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Emerging and Alternative Refrigeration Technologies for Food Industry

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Abstract
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 hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) as refrigerants a number of alternative systems and technologies are being developed that offer the potential for lower GHG (Green House Gases) emissions. Refrigeration has become an essential part of the food chain. It is used in all stages of the chain, from food processing, packaging, 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 –30°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. These alternative approaches and future technologies that could be used to reduce the energy consumption and GHG emissions associated with the refrigeration of food. The emerging refrigeration technologies have also potential to reduce the environmental impacts of refrigeration in the food industry.

1. Introduction

The food industry employs both chilling (cooling to a temperature above 0°C) and freezing (temperature between -18°C and –35°C) processes. Refrigeration is used in all stages of the cold chain, from food processing, to distribution, retail and final consumption. In the food sector still 23% food losses in the developing countries and 9% in developed countries take place due to lack of refrigeration. Thus there is an emerging need of increasing the use of refrigeration by development of cold storage infrastructure and cold chains especially in developing countries. This need would further rise with the increase in population, shifting of more population to the urban areas and also due to increasing westernized models.

A significant impact is greenhouse gas emissions. Sources of greenhouse gas emissions for the industry include CO2 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 hydro chlorofluorocarbons (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 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 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.

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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.

2. Emerging and Alternate Refrigeration Technologies

2.1 Vapor Absorption Refrigeration System

The vapour absorption refrigeration system is one of the oldest methods of producing refrigeration effect. The simple vapour absorption system consists of an absorber, a pump, a generator and a pressure reducing valve to replace the compressor of the vapour compression system. The other components of the system are condenser, receiver, expansion valve and evaporator as in the vapour compression refrigeration system. In this system, the vapour refrigerant from the evaporator is drawn into an absorber by the absorbent solution. This solution is pumped to a generator where it is heated by some external thermal energy. During the heating process, the vapour refrigerant is driven off from the solution and enters into the condenser, where it is liquefied. The liquid refrigerant then flows into the evaporator and thus the cycle is completed (Khurmi and Gupta, 2011).

Vapour absorption refrigeration systems are attractive and of increasing interest because they can be driven by low-temperature heat sources and provide an excellent way for converting solar energy or waste heat into useful refrigeration. They differ from compression systems due to the use of a heat source as energy input to operate; on the other hand, the refrigeration devices based on compression systems need mechanical energy to operate. This is the main advantage of absorption systems; which can run on burning fuel or using waste heat, recovered from other thermal systems. Most of industrial processes use a lot of thermal energy by burning fossil fuel to produce steam or heat. After the processes, heat is rejected to the surrounding as waste. This waste heat can be converted to useful refrigeration by using a heat operated refrigeration system, such as an absorption refrigeration cycle (Srikhirin et al., 2001).

A large number of researchers have carried out research in the field of vapor absorption refrigeration using different working pairs and the most common working pairs are LiBr-H2O and NH3-H2O. Renjith and Joshy (1999) studied the effect of operating temperature of generator, evaporator and condenser on the COP of vapour absorption refrigeration system using low grade energy. Alizadeh et al. (1997) carried out theoretical study on design and optimization of water–lithium bromide refrigeration cycle. They concluded that for a given refrigerating capacity higher generator temperature causes high cooling ratio with smaller heat exchange surface and low cost. There is a limiting factor for water lithium bromide cycles because of the problem of crystallization. Srikhirin et al. (2001) observed that the COP of the single effect vapour absorption refrigeration system increased up to 60% when a solution heat exchanger is used. Patek and Klomfae (1995) reported that the COP of the system increased with increase in number of effect. They found that a double effect absorption system has a COP of 0.96 when the corresponding single-effect system has a COP of 0.6.

The refrigeration system which operates using thermal energy has a scope for generation of chilled water required in dairy industries. The system is known as vapour absorption refrigeration (VAR) system. The thermal energy required may be in the form of steam, waste heat, natural gas etc. to supply necessary thermal energy for the system. The VAR system uses either water-ammonia or LiBr-water as working fluid. Thermal energy is required to liberate refrigerant from the mixer in place of compressor of VCR system. VAR system using LiBr-water can be used for generation of temperature above 0 ^{o}C. The system can be used for production of chilled water at about 4-5 ^{o}C, for chilling of milk, storage of fruits and vegetables, air conditioning in packaging of butter and other frozen food products.

2.2 Solar Refrigeration

The energy of solar radiations can be used in two ways either as a direct heat source or through generation of electric energy in a solar panel. Both the methods can be used in refrigeration. The heat energy of solar radiations can be used as direct input to a vapor absorption refrigeration system. The electric energy produced by a solar panel may be directly used as input to a conventional vapour compression refrigeration system. But like in other applications of solar energy, the use of storage batteries is essential for supply during night or during hours of no Sun. These batteries are an additional problem due to rise in the initial cost and maintenance cost of the system. The disposal of these lead acid batteries also poses a big threat to the environment. Due to these constraints, solar refrigeration is still not in widespread use. However this is still the most attractive choice as there is no running cost and no concern to environment control as far as energy production is concerned. The innovation uses a variable speed, direct current (DC) vapor compression cooling system, connected to a solar photovoltaic (PV) panel via novel electronic controls. This environment friendly system is ideal for use in commercial or household refrigerators, freezers, vaccine coolers, or solar ice-makers. It is particularly ideal for off-grid applications. It employs a PV panel, vapor compressor, thermal storage and reservoir, and electronic controls. The process that makes the refrigeration possible is the conversion of sunlight into DC electrical power, achieved by the PV panel. The DC electrical power drives the compressor to circulate refrigerant through a vapor compression refrigeration loop that extracts heat from an insulated enclosure. This enclosure includes the thermal reservoir and a phase change material (PCM). This material freezes as heat is extracted from the enclosure. This process effectively creates an "ice pack," enabling temperature maintenance inside the enclosure in the absence of sunlight.

2.3 Solar Vapour Absorption Refrigeration (Svar) System

Hot water is generated in the solar collector and it is stored in the insulated storage tank. The hot water from hot water storage tank is supplied to the generator to boil off water vapor from the solution of lithium bromide-water. The water vapor is cooled down in the condenser and then passed to the evaporator where it is again evaporated at lower pressure and temperature. The strong solution leaving the generator and flowing to the absorber passes the solution heat exchanger to preheat the weak solution entering the generator. In the absorber the strong solution absorbs the water vapor leaving the evaporator (Jesko, 2008).

3. Ejector Refrigeration System

Ejector or Jet refrigeration is also a thermally driven technology that is not new and has been used for cooling applications for many years. It is a simple method of refrigeration with no moving parts. But it has a much lower COP than vapour compression systems. The greatest advantage of this system has been recognized in their capability to produce refrigeration using waste heat or solar energy as a heat source at temperatures above 80oC. The ejector refrigeration system consists of two loops, the power loop and the refrigeration loop. In the power loop, low grade heat is used in a boiler or generator to evaporate high pressure liquid refrigerant known as the primary fluid. The high pressure vapour flows through the ejector where it accelerates through the nozzle. The reduction in pressure at the exit of nozzle sucks vapour known as the secondary fluid from the evaporator. 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. A portion of the liquid exiting the condenser 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. The refrigerant which evaporates in the evaporator due to vacuum created by the ejector produces refrigeration effect. The key driver to uptake this technology is better thermal integration of processes in food manufacturing. The barriers are lower COPs 0.2~0.3 and the unavailability of off the shelf systems to facilitate selection for particular applications.

4. Air Cycle Refrigeration

Air cycle refrigeration systems work on modified basic reversed Joule (or Brayton) cycle including regenerative heat exchanger. Air cycles can be classified as closed, open or semi-open/closed. Closed cycles are sealed systems and consequently there is no direct contact between the working fluid and the product being cooled. 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. Air cycle refrigeration is an environmentally friendly and reasonably well established, albeit under-exploited, technology. The COP is in the range of range 0.4 to 0.7 and is relatively unaffected under part-load conditions. It can deliver air temperatures down to -100°C or below, which is 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 in dairy/ food industry. The main barriers to uptake of air cycle technology are unavailability of packaged equipment off the shelf for application in the food sector and insufficient performance data from commercial applications to provide confidence in the application of the technology.

5. Magnetic Refrigeration

Magnetic refrigeration is a new technology for use in commercial refrigeration and is still undergoing extensive research. It is based on the magneto-caloric effect by which a magnetic material changes its thermodynamic properties under the influence of external magnetic field. However the observation of this effect is known since 1880 but in the past it was only used for low temperature physics to achieve near 0 K. It is a promising technology and has the potential of replacing the conventional MVC refrigeration systems. Its advantages over the existing systems are its very high COP (up to 100% more), silent operation and it is environmentally clean with the absence of harmful refrigerants. The working cycle here is similar to that in VCR system but the difference is that the compression and expansion processes are replaced by the magnetization and demagnetization of a magneto-caloric material like Gadolinium. On magnetization the material gets heated and on demagnetization it gets cooled and used for the refrigeration. Because of high frequency of the magnetization and demagnetization processes there is no time for heat exchange from the solid or porous material which is a real problem in these systems. In a typical design by Andrej Kitanovski a rotating disc of porous magneto-caloric material rotates and passes through four separate quadrants in which two opposite quadrants have magnetic field and also through which the cooling fluid flows to take away the heat of magnetized and heated portions of the disc. The refrigerated fluid passes through the other two quadrants and gets cooled by the cooling of demagnetized portions of the disc. Due to difficulty in exchanging heat between the rotating disc and fluid passing through it in a short time, it has to be operated at lower frequency not more than 100Hz i.e the disc has to be rotated at no more than 50 rpm. On the other hand for a given cooling effect the higher frequency of operation leads to lower mass of the permanent magnets assembly which is directly related to the size and cost of the machine. This is a key issue for wider/ deeper market penetrations of this kind of refrigeration systems (Pryds et al., 2010) High frequency modules with classical and nano-scale Peltier elements (Thermoelectric switch)

The solution to the key problem of a magnetic refrigeration system has been suggested by Kitanovski and Egolf (2010) by the use of high frequency modules in which a thin magnetocaloric material is built in a sandwich structure between two thermoelectric layers. Furthermore these three components are layered between two micro channels for constant flow of heating and cooling fluids separately on either side. The thermoelectric layers act as thermal switch between the magnetocaloric material and the fluids. These switches allow the flow of heat from the magnetocaloric material when it is in magnetized and hot condition to the cooling fluid side and from the refrigerated fluid to the magnetocaloric material when it is in demagnetized and cooled condition at a high frequency thus enhancing the overall performance.

With the use of new technology Nano-tubes Peltier elements the frequency can be raised to 1000 Hz. Now the limitation lies in the heat flow through magnetocaloric material itself. Finally many other practical aspects also must be investigated e.g. the durability of thermal switches and simple and cheap production methods.

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