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Review

A review of emerging technologies for food refrigeration applications

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ABSTRACT

Refrigeration has become an essential part of the food chain. It is used in all stages of the chain, from food processing, to distribution, retail and final consumption in the home. The food industry employs both chilling and freezing processes where the food is cooled from ambient to temperatures above 0 °C in the former and between −18 °C and −35 °C in the latter to slow the physical, microbiological and chemical activities that cause deterioration in foods. In these processes mechanical refrigeration technologies are invariably employed that contribute significantly to the environmental impacts of the food sector both through direct and indirect greenhouse gas emissions. To reduce these emissions, research and development worldwide is aimed at both improving the performance of conventional systems and the development of new refrigeration technologies of potentially much lower environmental impacts. This paper provides a brief review of both current state of the art technologies and emerging refrigeration technologies that have the potential to reduce the environmental impacts of refrigeration in the food industry. The paper also highlights research and development needs to accelerate the development and adoption of these technologies by the food sector.

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1. Introduction

In industrialised countries the food industry constitutes one of the largest industrial manufacturing groups and despite significant differences in per capita consumption of major food categories, there is a rising trend towards higher consumption of several food products with consequent increase in environmental impacts. A significant impact is greenhouse gas emissions. Sources of greenhouse gas emissions for the industry include CO_2 emissions from energy used in the manufacturing processes and for the environmental control of buildings, emissions of refrigerants from food refrigeration equipment and organic waste.

Since the emergence of chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants in the 1930s the vapour compression refrigeration cycle has gained dominance over alternative cooling technologies in all areas of food manufacturing, distribution and retail. In the 1980s, increased environmental awareness and the realization of the impact of CFC emissions on the ozone layer has prompted international agreements that led to the ban of CFCs and the establishment of time-scales for the phase-out of HCFCs. Even though new refrigerants, namely HFCs, have been developed with zero ozone depletion potential, these refrigerants invariably have high ozone depletion potential (GWP) and make significant contributions to greenhouse gas emissions both directly through refrigerant leakage and indirectly through emissions from power stations that generate the electrical energy required to drive them. Recent concerns about the impact of refrigerant leakage on global warming have prompted the introduction of the F-gas regulations by the European Union that are designed to contain and prevent emissions of fluorinated gases. F-gases include all HFC refrigerants, such as R134a, and blends containing F-gases such as R407C, R410A, R404A. [1]. Some European countries such as Denmark have gone further than the EU regulations and imposed restrictions on the quantity of HFC refrigerants that can be used in commercial and industrial refrigeration systems [2].

Since the early development of vapour compression refrigeration systems, ammonia has been used extensively in food processing and for cold storage due its low cost and high efficiency. Reciprocating and screw compressors are predominantly used in ammonia refrigeration plants. New systems will invariably employ some form of capacity control to match the compressor capacity to the load and improve system efficiency. With reciprocating compressors, capacity control is normally achieved by cylinder unloading of individual compressors, multiple compressor on–off cycling and/or variable speed control on a lead compressor. With semi-hermetic compressors capacity variation can be achieved by sliding vane control or variable speed control or a combination of the two. Plate heat exchangers are commonly used with ammonia because of their higher effectiveness and ability to operate with smaller temperature differences between the refrigerant and the process fluid and lower refrigerant charge compared to shell and tube designs. For large refrigeration capacities and energy efficiency, evaporative condensers are employed. Other energy efficiency measures that are or can be applied include head (condenser) pressure control in response to variation in ambient temperature with condenser fan on–off switching or variable speed fan control. Overall processing plant energy efficiency may also be improved through heat recovery from the ammonia compressor discharge gas and the use of heat pumps to raise the condenser heat to higher temperature and use it for process heating.

With the phase-out of R22, which together with ammonia was a popular refrigerant in food processing, R404A is now commonly used in place of R22 in smaller size refrigeration equipment, below 200–300 kW cooling capacity. Compressors will normally be of the reciprocating semi-hermetic type with air cooled condenser heat rejection. Energy efficiency design features as with ammonia plant may include compressor capacity control and head pressure control. Other approaches incorporated in the ‘Hy-save’ system are liquid pressure amplification and compressor discharge gas desuperheating through liquid injection [3].

Commercial refrigeration systems employed in retail food applications invariably use multi-compressor refrigeration packs or racks with air cooled condensers serving distributed evaporator coils in the cold rooms and refrigerated display cabinets in the sales area of the store. Modern systems in the UK normally use scroll compressors and R404A refrigerant. Capacity control is achieved through compressor on–off cycling and in some cases variable speed on the lead compressor. Head pressure control is now becoming a standard feature on new systems. The desire to reduce GHG emissions from refrigerant leakage systems has prompted the development and application of alternative system designs which employ secondary refrigerants as well as natural refrigerants such as CO_2, ammonia and hydrocarbons. These systems and energy conservation approaches in food retail refrigeration systems are described in detail in a paper by Tassou and Ge [4].

The retail food industry also uses a vast number of self contained ‘integral’ refrigerated display cabinets. These cabinets normally use reciprocating or rotary compressors. R404A is the predominant refrigerant but other refrigerants such as R134A, R407C and hydrocarbons are also extensively employed. Energy conservation approaches include the use of more efficient components, and the reduction of the refrigeration load through the minimisation of ambient air infiltration into the refrigerated space [4].

Transport refrigeration also relies exclusively on the vapour compression cycle. A description of transport refrigeration technologies, their environmental impacts and approaches to reduce their energy consumption are discussed in detail in Ref. [5].

Although the vapour compression cycle is well established in food refrigeration, the rising cost of electricity and pressure to reduce the environmental impacts and carbon footprint of food operations has renewed interest in thermally driven technologies and the development of new and innovative technologies that could offer both economic and environmental advantages over the conventional vapour compression cycle in the future. This paper provides a brief review of these technologies. Each review covers the principle of operation, the current state of development, application in the food sector, barriers to the uptake of the technology, key divers to encourage uptake and research and development needs.

2. Sorption refrigeration–adsorption systems

2.1. 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. Fig. 1 shows a schematic diagram of an adsorption chiller. It consists of two chambers and an evaporator and a condenser. Each chamber contains the adsorbent, for example silica-gel in a silica-gel water system, and a heat exchanger. The evaporator and condenser are connected to both chambers through a series of valves.

In one cooling cycle the following processes take place. In the adsorption phase the adsorption bed is linked to the evaporator and refrigerant is adsorbed in the bed at low temperature and pressure. When the bed becomes saturated with refrigerant, it is isolated from the evaporator and connected to the condenser and heat is applied to it, normally through hot water, to desorb the refrigerant. The resulting high pressure and temperature refrigerant vapour then flows to the condenser where it condenses and releases heat to a cooling medium. The condensate is then expanded and sprayed on the evaporator at low pressure and temperature where it evaporates and produces the refrigeration effect. The resulting vapour is then adsorbed in the adsorber for the repetition of the cycle.

Adsorption systems inherently require large heat transfer surfaces to transfer heat to and from the adsorbent materials which automatically makes cost an issue [6,7]. 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 [8].

2.2. State of development

Adsorption 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 [9]. NISHIYODO

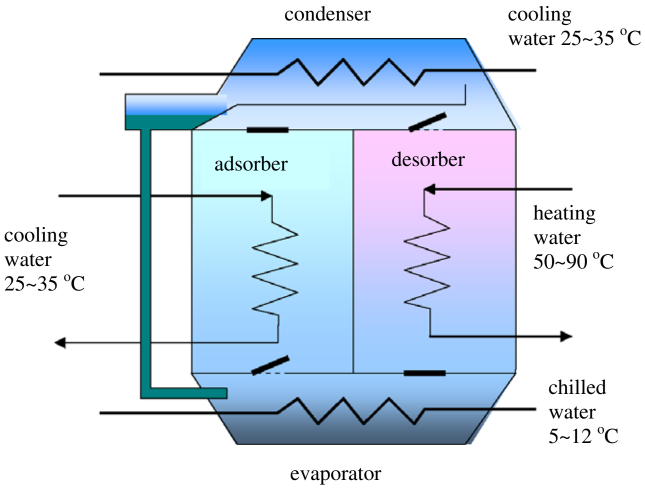

Fig. 1. Schematic diagram of adsorption refrigeration system.

KUCHOUKI CO. LTD, produce silica-gel/water adsorption chillers (ADCM models) with capacities between 70 and 1300 kW capable of being driven by low grade heat 50–90 °C and able to give COPs of around 0.7 [10]. 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 [11–13].

2.3. 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.

2.4. 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 °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.

2.5. 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.

2.6. 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 °C. This will require further development of working pairs (fluid and bed).

3. Ejector refrigeration systems

3.1. Description of technology

Ejector or jet pump refrigeration is a thermally driven technology that has been used for cooling applications for many years. In their present state of development they have a much lower COP than vapour compression systems but offer advantages of simplicity and no moving parts. Their greatest advantage is their capability to produce refrigeration using waste heat or solar energy as a heat source at temperatures above 80 °C.

Referring to the basic ejector refrigeration cycle and T–s diagram in Fig. 2, the system consists of two loops, the power loop and the refrigeration loop. In the power loop, low grade heat, Q_b, is used in a boiler or generator to evaporate high pressure liquid refrigerant (process 1–2). The high pressure vapour generated, known as the primary fluid, flows through the ejector where it accelerates through the nozzle. The reduction in pressure that occurs induces vapour from the evaporator, known as the secondary fluid, at point 3. The two fluids mix in the mixing chamber before entering the diffuser section where the flow decelerates and pressure recovery occurs. The mixed fluid then flows to the condenser where it is condensed rejecting heat to the environment, Q_c. A portion of the liquid exiting the condenser at point 5 is then pumped to the boiler for the completion of the power cycle. The remainder of the liquid is expanded through an expansion device and enters the evaporator of the refrigeration loop at point 6 as a mixture of liquid and vapour. The refrigerant evaporates in the evaporator producing a refrigeration effect, Q_e, and the resulting vapour is then drawn into the ejector at point 3. The refrigerant (secondary fluid) mixes with the primary fluid in the ejector and is compressed in the diffuser section before entering the condenser at point 4. The mixed fluid condenses in the condenser and exits at point 5 for the repetition of the refrigeration cycle.

3.2. State of development

The first steam ejector refrigeration system was developed by Maurice Leblanc in 1910 and gained in popularity for air

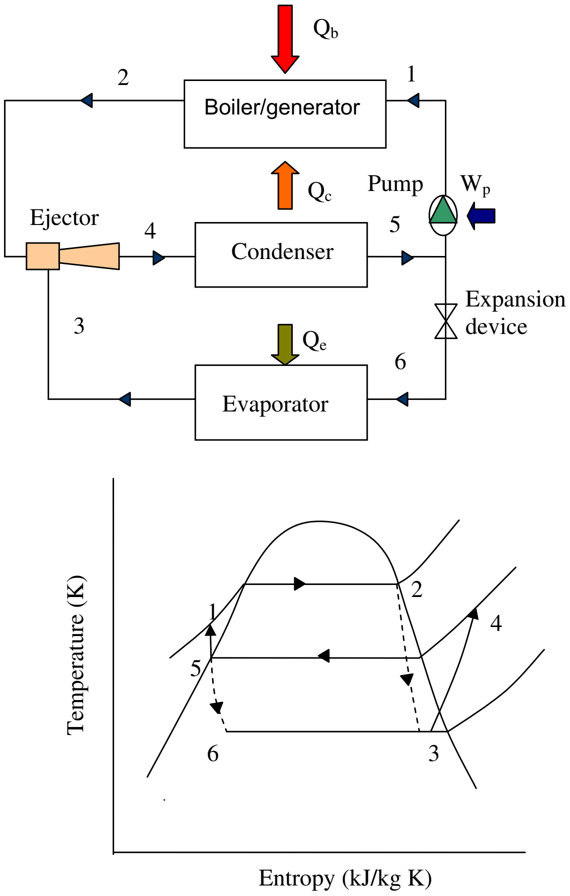

Fig. 2. Schematic and T–s diagram of ejector refrigeration system.

conditioning applications until the development of chlorofluorocarbon refrigerants in the 1930s and their use in the vapour compression cycle which was much more efficient than alternative thermally driven cycles. Research and development continued however and the ejector technology found applications in many engineering fields particularly in the chemical and process industries [14–17]. Systems have been developed with cooling capacities ranging from a few kW to 60,000 kW but despite extensive development effort the COP of the system, which can be defined as the ratio of the refrigeration effect to the heat input to the boiler, if one neglects the pump work which is relatively small, is still relatively low, less than 0.2. Ejector refrigeration systems are not presently commercially available off the shelf but a number of companies specialise in the design and application of bespoke steam ejector systems that use water as a refrigerant for cooling applications above 0 °C.

To improve the efficiency of the simple ejector cycle more complex cycles have been investigated [18] as well as the integration of ejectors with vapour compression and absorption systems. An example of this is the Denso transport refrigeration system [19]. Significant effort has also been devoted to the development of solar driven ejector refrigeration systems [20].

3.3. Applications in the food sector

Applications in the food sector will be primarily in areas where waste heat is available to drive the ejector system. Such applications can be found in food processing factories where the ejector refrigeration system can be used for product and process cooling and transport refrigeration. Other possible application is in tri-generation where the ejector refrigeration system can be used in conjunction with combined heat and power systems to provide cooling.

3.4. Barriers to uptake of the technology

The main barriers to uptake of ejector refrigeration technology are:

- lower COPs, 0.2–0.3, compared to vapour compression systems and other thermally driven technologies. The COP also drops significantly at operation away from the design point,
- unavailability of off the shelf systems to facilitate selection for particular applications and lack of performance data from commercial applications to provide confidence in the application of the technology.

3.5. 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.

3.6. Research and development needs

To increase the attractiveness and application of ejector refrigeration systems research and development is required to:

- increase the efficiency of steady flow ejectors particularly at operation away from the design point,
- develop alternative ejector types, such as rotodynamic ejectors [21] that offer potential for higher efficiencies,
- develop ejectors that can operate with other natural refrigerants apart from water, such as CO_2 and hydrocarbons, to extend the range of applications to below 0 °C,
- research into the optimisation of cycles and the integration of ejectors with conventional vapour compression and absorption systems.

4. Air cycle refrigeration

4.1. Description of technology

Air cycle systems 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. In practice the basic reversed Joule (or Brayton) cycle is modified by including regenerative heat exchange and, in some systems, multi-stage compression with intercooling as illustrated in Fig. 3.

Air cycles can be classified as closed, open or semi-open/closed [22]. 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

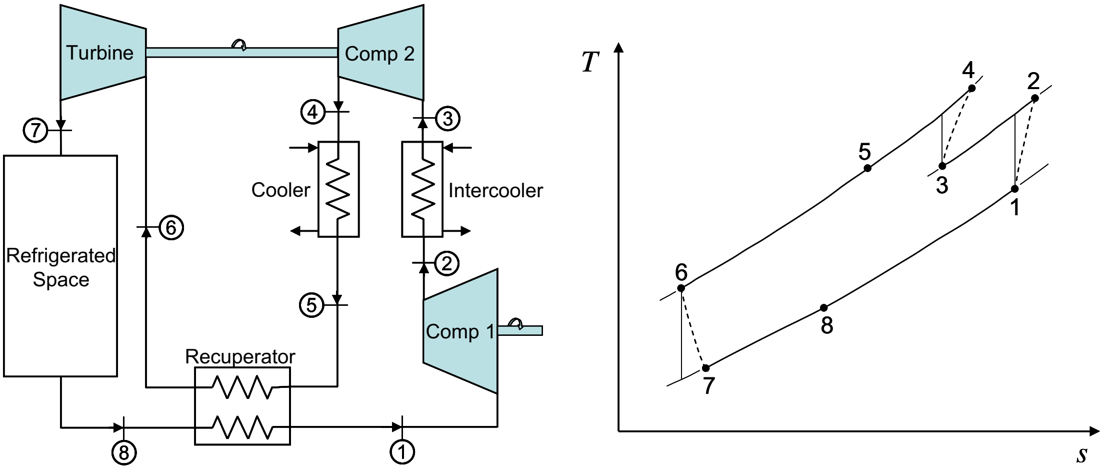

Fig. 3. Air cycle with regenerative heat exchange and two-stage compression with intercooling.

from the refrigeration load. Open cycles are open to the atmosphere on either the low-pressure side or the high-pressure side of the cycle and the cooled air passes directly through the refrigerated space. Semi-open/closed cycles are also open to the refrigerated space, but the air is then drawn back through the low-pressure side of the regenerator to the compressor.

4.2. State of development

Air cycle refrigeration is an environmentally friendly and reasonably well established, albeit under-exploited, technology. Plant and component operating characteristics are understood and issues such as condensation and icing have been addressed and solutions developed. Air cycle plants 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 or semi-open/closed systems [23–25]. Information on coefficient of performance for air cycle refrigeration systems is sparse but most values quoted are in the range 0.4–0.7. Furthermore, the efficiency of air cycle systems is relatively unaffected under part-load conditions.

4.3. Applications in the food sector

Air cycle refrigeration can deliver air temperatures down to −100 °C or below, giving it a niche position in the −50 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 can 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.

Air cycle technology has been evaluated for food sector applications including rapid chilling and/or freezing (including air blast, tunnel, spiral, fluidised bed and rotary tumble equipment); cold storage, refrigerated storage cabinets, refrigerated transport (trucks, containers, rail freight); and for integrated rapid heating and cooling (cook–chill–freeze or hot water/steam raising and refrigeration) [26–28].

4.4. 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.

4.5. Key drivers to encourage uptake

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

- 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.

4.6. Research and development needs

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

- successfully demonstrate the benefits of the technology in specific promising applications, such as: combined refrigeration and cooking/heating and transport refrigeration,
- 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.

5. Tri-generation

5.1. Description of technology

Tri-generation is a technology that can simultaneously provide three forms of output energy; electrical power, heating and cooling. Tri-generation is also known as CCHP (Combined Cooling, Heating and Power) or CHRP (Combined Heating, Refrigeration and Power) [29,30]. In essence, tri-generation 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 (Fig. 4).

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. Tri-generation systems can have overall efficiencies as high as 90% compared to 33–35% for electricity generated in central power plants.

5.2. State of development

Tri-generation systems have been in operation for many years [30]. 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

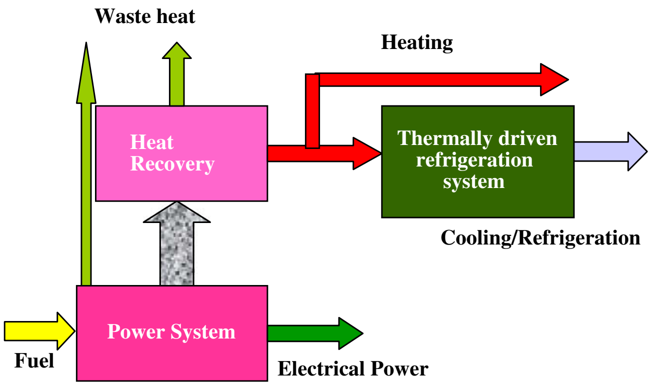

Fig. 4. Schematic of a tri-generation system.

[31] and (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 [32].

5.3. Applications in the food sector

There are a number of examples of application of tri-generation plants in the food industry [33]. 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 [30]. More recently, application of tri-generation 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.

5.4. 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 °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 tri-generation system. This makes it difficult to project energy savings accurately.

5.5. 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.

5.6. Research and development needs

To increase the attractiveness and application of tri-generation 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 °C,
- develop design, and integration strategies for tri-generation system components,
- develop strategies and controls for the optimum integration of tri-generation systems with other power and thermal systems for applications in food manufacturing, retail and storage facilities.

6. Stirling cycle refrigeration

6.1. Description of technology

The Stirling cycle cooler is a closed-cycle regenerative thermal machine [34]. Fig. 5 illustrates an idealized implementation of a Stirling refrigeration cycle in a β-type piston–displacer configuration. The piston alternately compresses and expands the working gas, while the displacer shuttles gas back and forth between the cold end, where heat is absorbed, and the warm end, where heat is rejected. In reality, the movements of the reciprocating components are continuous and maintain the correct phase relationship between the pressure oscillation and the cyclic variation of the gas space volumes. The heat pumping effect is sustained by net work input to the system at the piston. Stirling cycle cooler designs are categorized as kinematic machines, where the piston and displacer are mechanically linked to the drive shaft, or free-piston machines, where the piston is coupled to the power supply by an AC linear motor and the displacer motion is driven by the gas pressure fluctuation in the system.

6.2. State of development

Commercial exploitation of Stirling cycle cooling technology effectively began in the mid-1950s when the Philips Company introduced their first Stirling cycle air liquefier. Philips subsequently produced a variety of kinematically driven cryocooling machines with a wide range of capacities for low temperature refrigeration and gas liquefaction. In 1990, the cryogenerator technology developed by Philips was used to establish Stirling Cryogenics & Refrigeration BV, a company specializing in Stirling cycle cooling systems, including stand-alone liquid nitrogen production plants, with capacities up to 150 l/h, used to supply LN_2 for industrial food freezing.

The past two decades has seen the appearance of free-piston Stirling cryocoolers and free-piston Stirling coolers (FPSCs) for higher temperature applications. Development and commercialisation of the free-piston cooling technology originated at Sunpower is now led by Global Cooling for applications above 150 K [35,36]. Their compact, helium filled (to 20–30 atm), hermetically sealed FPSCs employ a moving magnet linear motor and feature gas bearings. Nominal maximum cooling capacities range from 40 to 150 W, with larger capacity units up to 600 W reported to be under development. Furthermore, a wide range of capacity modulation is possible without major efficiency loss by varying the drive voltage and hence the piston amplitude. Global cooling and appliance manufacturers have experimented with the integration of FPSCs into domestic and portable refrigerators and freezers as well as a beverage can vending machine [37,38]. External heat exchangers are fitted to the cold and warm heads to facilitate heat absorption from the refrigerated space and heat rejection to ambient, respectively. FPSC based products, including freezer boxes and a system for the marine refrigeration market, have been developed by licensees [39]. Measured COP values reported for FPSCs operating with warm head temperatures close to 30 °C are typically between 2 and 3 for cold head temperatures around 0 °C, falling to around 1 for temperatures approaching −40 °C [37].

6.3. Applications in the food sector

Stirling cycle cooling equipment can operate down to cryogenic temperatures and hence can be used in many food refrigeration applications. Current limitations are the low cooling capacities, and the lower COP and higher cost compared to vapour compression

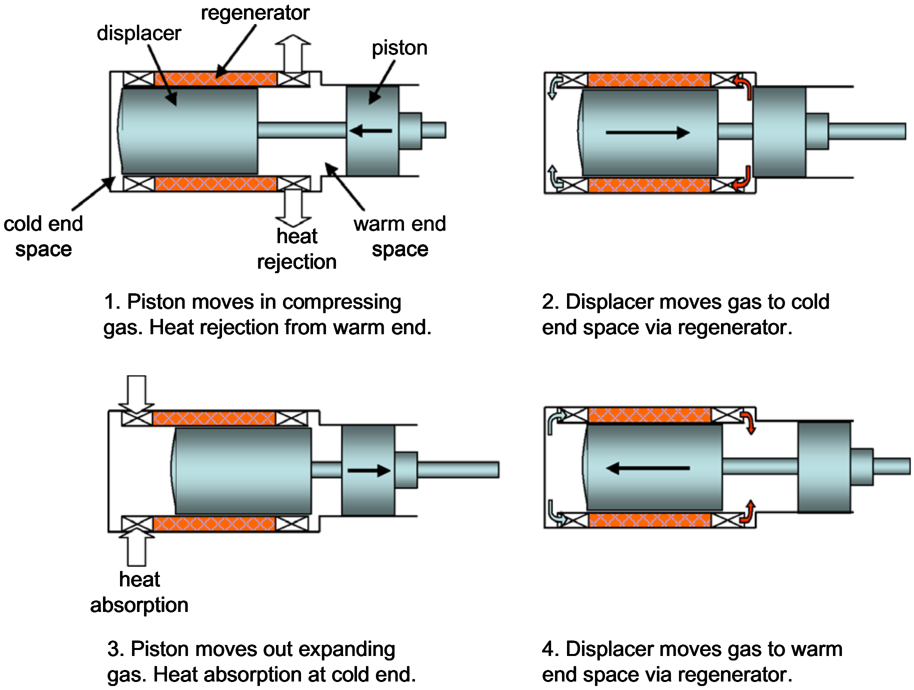

Fig. 5. Piston and displacer movements during a Stirling refrigeration cycle.

refrigeration. The market for FPSCs in the food sector is likely to be domestic and portable refrigerators and freezers and other integral refrigerated display equipment. Other possible applications of Stirling coolers are in food processing such as butter churning [40].

6.4. Barriers to uptake of the technology

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

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

6.5. Key drivers to encourage uptake

The main drivers to encourage uptake of the Stirling cycle 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.

6.6. Research and development needs

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

- development of units with increased cooling capacity and improved component designs, including linear motors, to increase efficiencies,
- improved heat exchange and better system integration to reduce temperature differences on the cold and warm sides.

7. Thermoelectric refrigeration

7.1. Description of technology

Thermoelectric cooling devices utilize the Peltier effect, which causes the junction of two dissimilar conducting materials to either cool down or warm up when a direct electric current passes through the junction, depending on the direction of the current.

Fig. 6 shows a pair of adjacent thermoelement legs joined at one end by a conducting metal strip to form a junction. 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 thermoelement 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). When a DC voltage is applied, as shown in Fig. 6, the junction experiences a temperature decrease, to T_c, accompanied by absorption of thermal energy from the cold side as electrons moving from

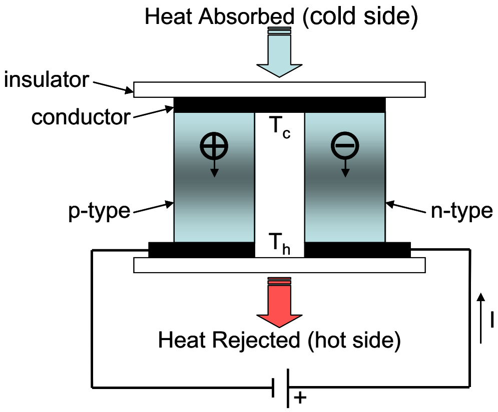

Fig. 6. Thermoelectric cooling (or Peltier) couple.

the p-type material to the n-type material jump to a higher energy level. The majority charge carriers transport the absorbed energy through the thermoelements to the hot side, at T_h, where heat is rejected as the electrons return to a lower energy level.

Thermoelectric cooling modules contain multiple thermoelectric couples connected in series, sandwiched between electrically insulating, but thermally conductive, substrates. As solid state devices they have no moving parts and, consequently, are highly reliable and virtually maintenance free. Further advantages include the absence of noise and vibration, the compactness and low weight construction, and the capacity for precise temperature control.

7.2. State of development

Thermoelectric modules are available to suit a wide range of small and medium cooling duties. Manufacturers' lists, for example [41], include single-stage modules with maximum cooling capacities from less than one watt up to 310 W. Module sizes range from a few millimetres square up to 62 mm × 62 mm and number of thermoelectric couples per module from less than 10 to 241. Module thicknesses are normally between 2 and 5 mm.

Almost all commercially produced modules use n-type and p-type thermoelements cut from bismuth telluride (Bi_2Te_3) based bulk materials, which are presently the best available for near room temperature operation and give a dimensionless figure of merit close to unity ($ZT \sim 1$). The maximum COP for a single-stage module is, however, limited to approximately 10% of the corresponding reversed Carnot cycle efficiency and a maximum temperature difference of around 70 K can be obtained. To achieve efficiencies comparable with vapour compression systems would require a material with a ZT of about 4. Research on ZT enhancement is directed towards reducing lattice thermal conductivity and includes preparation of new bulk materials with more favourable properties and fabrication of quantum thermoelectric structures [42].

In thermoelectric refrigeration applications the cooling module (or modules) must be interfaced with cold side and hot side heat exchange systems. The associated thermal resistances and power consumption can significantly influence the overall system coefficient of performance. A variety of heat transfer technologies, including air-cooled heat sinks, liquid-cooled microchannel heat sinks and systems involving heat pipes or two-phase thermosyphons, covering a wide range of heat flux capability, have been developed that help minimize the temperature difference across the thermoelectric module, and hence maintain efficiency [43,44].

7.3. Applications in the food sector

Thermoelectric cooling has been extensively applied in numerous fields, handling cooling loads from milliwatts up to tens of kilowatts in systems using multiple modules in parallel, and temperature differences from almost zero to over 100 K with multistage modules [45].

Thermoelectric cooling products available for the food sector include compact refrigerators (15–70 l) for hotel rooms (mini bar), mobile homes, trucks, recreational vehicles and cars; wine coolers; portable picnic coolers; beverage can coolers and drinking water coolers [46]. Prototype domestic refrigerators of larger capacity (115 l and 250 l) have been built and tested, achieving COPs up to 1.2 [47]. In addition, an overall COP of 0.44 was measured for a prototype 126 l refrigerator–freezer [48].

7.4. Barriers to uptake of the technology

The main barriers to the uptake of thermoelectric refrigeration are:

- lower efficiency than vapour compression technology,
- thermoelectric cooling modules are widely available but, apart from small capacity items, packaged thermoelectric refrigeration systems are not as yet available.

7.5. 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.

7.6. Research and development needs

Increased application of thermoelectric cooling in the food sector will require a significant improvement of COP to make it competitive with vapour compression technology. Principally, new thermoelectric materials or structures are needed with much higher figures of merit than currently achieved with established Bi_2Te_3 based bulk materials. Further work is also required to improve the performance and integration of heat exchange systems on both the hot and cold sides, to reduce module temperature differentials.

8. Thermoacoustic refrigeration

8.1. 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 characterized as either 'standing-wave' or 'travelling-wave' [49]. A schematic diagram of a standing-wave device is shown in Fig. 7.

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 [50].

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, Fig. 8.

8.2. State of development

A number of design concepts and prototypes are under development in many research establishments. The technology has the

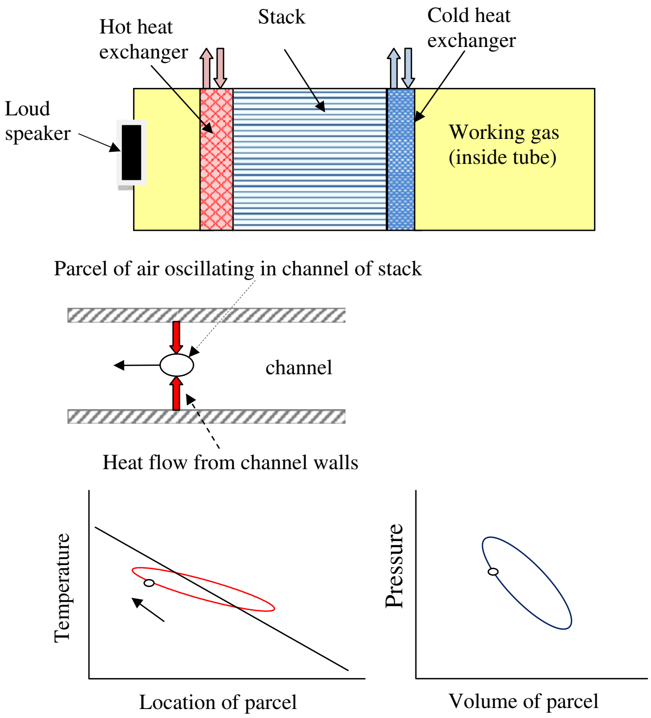

Fig. 7. Sound wave thermoacoustic refrigerator.

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.

8.3. 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 initially be in the low capacity equipment such as domestic and commercial refrigerators, freezers and cabinets.

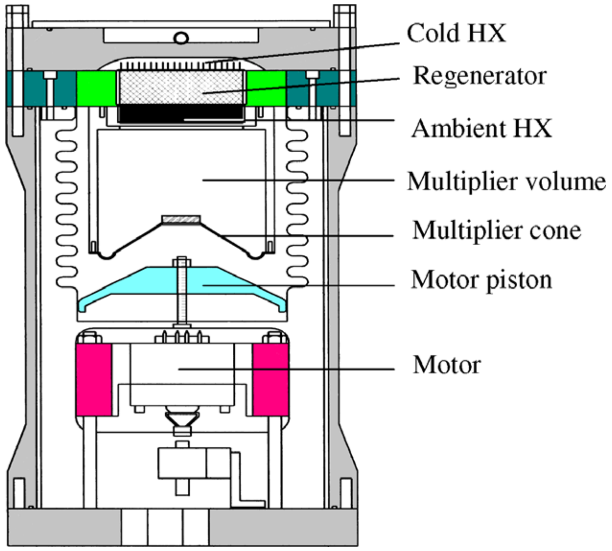

Fig. 8. Travelling wave thermoacoustic device (Ben & Jerry ice-cream cabinet [51]).

8.4. 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.

8.5. Key drivers to encourage uptake

The main drivers to encourage uptake of thermoacoustic technology once they become commercially available 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 and availability of systems that offer efficiency and cost advantages over vapour compression systems.

8.6. 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.

9. Magnetic refrigeration

9.1. Description of technology

Magnetic refrigeration is based on the magnetocaloric effect (MCE), a basic property of magnetic solids characterized by a reversible temperature rise when a magnetic field is applied adiabatically. The MCE peaks around the magnetic ordering (or Curie) temperature [52].

Magnetic refrigeration systems being developed for near room temperature applications mainly operate on the active magnetic regenerator (AMR) cycle, in which the magnetocaloric material functions simultaneously as the refrigerant and as the regenerator bed. A heat exchange fluid, usually a water-based solution, is forced in alternate directions through the porous AMR bed in sequence with periodic application and removal of the magnetic field, as illustrated in Fig. 9 [53]. The fluid links the magnetocaloric material with the cold and hot heat exchangers, establishing a temperature gradient along the AMR, thus allowing a useful source-to-sink temperature span to be generated which is exceeds the intrinsic adiabatic temperature rise. Improved performance can be achieved by employing a layered AMR composed of a number of different magnetocaloric materials with progressively increasing Curie temperatures arranged accordingly along the bed [54–56]. Net work input to the system is required to move the magnetic field relative to the magnetic material and for fluid pumping.

Magnetization and demagnetization of the magnetic refrigerant can be likened to compression and expansion in a vapour compression cycle but, in contrast, the magnetic processes are virtually loss free. Further advantages associated with solid-state

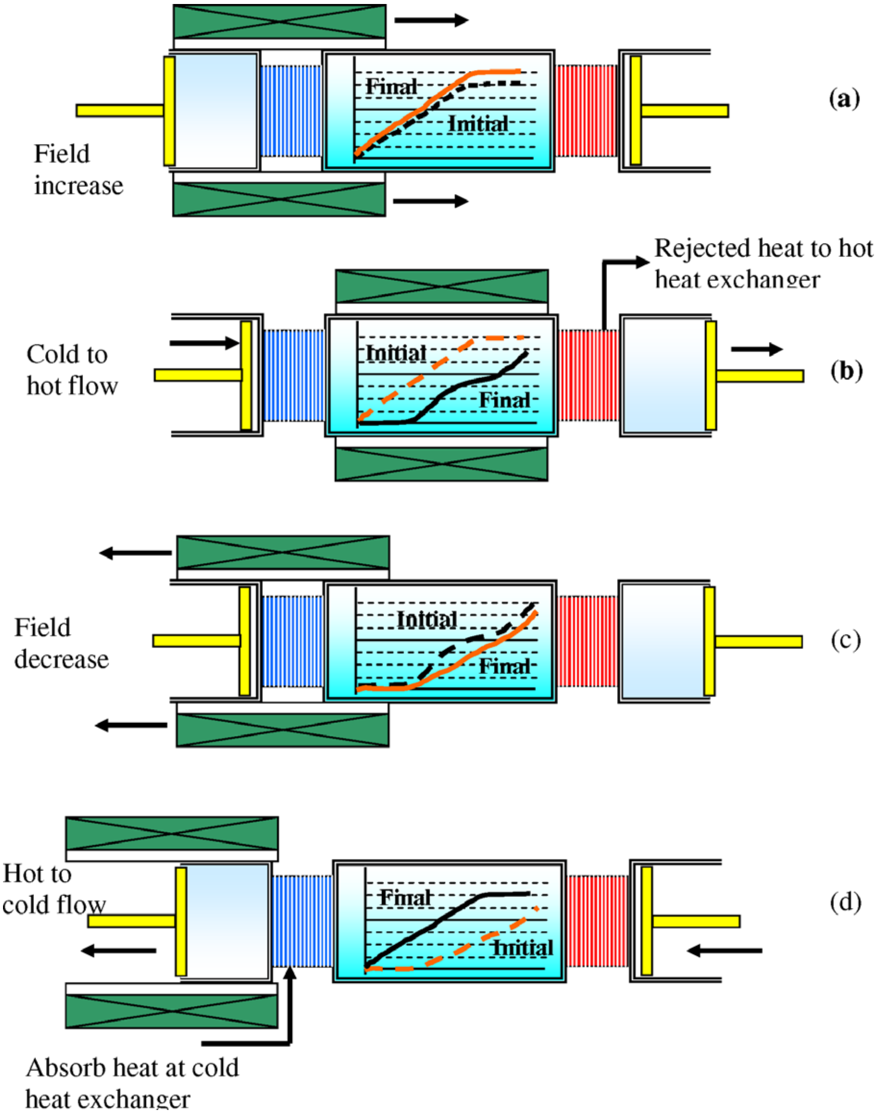

Fig. 9. Active magnetic regeneration cycle (from Russek and Zimm [53]).

refrigerants are the absence of vapour pressure, resulting in zero ODP and zero GWP, and a large magnetic entropy density, the key thermodynamic property determining the magnitude of the MCE [53,55].

9.2. State of development

The magnetocaloric effect has been exploited for cooling to deep cryogenic temperatures (<1 K) since the 1930s and is also used for gas liquefaction. The feasibility of using magnetic refrigeration at temperatures near to room temperature was first demonstrated in 1976, and research in this area has intensified at an increasing rate over the subsequent 30 years [56]. Continuing efforts are being made to search for and characterize new and better magnetic refrigerant materials with a range of magnetic ordering temperatures. Investigations in this area cover both conventional MCE materials, such as gadolinium, that undergo a second-order magnetic transition and advanced alloys that exhibit a giant MCE associated with a first-order magnetic-structural transition [57,58]. Significant progress has also be made during the past decade by teams in North America, the Far East and Europe with the design and realization of magnetic refrigeration systems and a number of AMR refrigerator prototypes (including both reciprocating and rotating designs) have been announced [59–61]. The more recent prototypes generally employ permanent magnet based field sources and the cooling capacities achieved are low. The maximum reported to date is 540 W, with a COP of 1.8, at a temperature span of 0.2 K and a hot end temperature of 21 °C [61].

Further research and development will be required before commercially viable magnetic refrigeration systems are produced for the market. It was recently estimated that the introduction of this new technology will reach the commercialisation stage around 2015 [56].

9.3. Potential application to the food sector

Although relatively little attention has been paid to specific future applications of magnetic refrigeration, it is evident that this technology has the potential for use across the food refrigeration temperature range, from near room temperature operation down to cryogenic temperatures. It is anticipated that the first commercial applications will be for low capacity stationary and mobile refrigeration and freezing systems.

9.4. Barriers to uptake of the technology

The main barriers to the uptake of magnetic refrigeration technology are:

- near room temperature refrigeration systems operating on the magnetocaloric effect are not yet commercially available,
- in their present state of development, the overall performance of prototype magnetic refrigerators does not match that of vapour compression systems, in terms of cooling power, temperature span and coefficient of performance. Albeit they have the potential to achieve higher energy efficiencies.

9.5. Key drivers to encourage uptake

The main drivers to encourage uptake of magnetic refrigeration technology in the food sector once it becomes commercially available 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,
- environmentally safe and compact refrigeration systems that offer the prospect of significant efficiency, and cost advantages over vapour compression systems.

9.6. Research and development needs

The requirement of prime importance is the identification and development of new magnetic refrigerant regenerator materials exhibiting strong MCEs. Candidate materials must also be evaluated against a number of other factors including problems of temperature hysteresis and adiabatic temperature rise time delay, large scale production and fabrication considerations (including associated costs), environmental concerns, friability and compatibility with heat exchange fluids. Further work is also needed on the development of permanent magnet arrays and magnetic field design to increase the applied magnetic field, minimize the amount of magnet material required and reduce the costs. Developments are also required in the design and operation of magnetic regenerators to improve heat transfer between the heat transfer fluid and the solid refrigerant, reduce pressure drops and minimize heat leakages, and to optimize the flow rate of the heat exchange fluid and the operating frequency.

10. Summary and conclusions

The food industry relies heavily on the vapour compression refrigeration cycle for food preservation and processing. To reduce the environmental impacts of vapour compression systems that employ HCFCs and HFCs as refrigerants a number of alternative systems and technologies are being developed that offer the potential for lower GHG emissions. This section summarises approaches and future technologies that could be used to reduce the energy consumption and GHG emissions associated with the refrigeration of food. The characteristics and likely future applications of these technologies are summarised in Table 1.

10.1. Transport refrigeration

In transport refrigeration there are opportunities to reduce thermal loads through better insulation materials such as vacuum insulation, and the size and energy use of the refrigeration system on the truck through thermal energy storage based on phase change materials (PCMs) that can be charged at base. Ice slurries are also under consideration for thermal storage in chilled distribution. Total loss systems (cryocoolers) are also been re-evaluated as a replacement for vapour compression systems. Other possible systems include air cycle, hybrid and solar powered systems. Magnetic refrigeration also offers potential for the future. Where greatest potential exists, though, is in the recovery of thermal energy from the engine exhaust and its use to drive sorption systems, ejector systems, thermoacoustic refrigerators and or/for power generation using thermoelectrics or turbogenerators.

10.2. Integral refrigeration equipment (cabinets)

Hydrocarbons are already being used as a replacement refrigerant for HFCs in many integral refrigerated cabinets. CO_2 systems have also been developed and a small number of integral CO_2 cabinets are now in service. Stirling cycle coolers are already commercially available and reduction in cost accompanied by efficiency improvements can make them serious contenders for cabinet

Table 1
Characteristics and applications of emerging refrigeration technologies.

Technology	State of development	Cooling/refrig. capacity of presently available or R&D systems	Efficiency/COP of presently available or R&D systems	Current/potential application area(s)
Tri-generation	Large capacity bespoke systems available. Smaller capacity integrated systems at R&D stage	12 kW–MW	Overall system efficiency 65–90%. Refrig. system COP: 0.3 at −50 °C 0.5 at −12 °C	Food processing; cold storage; food retail
Air cycle	Bespoke systems available	11kW–700 kW	0.4–0.7	Food processing; refrigerated transport
Sorption–adsorption	Available for cooling applications >0 °C. Systems for refrigeration applications at R&D stage	35 kW–MW	0.4–0.7	Food processing; cold storage; retail; refrigerated transport
Ejector	Bespoke steam ejector systems available	Few kW to 60 MW	Up to 0.3	Food processing; refrigerated transport
Stirling	Small capacity 'Free' piston systems available. Larger systems at R&D stage	15–300 W	1.0–3.0	Domestic refrigerators, vending machines, refrigerated cabinets
Thermoelectric	Low cost low efficiency systems available	Few Watts to 20 kW	0.6 at 0 °C	Hotel room mini bar refrigerators, refrigerators for trucks, recreational vehicles; portable coolers; beverage can coolers
Thermoacoustic	R&D stage. Predicted commercialisation: 5–10 years.	Few watts to kW capacity	Up to 1.0	Domestic and commercial refrigerators, freezers and cabinets
Magnetic	R&D stage. Predicted commercialisation 10 plus years from now	Up to 540 W	1.8 at room temperature	Low capacity stationary and mobile refrigeration systems

refrigeration systems. Other candidate technologies approaching commercialisation are thermoelectric and thermoacoustic refrigeration. Magnetic refrigeration is also a candidate technology but its commercialisation is further downstream and placed approximately 10 years from now.

10.3. Supermarket refrigeration systems

The environmental impacts of supermarket refrigeration systems can be reduced through the improvement of equipment efficiencies, reduction in the refrigerant charge and reduction or elimination of refrigerant leakage. There are also opportunities for thermal integration of refrigeration and HVAC systems and the application of CHP and tri-generation technologies. CO_2 based systems are also making inroads into the UK commercial refrigeration market and a number of different system configurations are currently being trialled. CO_2 systems on their own or in a cascade arrangement with hydrocarbon (HC) or ammonia (R717) systems are likely to become the dominant supermarket refrigeration technology in the future.

10.4. Food processing

Ammonia vapour compression systems are dominant in food processing. Plant energy savings can be achieved through improvements in component design and control and heat recovery. Possible system alternatives include CO_2 systems and CO_2/R717 cascade systems. Air cycle technology offers potential for low temperatures, below $-50\,^{\circ}C$ and for combined heating and cooling. Other possible approaches include the recovery and use of waste heat for refrigeration through sorption and ejector systems and for power generation (thermoelectric, Stirling, thermoacoustic, turbogenerators). There may also be possibilities for the use of biomass which may be a bioproduct of food processing for CHP and tri-generation.

10.5. Food storage (cold stores)

Large food storage facilities normally employ ammonia vapour compression plant and it is likely that this will continue in the future. Another possibility that offers heat recovery potential is the use of CO_2 as a refrigerant on its own or in combination with ammonia in a CO_2/R717 cascade arrangement. Because of their location, normally in sparsely populated areas, food storage facilities offer potential for the use of biomass for combined heat and power or for tri-generation. A small number of such plants is already in operation. Large food storage facilities also offer potential for the use of wind power and solar energy to generate electricity to drive vapour compression equipment and/or heat for sorption systems.

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