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REVIEW ARTICLE

Refrigeration technologies in food industries: a review

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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.

Keywords: Sorption refrigeration, adsorption systems, Ejector refrigeration, Air-cycle refrigeration, Trigeneration, Thermoelectric

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INTRODUCTION

In industrialized 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.This 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.

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Since the emergence of chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants in the 1930's the vapour compression refrigeration cycle has gained dominance over alternative cooling technologies in all areas of food manufacturing, distribution and retail. In the 1980's, increased environmental awareness and the realisation 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. This article provides a brief review of these technologies and their potential for application in the food sector.

SORPTION REFRIGERATION – ADSORPTION SYSTEMS

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 (Bansal, et al., 2000).

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 are already commercially available for air conditioning applications from a small number of manufacturers with capacities between 70kW and 1300kW capable of being driven by low grade heat 50 – 90°C and able to give COPs of about 0.71. 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 development2. Applications in the food sector will primarily be in areas where waste heat is available to drive the adsorption system. Such applications can be found in food factories and transport refrigeration. Another possible application is in tri-generation where adsorption systems can be used in conjunction with combined heat and power systems to provide refrigeration (Lu et al., 2006).

Adsorption systems inherently require large heat transfer surfaces to transfer heat to and from the adsorbent materials which automatically makes cost an issue (Ziegler, 2002 and Critoph et al., 2004). 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 (Yong et al., 2007).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 further requires development of working pairs of fluid and bed (Tassou et al., 2010).

EJECTOR REFRIGERATION SYSTEMS

Ejector or jet pump refrigeration is a thermally driven technology that has been used for cooling applications for many years. Their greatest advantage is their capability to produce refrigeration using waste heat or solar energy as a heat source at temperatures above 80°C. Systems have been developed with cooling capacities ranging from a few kilowatts to 60 MW but despite extensive development efforts, the COP of the system, which can be defined as the ratio of the refrigeration effect to the heat input to the boiler, is still relatively low at less than 0.2. Applications in the food sector will primarily be 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.

Applications in the food sector are 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.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 (Hong et al., 2004) 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 below0^{o}C. Further research into the optimisation of cycles and the integration of ejectors with conventional vapour compression and absorption systems is also required (Tassou et al., 2010).

AIR CYCLE REFRIGERATION

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. In practice the basic reversed Joule (or Brayton) cycle is modified by including regenerative heat exchange and, in some systems, multistage compression with intercooling.

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 300kW for open systems (Kikuchiet al., 2005). Information on the coefficient of performance for refrigeration is sparse but most values quoted are in the range between 0.4 to 0.7. It is also noted that the efficiency of air cycle systems is relatively unaffected under part load conditions.

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 a vapour compression plant. 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 and for integrated rapid heating and cooling (Spence et.al., 2005 and Evans et al., 2006)**.**Air cycle refrigeration can deliver air temperatures down to -100°C or below, 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 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 including cook-chill-freeze or hot water/steam raising and refrigeration (Spence et al., 2005).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, and develop component sizing, integration and control strategies for specific applications to increase system efficiency at reasonable cost (Tassou et al., 2010).

TRIGENERATION

Tri-generation is a technology that can simultaneously provide 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 (Maidment et al., 2000 and Bassols et al., 2002). Trigeneration systems can have overall efficiencies as high as 90 per cent compared to 33 -35 per cent for electricity generated in central power plants. Trigeneration systems have been in operation for many years7. 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 (Bassols et al., 2002).

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 (Tassou et. al., 2008). 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 (Tassou et. al., 2007). 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°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 (Tassou et. al., 2010).

STIRLING CYCLE REFRIGERATION

The Stirling cycle cooler is a closed-cycle regenerative thermal machine in which gas is shuttled backwards and forwards between the hot end and cold end spaces of the system by a piston and a displacer, so that the temperature of the system during compression is, on average, higher than during expansion. The heat generated in the cycle is rejected through 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. The Stirling cycle was first commercially employed for refrigeration in the 1950s by the Philips company in Eindhoven. Little development was done on the Stirling cycle for higher temperature commercial refrigeration applications until the 1990s, which saw the beginning of the development of free-piston Stirling coolers (Sun et al., 2008). FPSC units with nominal maximum cooling capacities of 40W and 100W have been produced, with larger capacity units, up to 300W, reported to be under development8.

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 two and three have been reported for cold head temperatures around 0°C, and values around one for cold head temperatures approaching – 40°C. FPSCs can operate down to cryogenic temperatures and hence can be used in many food refrigeration applications. The 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.

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 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 (Sun et al., 2008).Research and development needs wider application of FPSCs to the food sector requiring higher cooling capacities and higher system COPs, and improved heat exchange and better system integration to reduce temperature differences on the cold and warm sides (Tassou et al., 2010).

THERMOELECTRIC REFRIGERATION

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 (Bansal, et al., 2000).Thermoelectric modules are available commercially to suit a wide range of small and medium cooling duties. 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 COP of the system.Thermoelectric cooling systems offer advantages of no moving parts and good reliability, absence of noise and vibration, compactness and low weight. However, they have lower COP and higher capital cost than vapour compression systems (Riffatt et al., 2003). 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 and drinking water coolers. Other potential future applications include domestic and commercial refrigerators and freezers, and mobile refrigeration and cooling systems.

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 (Stockholm, 1997). Thermoelectric cooling products available for the food sector include compact refrigerators (15-70 litre) for hotel rooms (mini-bar), mobile homes, trucks, recreational vehicles and cars; wine coolers; portable picnic coolers; beverage can coolers and drinking water coolers (Riffatt et al., 2003). Prototype domestic refrigerators of larger capacity (115 litre and 250 litre) have been built and tested, achieving COPs up to 1.2 (Min et al., 2006).

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 (Tassou et al., 2010).

THERMOACOUSTIC REFRIGERATION

Thermoacoustic refrigeration systems operate by using sound waves and a non-flammable mixture of inert gas (helium, argon, air) in a resonator to produce cooling. Thermoacoustic devices are typically characterised as either ‘standing-wave’ or ‘travelling-wave’ (Bammann et al., 2005).

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. The temperature difference is used to remove heat from the cold side and reject it at the hot side of the system. 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.

Thermoacoustic refrigerators have the potential to cover the whole spectrum of refrigeration down to cryogenic temperatures. A number of design concepts and prototypes are under development in many research establishments. Research effort is currently directed to the development of flow-through designs (open systems) which will reduce or eliminated the use of heat exchangers. 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. 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(Tassou et al., 2010).

MAGNETIC REFRIGERATION

A magnetic refrigeration cycle employs a solidstate magnetic material as the working refrigerant, and exploits the magnetocaloric effect (MCE), the ability of a material to warm-up in the presence of a magnetic field and cool down when the field is removed. Magnetisation and demagnetisation 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. Further advantages associated with the solid-state nature of magnetic refrigerants are zero ODP and zero GWP which offer the prospect of efficient, environmentally friendly and compact cooling. Magnetic refrigeration technology is under active development and a number of prototype systems (including both reciprocating and rotary designs) have been announced. Cooling capacities of prototypes are low, with a COP of 1.8 at room temperature (Pecharsky et al., 2006)**.**

Although relatively little attention has been paid to specific future applications of magnetic refrigeration, it is evident that Magnetic refrigeration has the potential for use across the whole refrigeration temperature range, down to cryogenic temperatures but further research and development is still required for the development of materials with high magnetocaloric effect, to reduce the size, weight and cost of the system. It is anticipated that the first commercial applications will be for low capacity stationary and mobile refrigeration systems. 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 (Tassou et al., 2010).

CONCLUSION

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.

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) have also been re-evaluated as a replacement of vapour compression systems. Other possible systems include air cycle, hybrid and solar powered systems and recovery of thermal energy from the engine exhaust and use it to drive sorption systems, ejector systems, thermoacoustic refrigerators and or/for power generation using thermoelectrics or turbogenerators.

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 refrigeration systems. Other candidate technologies approaching commercialisation are thermoelectric, thermoacoustic and magnetic refrigeration.

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 trigeneration technologies. CO_2 based systems are also fast gaining in popularity and a number of different system configurations have already been adopted.

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°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 bi-product of food processing for CHP and trigeneration.

Food storage (cold stores): Large food storage facilities normally employ ammonia vapour compression plant and this is likely to 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 not densely populated areas, food storage facilities offer potential for the use of biomass for combined heat and power or trigeneration. A small number of such plants are 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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