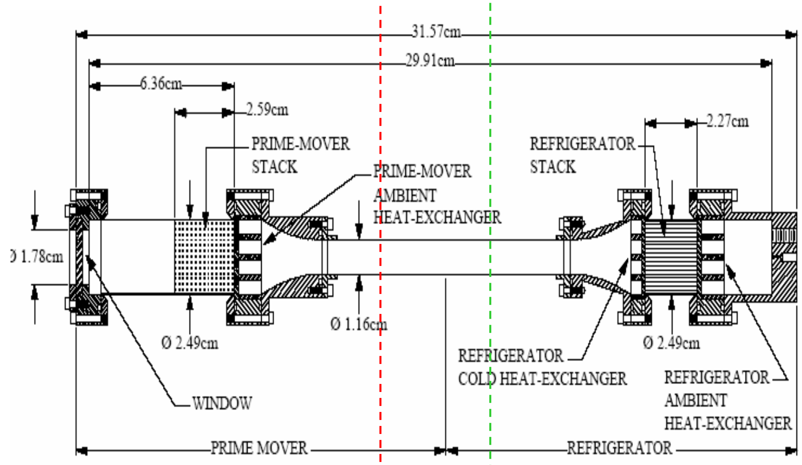
Thermoacoustic Refrigeration

State of development

- In their present state of development the efficiency of prototype systems is lower than that of vapour compression systems, around 1.0.
- Systems operating on the thermoacoustic principle are not yet commercially available.

Applications in the food sector

- It is likely that potential market for food applications will be in the low capacity equipment range such as domestic and commercial refrigerators, freezers and cabinets.



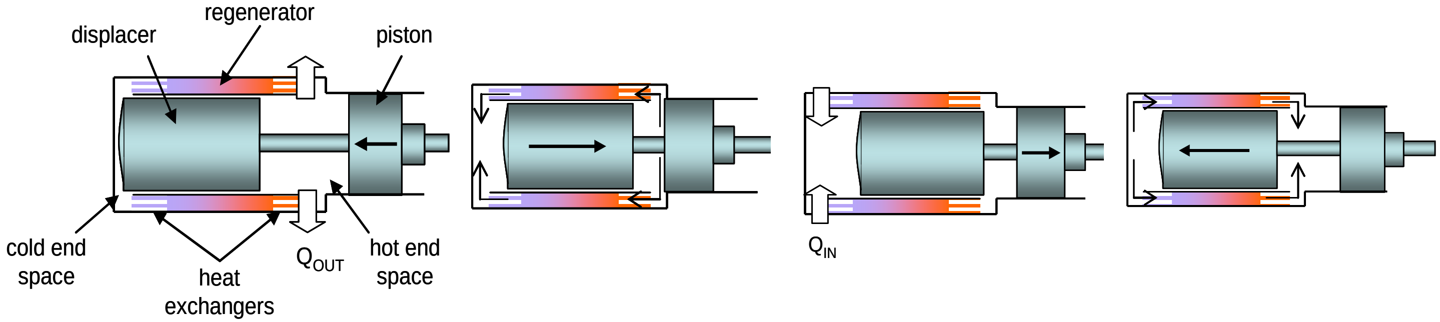
Addef and Hofler, 2000

Thermoacoustic engine

Thermoacoustic refrigerator

- Other potential applications include the use of waste heat to drive a thermoacoustic engine which in turn drives a thermoacoustic refrigerator

Stirling Cycle Refrigeration



Piston moves in compressing gas. Heat rejection from hot end

Displacer moves to cold end space via regenerator

Piston moves out expanding gas. Heat absorption at cold end

Displacer moves gas to hot end space via regenerator

Figure 1 Piston and Displacer movements during Stirling refrigeration cycle

(a) The Stirling cycle cooler is a member of a family of closed-cycle regenerative thermal machines known as Stirling cycle machines.

(b) Gas in the system is moved backwards and forwards between the hot end and cold end spaces.

(c) Heat is rejected via a heat exchanger at the hot end, and heat is absorbed from the space to be cooled via a heat exchanger at the cold end.

Stirling Cycle Refrigeration

Free Piston Stirling Module and Freezer

State of development

- FPSC units with nominal maximum cooling capacities of 40 W and 100 W have been produced.
- Larger capacity units, up to 300 W, reported to be under development.
- FPSC based products, including freezer boxes and a system for the marine refrigeration market, have been developed by licensees.

- Values of *COP* between 2 and 3 have been reported for cold head temperatures around 0° C, and values around 1 for cold head temperatures approaching -40° C.

Applications in the food sector

- FPSCs can operate down to cryogenic temperatures and hence can be used in many food refrigeration applications.
- Most likely market for FPSCs in the food sector is domestic and portable refrigerators and freezers, can vending machines and other integral refrigerated display equipment.

Thermoelectric Refrigeration

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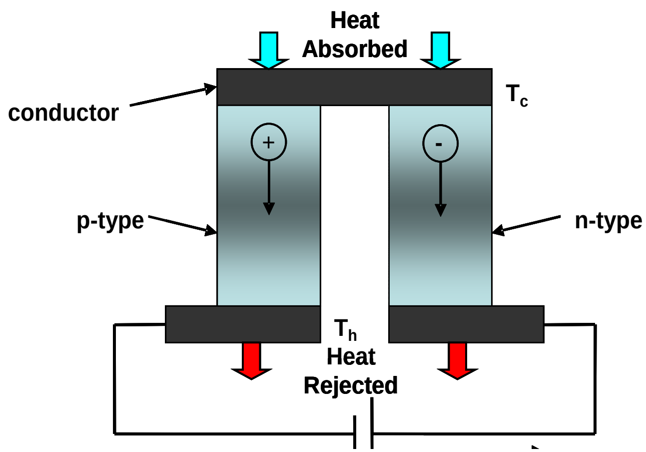
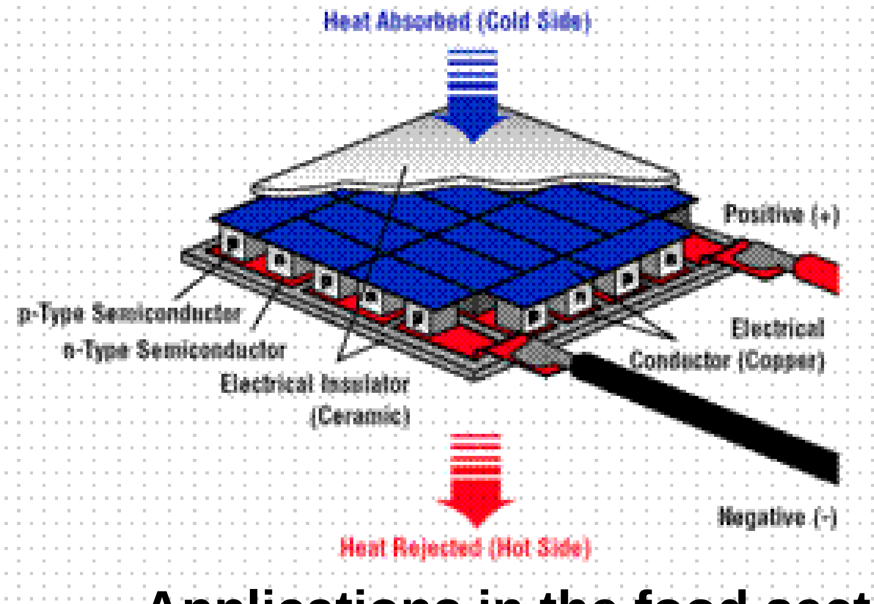


Thermoelectric cooling (or Peltier) couple



State of development

- Thermoelectric modules are available commercially with maximum cooling capacities up to 200 W and COP around 0.6 at 0°C cooling temperature.
- Interface with heat exchange systems to facilitate heat transfer adversely influences COP.

Applications in the food sector

- Hotel room, mobile home, recreational vehicles and cars; portable picnic coolers; wine coolers; beverage can coolers; drinking water coolers.
- Potential applications include domestic and commercial refrigerators and freezers, and mobile refrigeration and air conditioning.

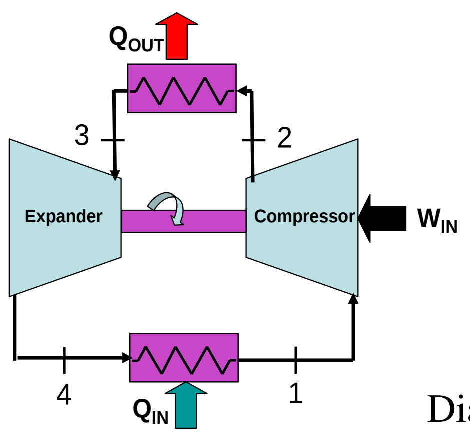
Air Cycle Technology

State of development

- Air is used as the working fluid.
- Reasonably well established technology.
- Closed and open air cycle systems have been developed with refrigeration capacities ranging from 11 to 700 kW.
- Current R&D on transport refrigeration (QUB) and integrated heating and cooling (Bristol funded by Defra)

Application in the food sector

- Rapid chilling and/or freezing (including air blast, tunnel, spiral, fluidised bed and rotary tumble equipment);
- Refrigerated transport (trucks, containers, rail freight, ships)
- Integrated heating and cooling



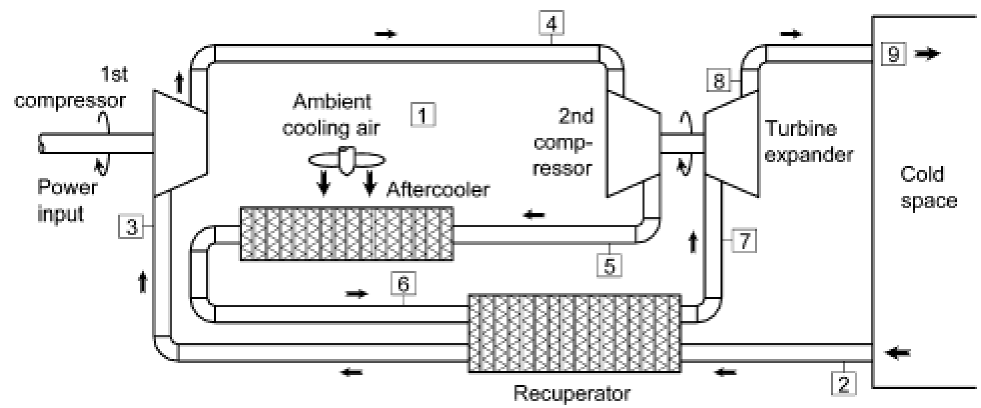
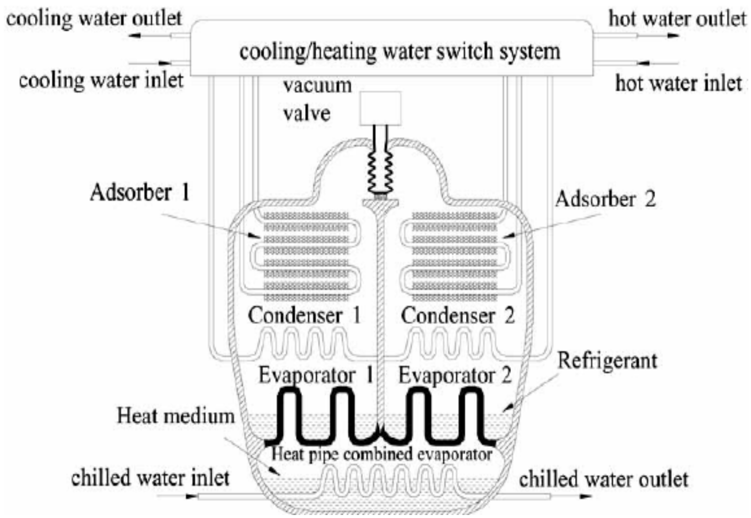


Diagram of Air Cycle (Spence et.al., 2005)

Sorption Technologies - Adsorption



Schematic Diagram of Adsorption chiller (Wang, 2006)

State of development

- Already available for air conditioning applications 35 and 1300 kW capable of being driven by low grade heat 50° C to 90 ° C and able to give COPs of around 0.7. at temp. above 0°C
- R&D on development of systems for refrigeration applications.

Applications in the food sector

- Applications in the food sector will be primarily in areas where waste heat is available to drive the adsorption system.
- Such applications can be found in food factories, transport refrigeration.
- Use with CHP systems for tri-generation

Tri-generation

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Potential for energy and GHG emissions savings

State of development

- Progress in power systems (ICs, microturbines, fuel cells)
- Heat recovery systems
- Design and controls
- R&D in Brunel funded by Defra

Application in the food sector

- Large food manufacturing facilities for many years
- More recently in supermarkets for HVAC applications
- Potential for the use of biofuels (food manufacturing facilities and RDCs)

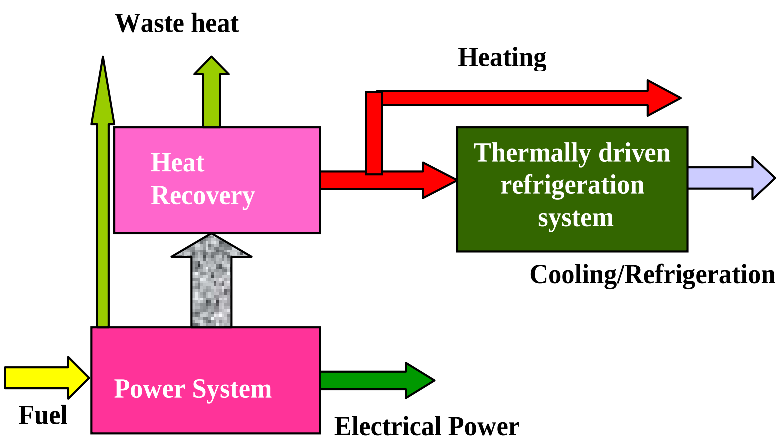
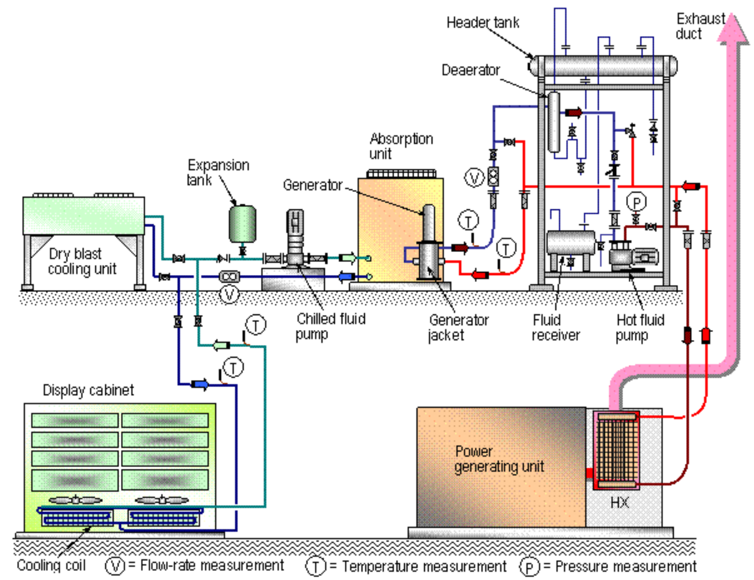


Figure 1. Schematic of a trigeneration system



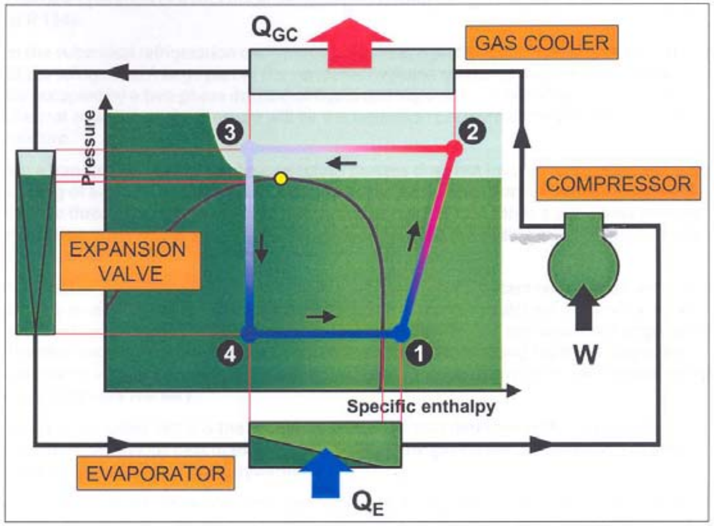
Experimental facilities at Brunel University

Current State of the Art – CO_2 refrigeration systems

- Natural refrigerant
- High pressures compared to HFCs and ammonia
- Potential for energy and GHG emissions savings

State of Development

- Becoming established in Scandinavia, and Northern Europe.
- Different system arrangements – Cascade Transcritical, booster etc



Transcritical operation (Courtesy Knudsen)


CO_2 pack (Courtesy Linde)

Current State of the Art – CO_2 refrigeration systems

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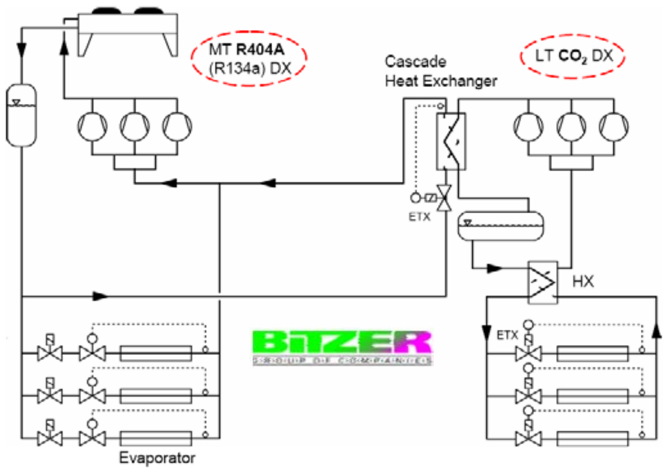
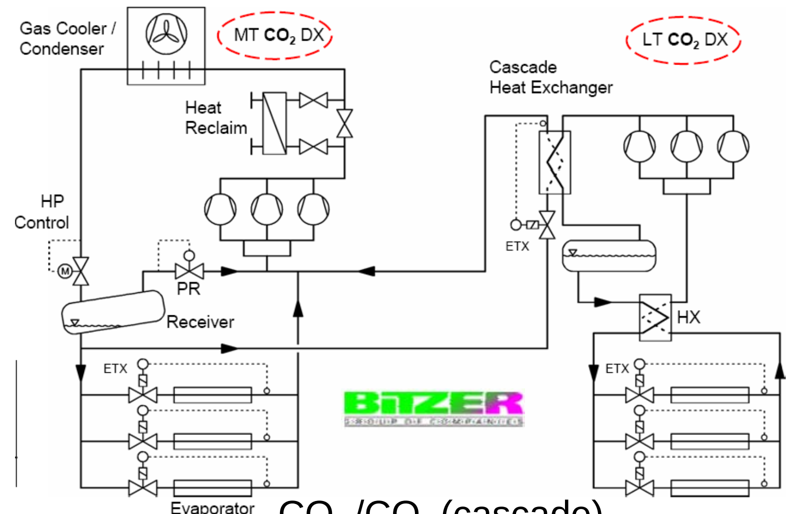
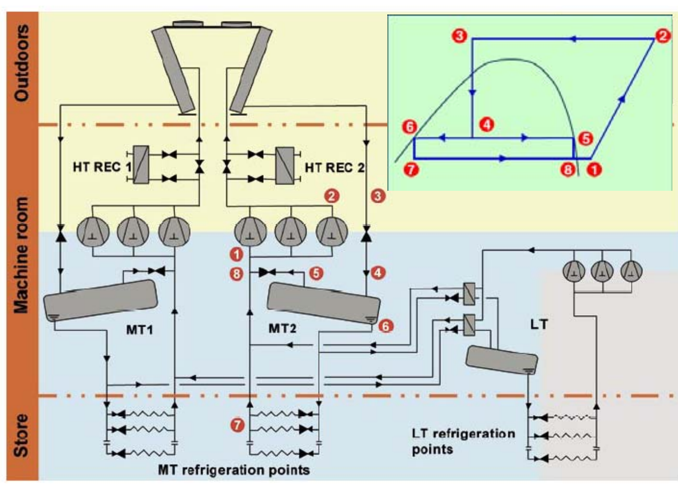


HFC/CO_2 (cascade)

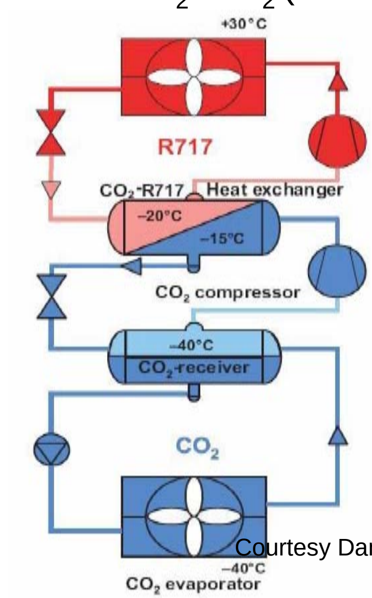


CO_2 /CO_2 (cascade)



DIE KÄLTE & Klimatechnik 2/2005

CO_2 /CO_2 (compound)



Courtesy Danfoss

R717/CO_2 (cascade)

Current State of the Art – CO_2 refrigeration systems

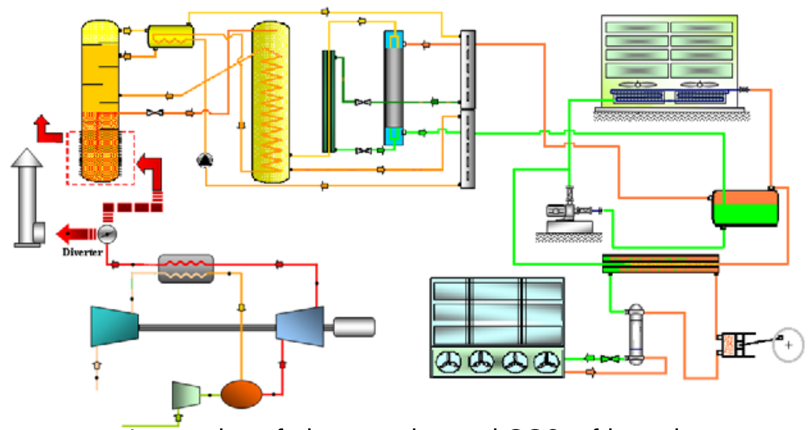
Application in the food sector

- Supermarkets
- Food processing (all types competes with ammonia)
- Transport refrigeration
- Beverage cooling

Activities in the UK

- Limited design and manufacturing capability in the UK for batch production (Star, Space)
- Some applications in supermarkets
- Some research and development in Universities (Brunel, London South Bank)

STAR REFRIGERATION	Evap CO2	Evap NH3	Cond CO2	Cond NH3	COP
	Deg C	Deg C	Deg C	Deg C	-
CO2 Transcritical	-10	-	29	-	2.25
CO2/NH3 Cascade	-10	2	5	25	2.6
CO2/NH3 volatile secy.	-10	-13	-10	25	3.32



Integration of tri-generation and CO2 refrigeration systems (Brunel Univerity, funded by Defra)

Technology Development and Applications

Transport Refrigeration

- Reduce loads (vacuum insulation)
- PCM thermal storage (charge at base – RDC)
- Total loss systems
- Air cycle
- Hybrid and solar driven systems, magnetic refrigeration
- Utilise thermal energy in engine exhaust (sorption refrigeration systems, power generation, thermoacoustic refrigeration)

Supermarkets

- CO_2 systems (optimum configuration for UK yet to be established)
- Thermal integration (heat recovery and CHP/Tri-generation)
- Reduction in refrigerant charge and improvement in component efficiencies.
- Integration of renewable sources, wind, solar and ground thermal energy (heating/cooling).

Technology Development and Applications

Integral refrigeration systems (cabinets)

- HC and CO_2 refrigerants
- Thermoelectric cooling
- Stirling cycle cooling
- Thermoacoustic
- Magnetic refrigeration

Food processing

- CO_2 systems and CO_2 /R717 cascade systems
- Air cycle technology for low temperatures and combined heating and cooling
- Thermal integration
- Waste heat recovery for refrigeration (sorption systems) and power generation (thermoelectric, Stirling, thermoacoustic, turbo-generators)
- Tri-generation (use of biofuels)

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Technology Development and Applications

Food Storage (cold stores)

- Biomass – sorption refrigeration systems
- Biomass – tri-generation
- CO_2 and CO_2/R717 cascade systems
- Use of solar wind to generate electricity/heat to drive vapour compression/sorption systems