Fostering the Development of Technologies and Practices to Reduce the Energy Inputs into the Refrigeration of Food

Alternative and Emerging Refrigeration Technologies for Food Refrigeration Applications

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1. TRIGENERATION

Description of technology

Tri-generation technology is a technology that can provide simultaneously three forms of output energy; electrical power, heating and cooling. Trigeneration is also known as CCHP (Combined Cooling, Heating and Power) or CHRP (Combined Heating, Refrigeration and Power). In essence, trigeneration systems are CHP (Combined Heat and Power) or co-generation systems, integrated with a thermally driven refrigeration system to provide cooling as well as electrical power and heating.

CHP systems consist of a power system which can be an internal combustion engine driven by a fossil fuel or a biofuel, an external combustion engine or other thermally or chemically driven systems coupled to a generator which produces electricity. A heat recovery system recovers heat from the power system and exhaust gases to be used for heating applications. Effective operation of CHP systems requires maximum utilisation of both electrical power and heat. Where there are seasonal variations in heat demand, the utilisation efficiency of CHP systems can be increased if the excess heat is used to power thermally driven refrigeration technologies. Trigeneration systems can have overall efficiencies as high as 90% compared to 33%-35% for electricity generated in central power plants

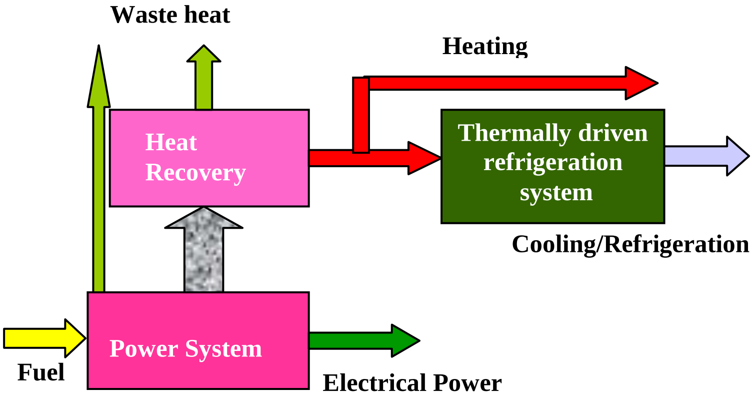


Figure 1. Schematic of a trigeneration system

State of Development

Trigeneration systems have been in operation for many years. Developments in recent years have mainly concentrated on individual subsystems such as the power system, heat recovery system, thermally driven refrigeration machines and system integration and control.

On the power systems front the main developments have been on: i) improvement of the efficiency of internal combustion engines, particularly gas and diesel engines and the development of engines that can operate with biofuels; ii) development of microturbines that enable the availability of reject heat at a much higher temperature than internal combustion engines; iii) development of fuel cells that offer higher electrical power generation efficiencies than internal combustion engines and microturbines. Progress in thermally driven cooling machines has mainly been on the development of adsorption cooling systems and multi-effect absorption systems to improve efficiency. Advances in heat transfer and heat exchanger technology now enable the manufacture of more compact heat recovery systems.

Applications in the food sector

There are a number of examples of application of trigeneration plants in the food industry. The majority of these are large plants in the MW range in food factories where bespoke ammonia plant are linked to gas turbines, or internal combustion engines. More recently, application of trigeneration has been extended to supermarkets with a very small number of installations in the USA, the UK and Japan. These systems are mainly used for space cooling applications and are based on internal combustion engines or microturbines and Li-Br/H_2O absorption refrigeration systems. A pilot installation is currently planned in the UK of a system employing an adsorption chiller.

Barriers to uptake of the technology

The main barriers to uptake of tri-generation technology are:

- application range of off the shelf systems is currently limited to temperatures above 0 ^{o}C,
- insufficient experience and performance data from applications in retail food stores to provide confidence in the application of the technology,
- economics are very sensitive to the relative difference between the price of grid electricity and fuel used by the trigeneration system. This makes it difficult to project accurately energy savings.

Key drivers to encourage uptake

The main drivers to encourage uptake of the technology in the food sector are:

- legislation that limits or prohibits the use of HFCs.
- greater availability of biofuels and legislation that requires significant reductions in emissions from food manufacturing and retailing.
- policies to encourage local/embedded power generation through subsidies and other instruments.

Research and development needs

To increase the attractiveness and application of trigeneration systems research and development work is required to:

- increase efficiency and reduce cost of power systems (engines, microturbines and fuel cells) and sorption refrigeration machines (absorption, adsorption)
- develop packaged systems for low temperature applications below 0 ^{o}C.
- develop design, and integration strategies for trigeneration system components.
- develop strategies and controls for the optimum integration of trigeneration systems with other power and thermal systems for applications in food manufacturing, retail and storage facilities.

2. AIR CYCLE REFRIGERATION

Description of technology

Air cycle systems can produce low temperatures for refrigeration by subjecting the gaseous refrigerant (air) to a sequence of processes comprising compression, followed by constant pressure cooling, and then expansion to the original pressure to achieve a final temperature lower than at the start of compression. Air cycle refrigeration is based on the reversed Joule (or Brayton) cycle illustrated in figure 1.

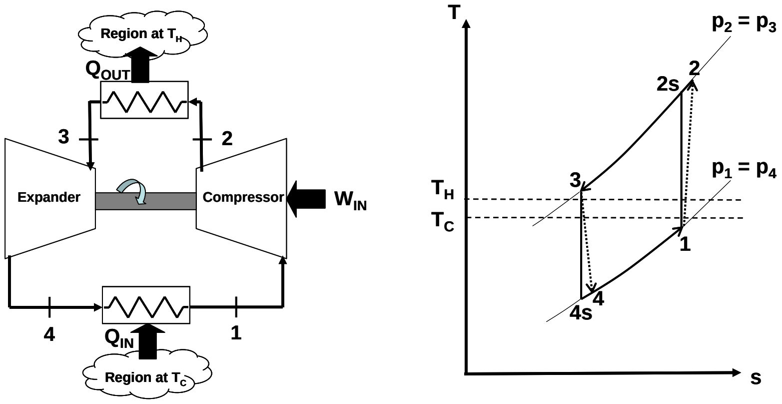


Figure 1 Reversed joule cycle

Air cycles can be classified as closed, open or semi-open/closed. **Closed cycles** are, by definition, sealed systems and consequently there is no direct contact between the working fluid and the product being cooled. Hence, in comparison with open and semi-open/closed cycles an additional heat exchanger (with associated temperature difference) is required for transferring heat from the refrigeration load. **Open cycles** can be open on either the low-pressure side or the high-pressure side of the cycle. Cold air leaving the system passes through the refrigerated space coming in direct contact with the product being cooled. **Semi-Open/Closed cycles** are also open to the refrigerated space, where the cold air comes into direct contact with the product being cooled but the air is then drawn back through the low-pressure side of the regenerator to the compressor.

State of Development

Air cycle is a reasonably well established technology. Plant operating characteristics are understood and issues such as condensation and icing have been addressed and solutions developed. Closed and open air cycle systems have been developed by industrial companies with refrigeration capacities ranging from 11 to 700 kW for closed systems and from 15 to 300 kW for open systems. Information on coefficient of performance for refrigeration is sparse but most values quoted are in the range 0.4 to 0.7. It is also noted that the efficiency of air cycle systems is relatively unaffected under part load conditions.

Applications in the food sector

Air cycle refrigeration can deliver air temperatures down to -100°C, giving it a niche position in the -50°C to -100°C range, beyond the capability of vapour compression plant, and is a cost-effective alternative to the use of cryogenics for low temperature food freezing operations. Air cycles also generate high air temperatures, typically of over 200°C, that can be used in combination with the low temperatures to integrate cooking and refrigeration processes.

In the food sector air cycle technology can be applied to rapid chilling and/or freezing (including air blast, tunnel, spiral, fluidised bed and rotary tumble equipment); for refrigerated transport (trucks, containers, rail freight, ships, air cargo); and for integrated rapid heating and cooling (cook-chill-freeze or hot water/steam raising and refrigeration).

Barriers to uptake of the technology

The main barriers to uptake of air cycle technology are:

- unavailability of packaged equipment off the shelf for application in the food sector
- insufficient experience and performance data from commercial applications to provide confidence in the application of the technology.

Key drivers to encourage uptake

The main drivers to encourage uptake of the technology in the food sector are:

- successful demonstration of the benefits of the technology in specific promising applications, such as: combined refrigeration and cooking/heating and transport refrigeration.
- rising energy costs and requirement for faster food processing to increase throughput and reduce energy consumption.
- more stringent regulations on the use of HFC refrigerants and other natural refrigerant alternatives

Research and development needs

To increase the attractiveness of air cycle systems, research and development is required to:

- increase the efficiency and availability of small turbo-machines.
- improve the effectiveness and reduce costs of compact heat exchangers
- develop component sizing, integration and control strategies for specific applications to increase system efficiency at reasonable cost.

3. SORPTION REFRIGERATION - ADSORPTION SYSTEMS

Description of technology

Sorption refrigeration technologies such as absorption and/or adsorption are thermally driven systems, in which the conventional mechanical compressor of the common vapour compression cycle is replaced by a ‘thermal compressor’ and a sorbent. The sorbent can be either solid in the case of adsorption systems or liquid for absorption systems. When the sorbent is heated, it desorbs the refrigerant vapour at the condenser pressure. The vapour is then liquefied in the condenser, flows through an expansion valve and enters the evaporator. When the sorbent is cooled, it reabsorbs vapour and thus maintains low pressure in the evaporator. The liquefied refrigerant in the evaporator absorbs heat from the refrigerated space and vaporises, producing the cooling effect.

Adsorption refrigeration unlike absorption and vapour compression systems, is an inherently cyclical process and multiple adsorbent beds are necessary to provide approximately continuous capacity. Adsorption systems inherently require large heat transfer surfaces to transfer heat to and from the adsorbent materials which automatically makes cost an issue. High efficiency systems require that heat of adsorption be recovered to provide part of the heat needed to regenerate the adsorbent. These regenerative cycles consequently need multiples of two-bed heat exchangers and complex heat transfer loops and controls to recover and use waste heat as the heat exchangers cycle between adsorbing and desorbing refrigerant.

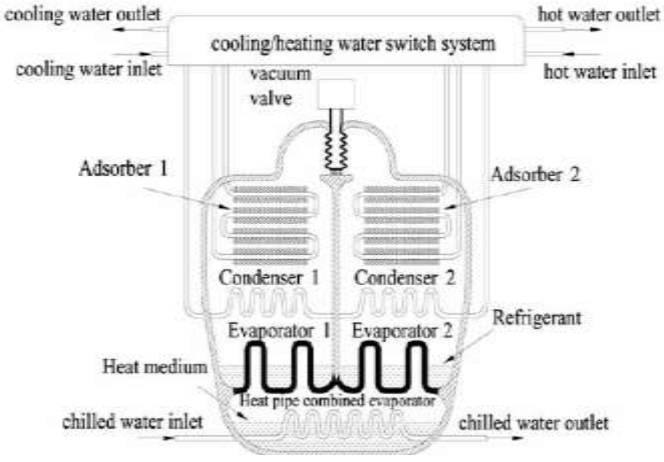


Figure. Schematic diagram of silica gel-water adsorption chiller, Xia, et al (2005).

State of Development

Adsoprtion systems for air conditioning applications are already commercially available from a small number of manufacturers . "MYCOM", Mayekawa Mfg. Co., Ltd. are producing Silica-gel/water adsorption chiller (ADREF-models) with ranges between 35 and 350 kW for use in the air-conditioning industry. NISHIYODO KUCHOUKI CO. LTD, produce Silica-Gel/Water adsorption chillers (ADCM models) with capacities between 70 kW and 1300 kW capable of being driven by low grade heat 50 – 90 °C and able to give COPs of over 0.7. Research and development is also underway to produce systems for refrigeration applications. Research prototypes for refrigeration temperatures down to – 25 °C are currently in operation or under development.

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 and transport refrigeration. Other possible application is in tri-generation where adsorption systems can be used in conjunction with combined heat and power systems to provide refrigeration. Such an application is currently under consideration in the UK by a major food retailer. The intended use is for air conditioning and sub-cooling of refrigerant liquid of the multi-compressor refrigeration packs.

Barriers to uptake of the technology

The main barriers to uptake of adsorption refrigeration technology:

- in their current state of development systems are bulky and of higher cost compared to competing vapour absorption systems

- only two manufacturers of commercial products and distribution channels are not well established
- application range of commercial products is currently limited to temperatures above 0 ^{o}C. unavailability of packaged equipment off the shelf for application in the food sector
- insufficient experience and performance data from commercial applications to provide confidence in the application of the technology.

Key drivers to encourage uptake

The main drivers to encourage uptake of the technology in the food sector are:

- successful demonstration of the benefits of the technology in applications where there is sufficient waste heat or in tri-generation systems.
- rising energy costs that could encourage the more effective utilisation of waste heat and better thermal integration of processes in food manufacturing and retail facilities.

Research and development needs

To increase the attractiveness and application of adsorption systems, research and development is required to:

- increase efficiency and reduce size and cost of systems through heat and mass transfer enhancement.
- develop systems for low temperature applications below 0 ^{o}C. This will require further development of working pairs (fluid and bed).

4. THERMOELECTRIC REFRIGERATION

Description of technology

Thermoelectric cooling devices utilise the Peltier effect, whereby the passage of a direct electric current through the junction of two dissimilar conducting materials causes the junction to either cool down (absorbing heat) or warm up (rejecting heat), depending on the direction of the current.

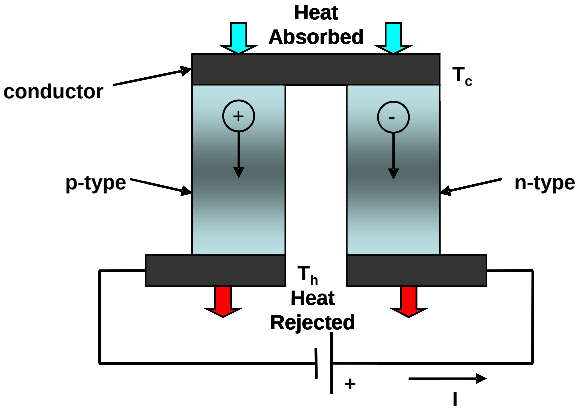


Figure 1 Thermoelectric cooling (or Peltier) couple

Figure 1, shows a pair of adjacent thermo-element legs joined at one end by a conducting metal strip forming a junction between the legs. Thus, the legs are connected in series electrically but act in parallel thermally. This unit is referred to as a thermoelectric couple and is the basic building block of a thermoelectric (or Peltier) cooling module. The thermo-element materials are doped semiconductors, one n-type with a majority of negative charge carriers (electrons) and the other p-type with a majority of positive charge carriers (holes). The majority of commercially available thermoelectric cooling modules are assembled from n-type and p-type thermo-elements cut from bismuth telluride (Bi_2Te_3) based bulk materials.

State of Development

Thermoelectric modules are available commercially to suit a wide range of small and medium cooling duties. Manufacturers' lists include single-stage modules with maximum cooling capacities from less than one watt to 186 W. Maximum heat flux densities are mostly in the range 2-6 W/cm^2 but individual modules with up to 9 W/cm^2 are available. In a thermoelectric refrigeration system the Peltier module (or modules) must be interfaced with heat exchange systems to facilitate heat removal from the refrigerated space to the cold-side and heat rejection from the hot-side to the surroundings. The thermal resistances introduced by the heat exchange systems have a significant influence on the overall coefficient of performance of the refrigeration system.

Applications in the food sector

Thermoelectric modules and systems have been extensively applied in numerous fields, handling cooling loads from milliwatts up to tens of kilowatts with temperature differences from almost zero to over 100 K. They offer advantages of no moving parts and good reliability, absence of noise and vibration, compactness and light weight. They have, however, lower COP and higher capital cost than vapour compression systems. To improve the COP, efficient heat transfer systems are required to reduce the temperature difference across the module. Current applications in the food sector include: hotel room (mini-bar) refrigerators; refrigerators for mobile homes, trucks, recreational vehicles and cars; portable picnic coolers; wine coolers; beverage can coolers; drinking water coolers.

Other potential future applications include domestic and commercial refrigerators and freezers, and mobile refrigeration and cooling systems.

Barriers to uptake of the technology

The main barriers to the uptake of thermoelectric refrigeration are:

- lower efficiency than competing vapour compression technology.

- thermoelectric cooling modules are commercially available but packaged thermoelectric refrigeration systems are not as yet available.

Key drivers to encourage uptake

The main drivers to encourage uptake of thermoelectric cooling technology in the food sector are:

- legislation that significantly limits or prohibits the use of HFCs in small capacity, self contained refrigeration equipment.
- limits imposed on the amount of flammable refrigerant that can be used in self contained refrigerated cabinets.
- increased efficiency of thermoelectric modules.

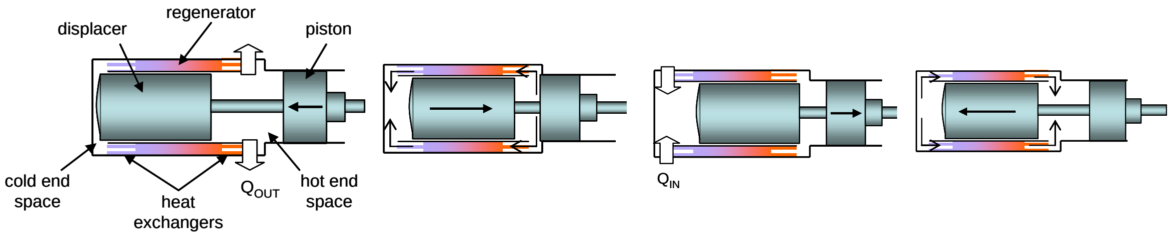
Research and development needs

Application of thermoelectric cooling technology to the food sector will require improvement of the COPs of thermoelectric refrigeration systems to approach those of vapour compression systems. To achieve this it is necessary to develop materials with much better thermoelectric properties than the figures of merit (ZT=1.0) currently available. Research is also required to improve the efficiency of heat exchange systems on both the hot and cold side, to reduce the temperature difference across the Peltier module.

5. STIRLING CYCLE REFRIGERATION

Description of Technology

The Stirling cycle cooler is a member of a family of closed-cycle regenerative thermal machines, including prime movers as well as heat pumps and refrigerators, known collectively as Stirling cycle machines. In any refrigeration cycle, including the reversed Stirling cycle, net work input is necessary in-line with the second law of thermodynamics. This is achieved by shuttling the gas in the system backwards and forwards between the hot end and cold end spaces so that the temperature of the system during compression is, on average, higher than during expansion. As a result the work done on the gas during compression is greater than the work done by the gas during expansion, Figure 1. Accordingly, the hot end and cold end gas spaces are also referred to as the compression space and the expansion space respectively. Furthermore, for operation as a refrigerator, heat must be rejected via a heat exchanger at the hot end, and heat must be absorbed from the space to be cooled via a heat exchanger at the cold end.



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

State of Development

Free-piston machines (FPSC): This relatively recent development of free-piston technology, where the piston and displacer are not mechanically connected to a crankshaft, but supported by planar springs or gas springs and work transfer at the piston is achieved by employing a moving magnet linear motor, originated at Sunpower but is now led by Global Cooling. FPSCs are compact, helium filled (to 20-30 atm), hermetically sealed Stirling refrigeration machines. Heat exchangers must be attached to the cold and warm heads of the FPSC unit to facilitate heat absorption and heat rejection respectively. FPSC units with nominal maximum cooling capacities of 40 W and 100 W have been produced, with larger capacity units, up to 300 W, reported to be under development. FPSCs have been evaluated experimentally by Global Cooling and appliance manufacturers for application to domestic and portable refrigerators and freezers as well as a beverage can vending machine. FPSC based products, including freezer boxes and a system for the marine refrigeration market, have been developed by licensees. Coefficients of performance measured for FPSCs with warm head temperatures close to 30°C vary with the cold head temperature. 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. Current limitations are the low cooling capacities, lower COP and higher cost compared to the vapour compression cycle. Market for FPSCs in the food sector is likely to be domestic and portable refrigerators and freezers as well as beverage can vending machines and other integral refrigerated display equipment

Barriers to uptake of the technology

The main barriers to uptake of Sterling cycle refrigeration technology are:

- currently only small capacity units are available which in their present state of development cannot compete on price and efficiency with vapour compression systems.
- application of FPSC machines is tightly controlled by Global Cooling which determine the areas of application through licensing of the technology.

Key drivers to encourage uptake

The main drivers to encourage uptake of the technology in the food sector are:

- legislation that significantly limits or prohibits the use of HFCs in small capacity, self contained refrigeration equipment.
- limits imposed on the amount of flammable refrigerant that can be used in self contained refrigerated cabinets

Research and development needs

Wider application of FPSCs to the food sector will require higher cooling capacities and higher system COPs. Important areas of research are:

- development of higher efficiency linear motors and design to increase cooling capacity,
- improved heat exchange on the cold and hot sides and better component integration.

6. THERMOACOUSTIC REFRIGERATION

Description of technology

Thermoacoustic refrigeration systems operate by using sound waves and a non-flammable mixture of inert gas (helium, argon, air) or a mixture of gases in a resonator to produce cooling. Thermoacoustic devices are typically characterised as either ‘standing-wave’ or ‘travelling-wave’. A schematic diagram of a standing wave device is shown in figure 1. The main components are a closed cylinder, an acoustic driver, a porous component called a "stack, and two heat-exchanger systems. 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. This temperature change comes from compression and expansion of the gas by the sound pressure and the rest is a consequence of heat transfer between the gas and the stack. The temperature difference is used to remove heat from the cold side and reject it at the hot side of the system. As the gas oscillates back and forth because of the standing sound wave, it changes in temperature. Much of the temperature change comes from compression and expansion of the gas by the sound pressure (as always in a sound wave), and the rest is a consequence of heat transfer between the gas and the stack.

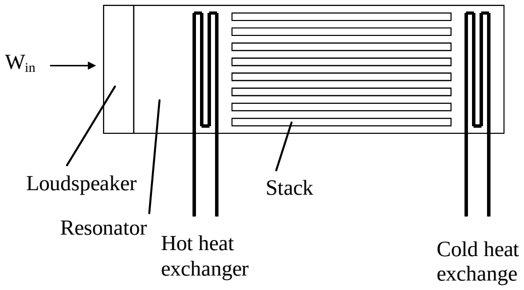


Figure 1 Sound wave Thermoacoustic engine

In the travelling-wave device, the pressure is created with a moving piston and the conversion of acoustic power to heat occurs in a regenerator rather than a stack. The regenerator contains a matrix of channels which are much smaller than those in a stack and relies on good thermal contact between the gas and the matrix. The design is such that the gas moves towards the hot heat exchanger when the pressure is high and towards the cold heat exchanger when the pressure is low, transferring heat between the two sides. An example of a travelling wave thermoacoustic device is the Ben & Jerry ice-cream cabinet, figure 2.

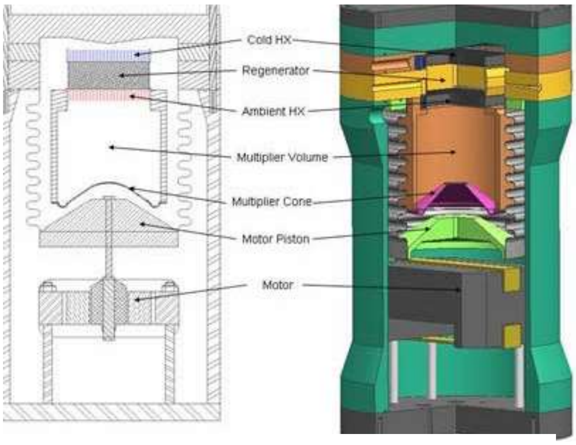


Figure 2. A travelling-wave thermoacoustic refrigerator (Source: Sounds Cool! The Ben & Jerry’s Project, 2005)

State of Development

A number of design concepts and prototypes are under development in many research establishments. The technology has the potential to offer another refrigeration option but improvements in design are necessary to increase COPs to the level of vapour compression systems. Research effort is currently directed to the development of flow-through designs (open systems) which will reduce or eliminated the use of heat exchangers.

Potential applications in the food sector

Thermoacoustic refrigerators have the potential to cover the whole spectrum of refrigeration down to cryogenic temperatures. It is likely that potential market for food applications will be in the low capacity equipment such as domestic and commercial refrigerators, freezers and cabinets.

Barriers to uptake of the technology

The main barriers to the uptake of thermoacoustic technology are:

- in their present state of development the efficiency of prototype therrmoacoustic refrigeration systems is lower than that of vapour compression systems.
- systems operating on the thermoacoustic principle are not yet commercially available.

Key drivers to encourage uptake

The main drivers to encourage uptake of thermoacoustic technology in the food sector are:

- environmental considerations and legislation that significantly limits or prohibits the use of HFCs in small capacity, self contained refrigeration equipment.
- limits imposed on the amount of flammable refrigerant that can be used in self contained refrigerated cabinets.
- development of systems that offer efficiency and cost advantages over vapour compression systems.

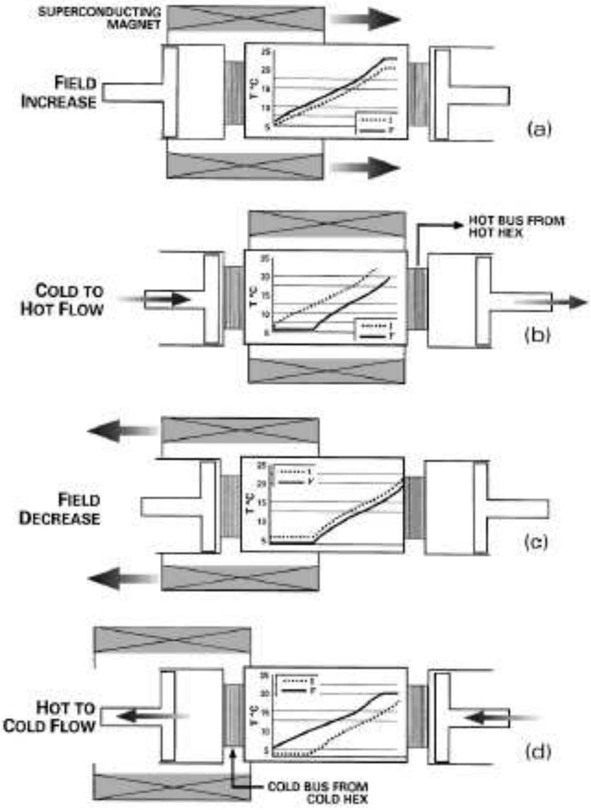
Research and development needs

To improve efficiency and reduce cost, developments are needed in the design of stacks, resonators and compact heat exchangers for oscillating flow. Research is also required in the development of flow-through designs (open systems) which will reduce or eliminated the use of heat exchangers and will reduce complexity and cost.

7. MAGNETIC REFRIGERATION

Description of Technology

A magnetic refrigeration cycle employs a solid-state magnetic material as the working refrigerant, and exploits the magnetocaloric effect (MCE), or the ability of a material to warm-up in the presence of a magnetic field and cool down when the field is removed. Heat absorption and heat rejection are facilitated by thermally linking the magnetic material with the cold source and hot sink respectively, using an environmentally benign heat transfer fluid such as water, anti-freeze mixture or a gas, depending on the operating temperature range. The forces involved in applying and removing the magnetic field provide the necessary net work input to the cycle for heat pumping from the source to the sink.



Active magnetic regeneration cycle (from Russek and Zimm, International Journal of Refrigeration, 29, 1366-1373, 2006.

Magnetization and demagnetization of a magnetic refrigerant can be viewed as analogous to compression and expansion in a vapour compression refrigeration cycle, but in contrast these magnetic processes are virtually loss-free and reversible for soft ferromagnetic materials. Further advantages associated with the solid-state nature of magnetic refrigerants are the absence of vapour pressure, resulting in zero ODP and zero GWP, and a large magnetic entropy density which is the key thermodynamic property determining the magnitude of the MCE. Magnetic refrigeration therefore offers the prospect of efficient, environmentally friendly and compact cooling.

State of development

Magnetic refrigeration technology for operating temperatures near to room temperature, including both magnetic materials and systems design, is under active development by several teams in North America, the Far East and Europe and a number of prototype systems (including both reciprocating and rotary designs) 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.

Potential application to the food sector

Considerable research and development is still required for the successful commercialisation of magnetic refrigeration systems. The most important challenge is the development of materials with high magnetocaloric effect, to reduce the size, weight and cost of the system. Other important areas of research are the development of effective methods of heat transfer between the refrigerant and secondary heat transfer fluid and overall thermal management and control.

Magnetic refrigeration has the potential for use across the whole refrigeration temperature range, down to cryogenic temperatures. 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.